Introduction to Aerospace Engineering

Lecture slides

Introduction to Aerospace Engineering I (AE1102)

Dept. Space Engineering

Astrodynamics & Space Missions (AS)

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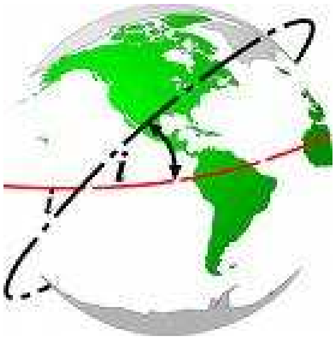

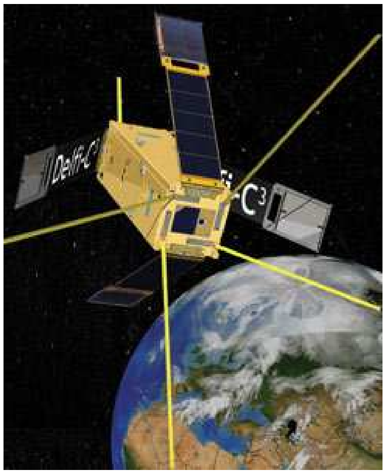

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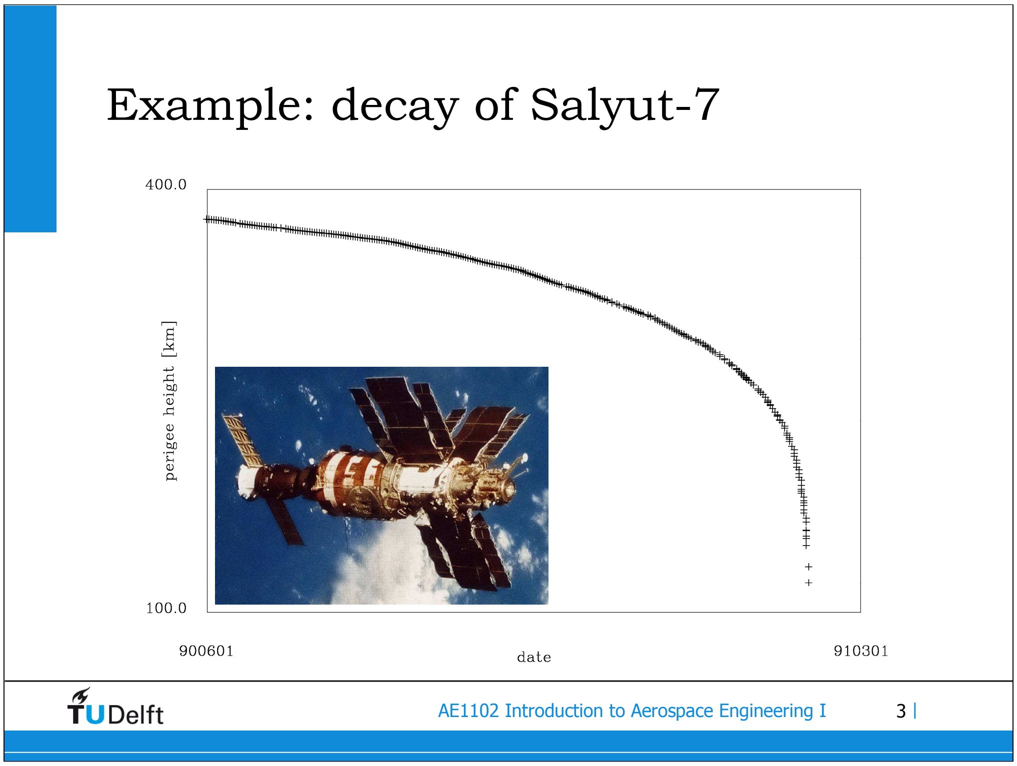
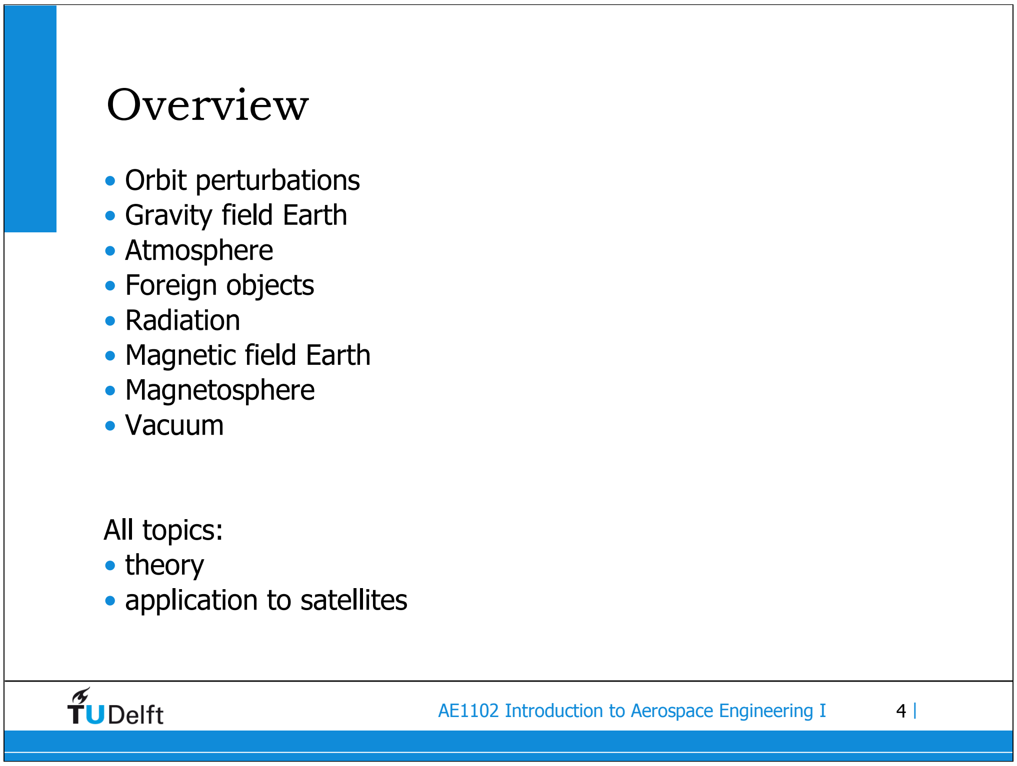
Space environment



Example: decay of Salyut-7

Not knowing the environment in which a satellite will be operating, can result in a disaster. This example shows the effect of atmospheric drag on the pericenter height of the Russian space station Salyut-7, which was abandoned in 1986 and left to decay in the subsequent years.



Overview

- Orbit perturbations
- Gravity field Earth
- Atmosphere
- Foreign objects
- Radiation
- Magnetic field Earth
- Magnetosphere
- Vacuum

All topics:
- theory
- application to satellites

Although related to the environment of the Earth, similar phenomena of course are present in interplanetary space or in the direct vicinity of other planets or moons. For all topics treated here, first a concise description of the phenomenon itself will be given, followed by a discussion on the effects on spacecraft.

Learning goals

The student should be able to:

- describe the elements in the space environment
- describe and explain the relations between a spacecraft and its natural environment
- quantify the elements of the space environment as a function of relevant parameters (e.g. altitude)
- quantify the impact of space environment on a mission design

Lecture material:

- these slides (incl. footnotes)

Relevance

These 2 lectures deal with the space environment and its interaction with a spacecraft around the Earth. Of course, the theories and fundamentals of these interactions also apply for situations near other celestial bodies (albeit with different numbers). For more information on other planets etcetera, use for instance:

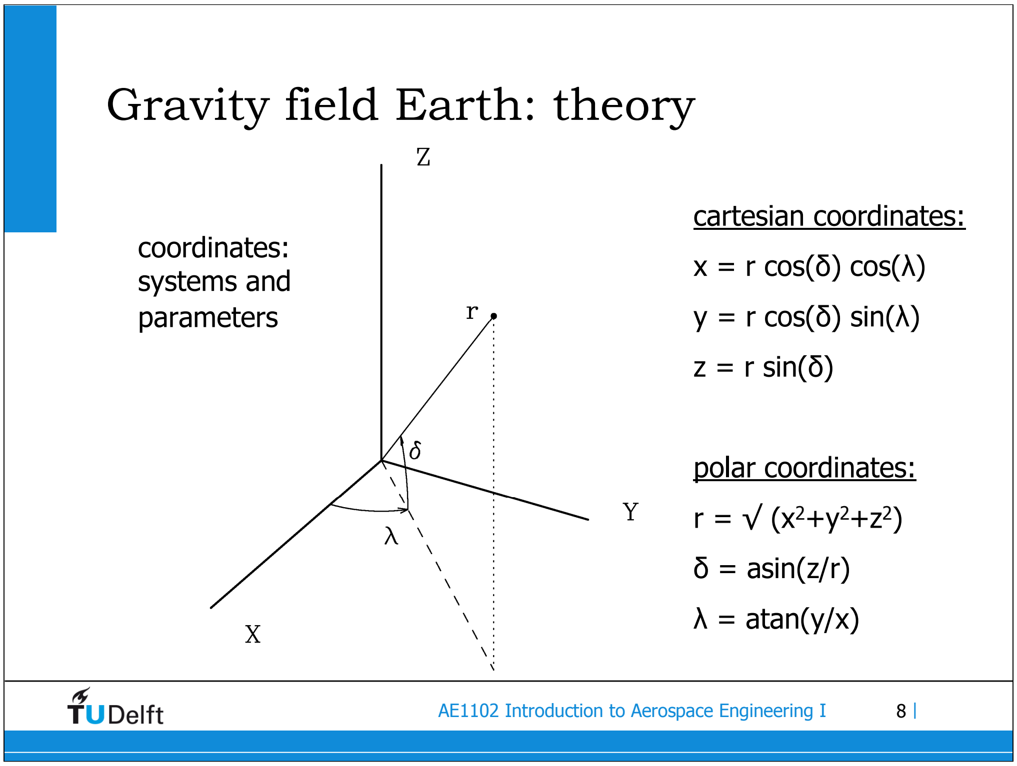
- www.solarviews.com/eng/data.htm
- pds.jpl.nasa.gov/planets/
- hyperphysics.phy-astr.gsu.edu/HBASE/solar/soldata2.html
- nssdc.gsfc.nasa.gov/planetary/

Orbit perturbations (general)

- Deviations from the “ideal” gravity field (10^-3)
- Atmospheric drag (10^-3 till 0)
- 3rd body gravitational effects (10^-5)
- Solar radiation pressure (10^-6)
- Albedo (10^-7)
- Interaction with magnetic fields (10^-9)
- Relativistic effects (10^-9)
- ???

Only basics here… More details in 2nd year lectures

NB. Order of magnitudes are relative to central gravity field force for LEO



Gravity field Earth: theory

coordinates:
systems and
parameters

<u>cartesian coordinates:</u>

$x = r \cos(\delta) \cos(\lambda)$

$y = r \cos(\delta) \sin(\lambda)$

$z = r \sin(\delta)$

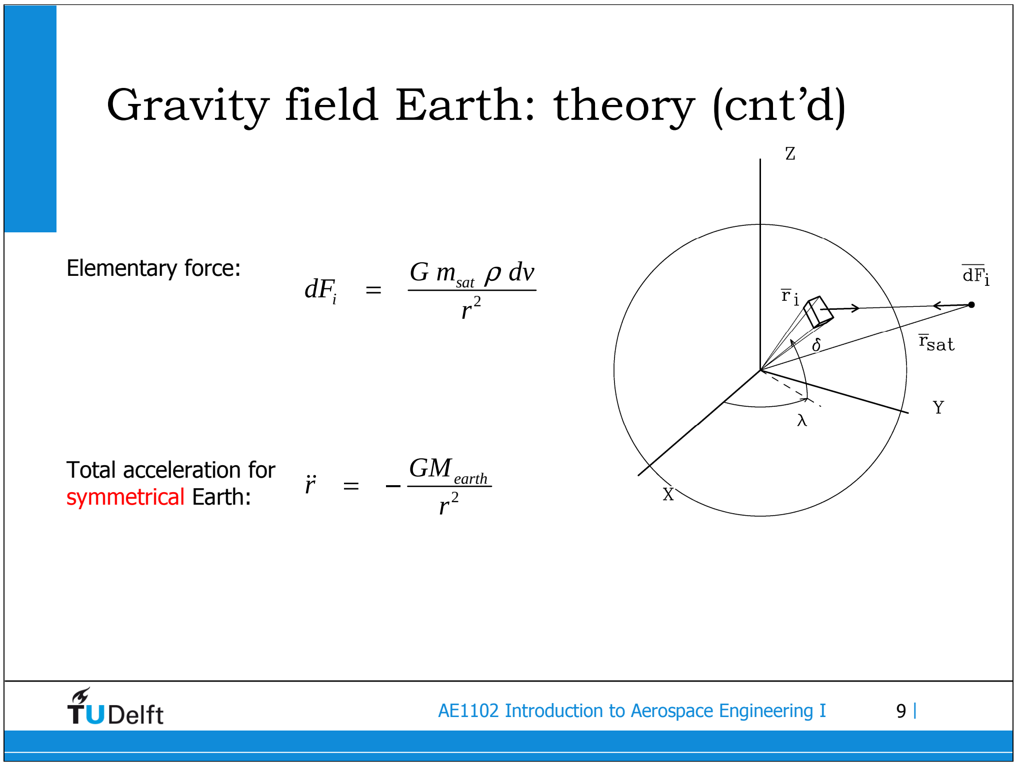
<u>polar coordinates:</u>

$r = \sqrt{(x^2+y^2+z^2)}$

$\delta = \mathrm{asin}(z/r)$

$\lambda = \mathrm{atan}(y/x)$

Selecting a proper reference system and a set of parameters that describe a position in 3 dimensions is crucial to quantify most of the phenomena treated in this chapter, and to determine what a satellite mission will experience. Option 1: cartesian coordinates, with components x, y and z. Option 2: polar coordinates, with components r (radius, measured w.r.t. the center-of-mass of the central object; not to be confused with the altitude over its surface), δ (latitude) and λ (longitude).



Gravity field Earth: theory (cnt'd)

Elementary force: $$dF_i = \frac{G\, m_{sat}\, \rho\, dv}{r^2}$$

Total acceleration for symmetrical Earth: $$\ddot{r} = -\frac{GM_{earth}}{r^2}$$

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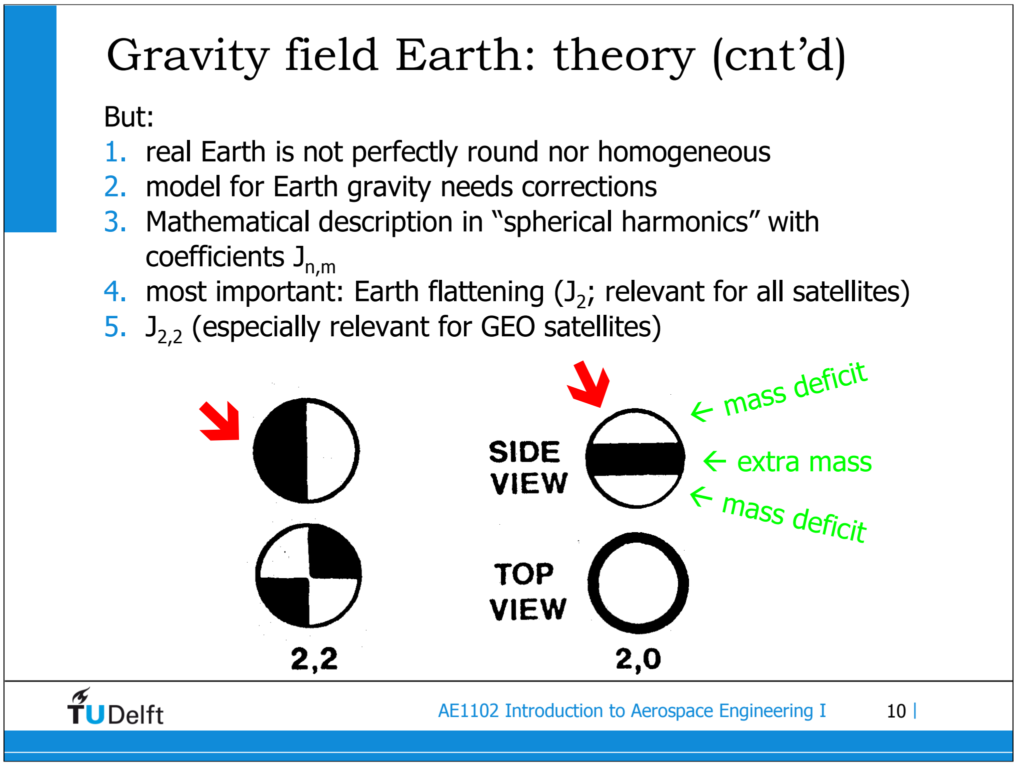
Parameter “G” is the universal gravitational constant (6.67259×10^{-11} $m^3/kg/s^2$), “m_{sat}” represents the mass of the satellite, “r” is the distance between the satellite and a mass element of the Earth (1st equation) or between the satellite and the center-of-mass of the Earth (2nd equation), “ρ” is the mass density of an element “dv” of the Earth [kg/m^3], “M_{earth}” is the total mass of the Earth (5.9737×10^{24} kg). The product of G and M_{earth} is commonly denoted as “μ” , which is called the gravitational parameter of the Earth ($=G\times M_{earth}=398600.44\times10^9$ m^3/s^2).



Gravity field Earth: theory (cnt'd)

But:

1. real Earth is not perfectly round nor homogeneous
2. model for Earth gravity needs corrections
3. Mathematical description in "spherical harmonics" with coefficients $J_{n,m}$
4. most important: Earth flattening (J_2; relevant for all satellites)
5. $J_{2,2}$ (especially relevant for GEO satellites)

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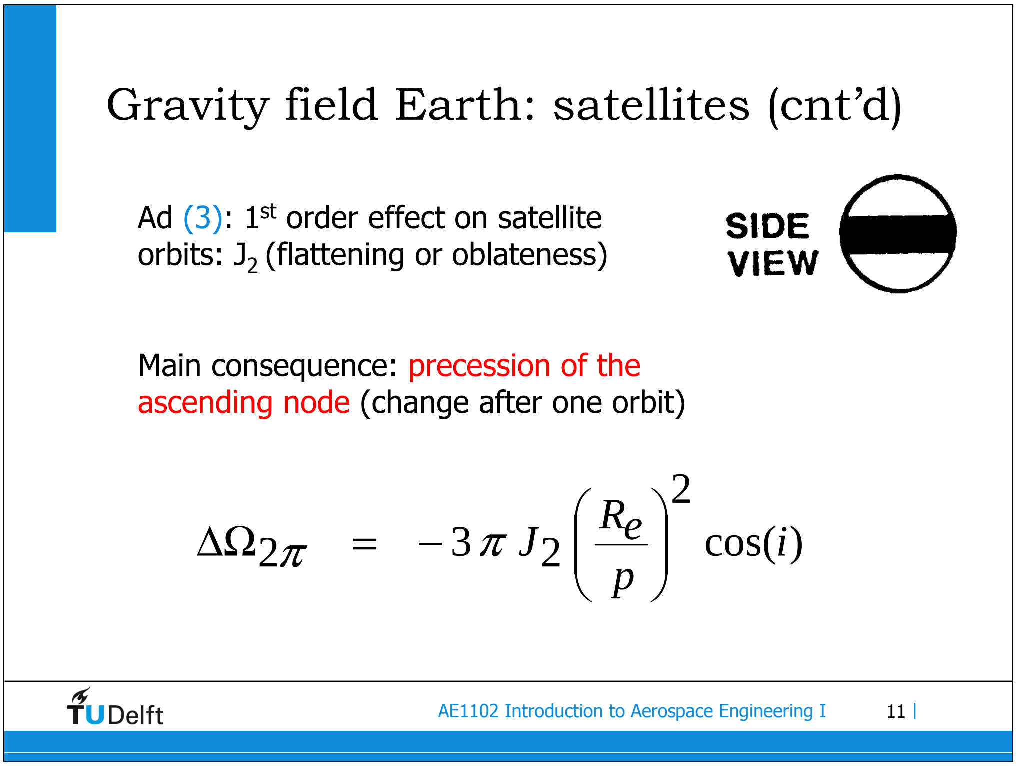
The collection of these (and other) terms can be regarded as corrections to the 1st order model of a spherical, radially symmetric Earth. The equatorial bulge is represented by the J_2 (or $J_{2,0}$, as depicted in this plot) term, which is the dominant correction term in the Earth's gravity field model.



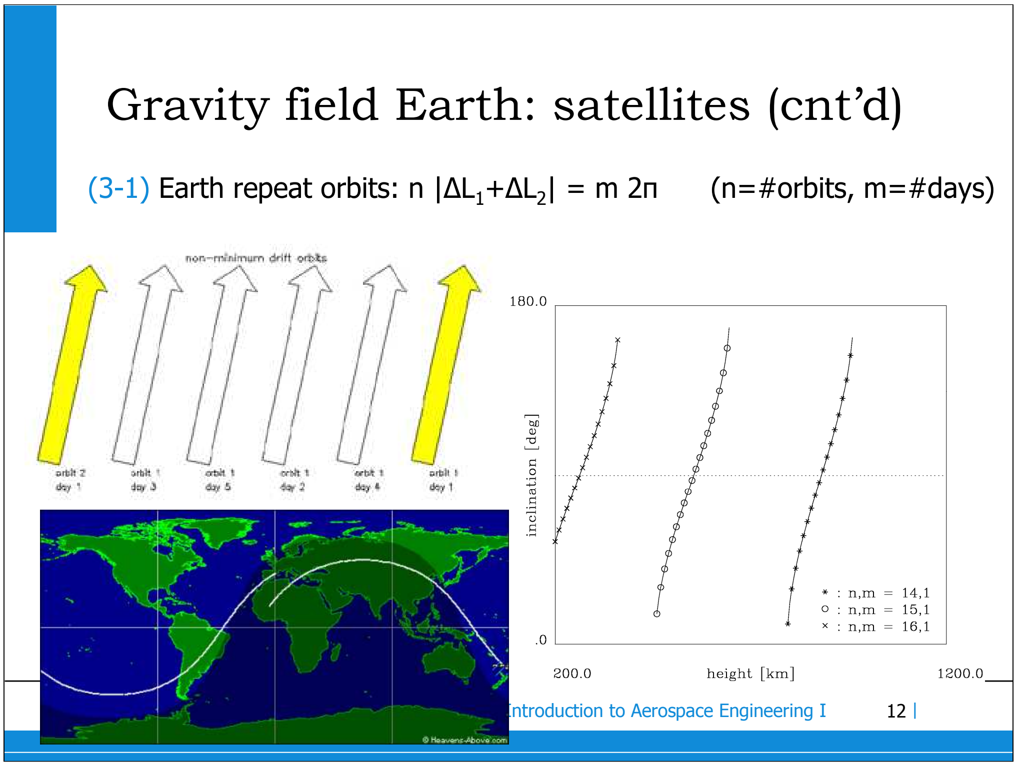
Gravity field Earth: satellites (cnt'd)

Ad (3): 1st order effect on satellite orbits: J_2 (flattening or oblateness)

Main consequence: precession of the ascending node (change after one orbit)

$$\Delta\Omega_{2\pi} = -3\,\pi\,J_2\left(\frac{R_e}{p}\right)^2 \cos(i)$$

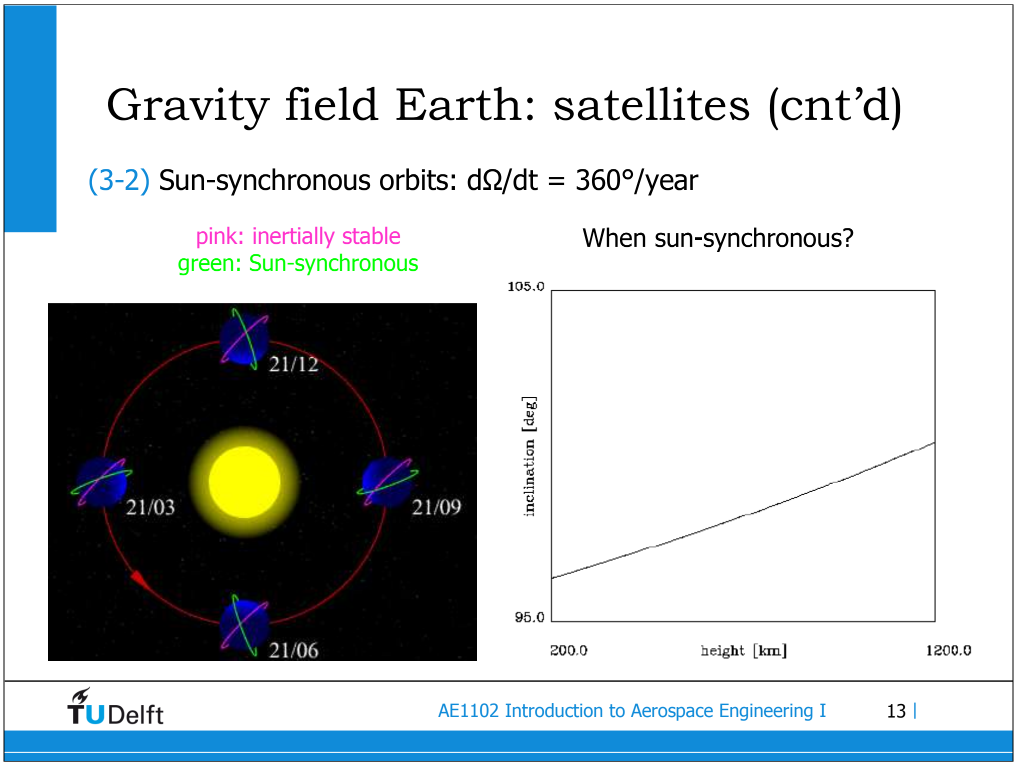
The net change in Ω, after 1 complete revolution of the satellite around the Earth. Parameter ”p” represents the semi-latus rectum ($p=a(1-e^2)$). J_2 is about 1082×10^{-3}.



Gravity field Earth: satellites (cnt'd)

(3-1) Earth repeat orbits: $n\ |\Delta L_1+\Delta L_2| = m\ 2\pi$ (n=#orbits, m=#days)

ΔL_1 represents the change in position over the equator, after 1 full (unperturbed) revolution of the satellite (NOTE: in an Earth-fixed, co-rotating system!). ΔL_2 represents the effect of J_2 on this position (so the total shift is the summation of the two). Earth repeat orbit: the orbital parameters can be chosen such, that the ground track of the orbit (*i.e.* the projection of the orbit on the Earth's surface) repeats after an integer number of days and orbits; the effect is due to the rotation of the Earth itself and the precession of the ascending node (as shown on the previous sheet). For instance, a satellite could fly 14 orbits in a day, and the 15th (*i.e.* the 1st one of the next day) would overlap perfectly with the 1st one of the previous day. The plot on the right shows options for a repeat cycle of 1 day, but similar lines can be drawn for repeat cycles of 3 days, 5 days, or any arbitrary integer number.



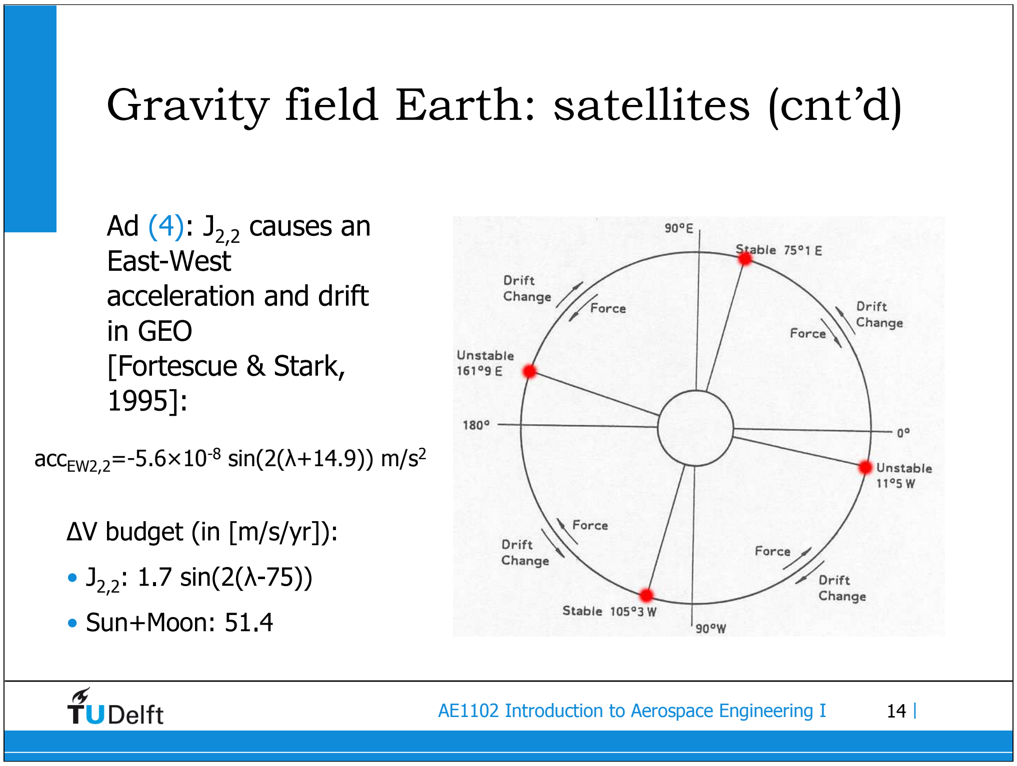
Gravity field Earth: satellites (cnt'd)

(3-2) Sun-synchronous orbits: dΩ/dt = 360°/year

pink: inertially stable
green: Sun-synchronous

When sun-synchronous?

Sun-synchronous orbit: the orbital parameters can be chosen such, that the orientation of the orbit w.r.t. the Sun remains more-or-less constant (ignoring the North-South motion of the Sun w.r.t. the Earth's equator). The effect is due to the precession of the ascending node (as shown on the previous sheets). The requirement on the precession of the ascending node translates into a strict combination of semi-major axis and inclination (*right*). The absolute value of Ω is still a free choice.



Gravity field Earth: satellites (cnt'd)

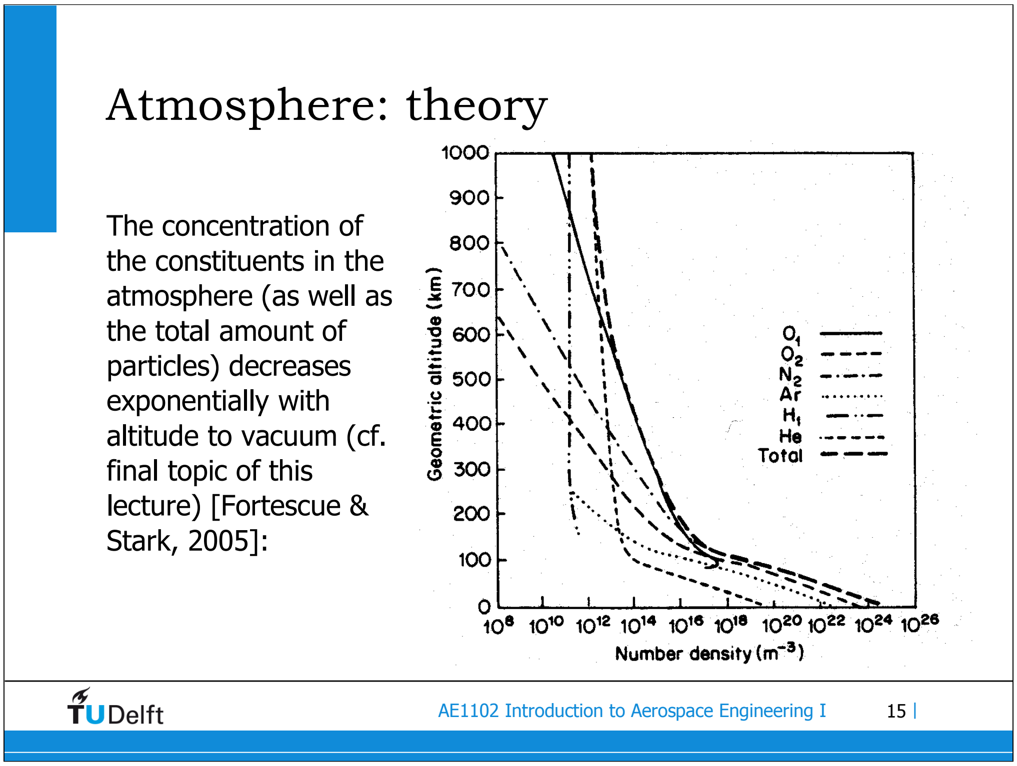
Ad (4): $J_{2,2}$ causes an East-West acceleration and drift in GEO [Fortescue & Stark, 1995]:

$$acc_{EW2,2} = -5.6 \times 10^{-8} \sin(2(\lambda + 14.9))\ \mathrm{m/s^2}$$

ΔV budget (in [m/s/yr]):

- $J_{2,2}$: $1.7 \sin(2(\lambda - 75))$
- Sun+Moon: 51.4

Although its magnitude is very small, the East-West acceleration on geostationary satellites caused by $J_{2,2}$ acts continuously in the same direction (the satellite is Earth-fixed!), and hence can build up into a significant effect. This plot gives the acceleration in an Earth-fixed (*i.e.*, co-rotating) system; the effect of the perturbing acceleration is in opposite direction of the acceleration itself. Four equilibrium points can be distinguished. When a satellite is not located in one of these equilibrium points, this acceleration adds to the ΔV budget. The equilibrium points depicted here do not perfectly match the zero-crossings of the equation, since they also include effects of other perturbations from the gravity field.



Atmosphere: theory

The concentration of the constituents in the atmosphere (as well as the total amount of particles) decreases exponentially with altitude to vacuum (cf. final topic of this lecture) [Fortescue & Stark, 2005]:

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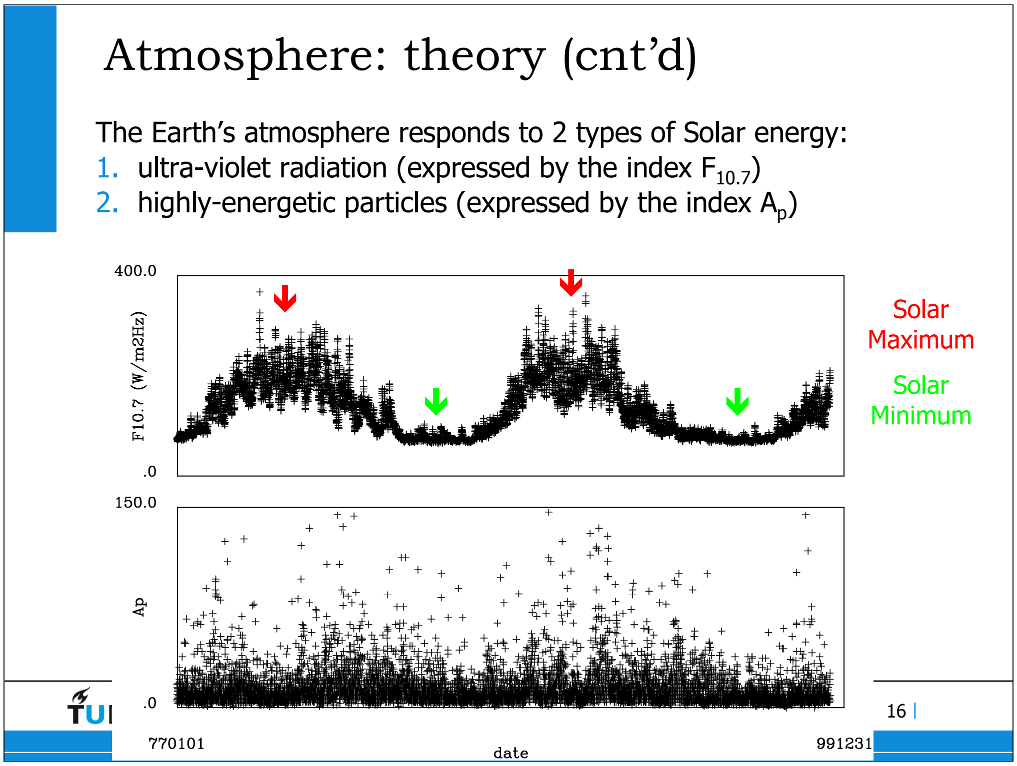
To first order: $\rho(z)=\rho(z_0)\times\exp((z_0-z)/H)$, where ρ is mass density, z_0 is a reference altitude and H is the so-called density scale height ($H= RT/M_i g$) (R = universal gas constant, T = temperature, M_i = molar mass of constituent, g = gravitational acceleration).



Atmosphere: theory (cnt'd)

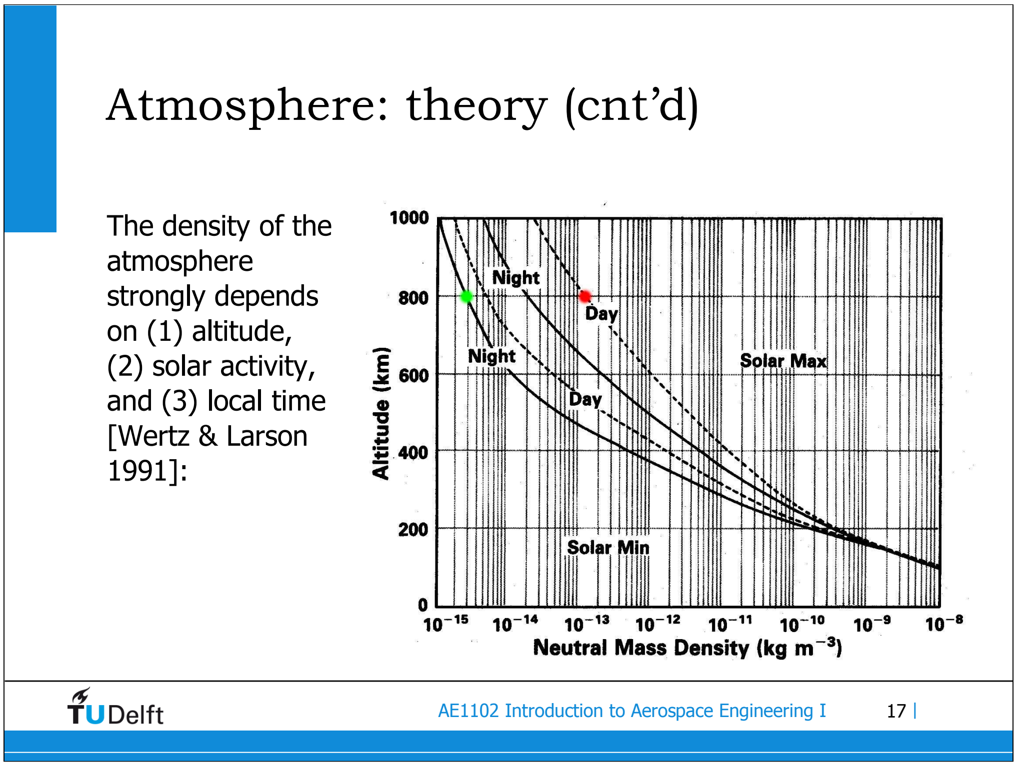
The Earth's atmosphere responds to 2 types of Solar energy:

1. ultra-violet radiation (expressed by the index $F_{10.7}$)
2. highly-energetic particles (expressed by the index A_p)

Solar Maximum

Solar Minimum

The intensity of ultraviolet radiation (at wavelengths of about 10^{-7} m) is expressed by the intensity of solar radiation with wavelength 10.7 cm (a so-called "proxy"). The intensity of UV radiation clearly follows the 11-year solar cycle. The amount of highly-energetic particles is measured by monitoring their perturbation of the Earth's magnetic field. Their concentration shows a weak correlation with solar activity.



Atmosphere: theory (cnt'd)

The density of the atmosphere strongly depends on (1) altitude, (2) solar activity, and (3) local time [Wertz & Larson 1991]:

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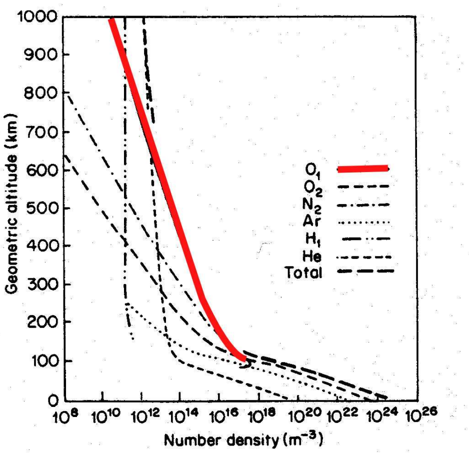
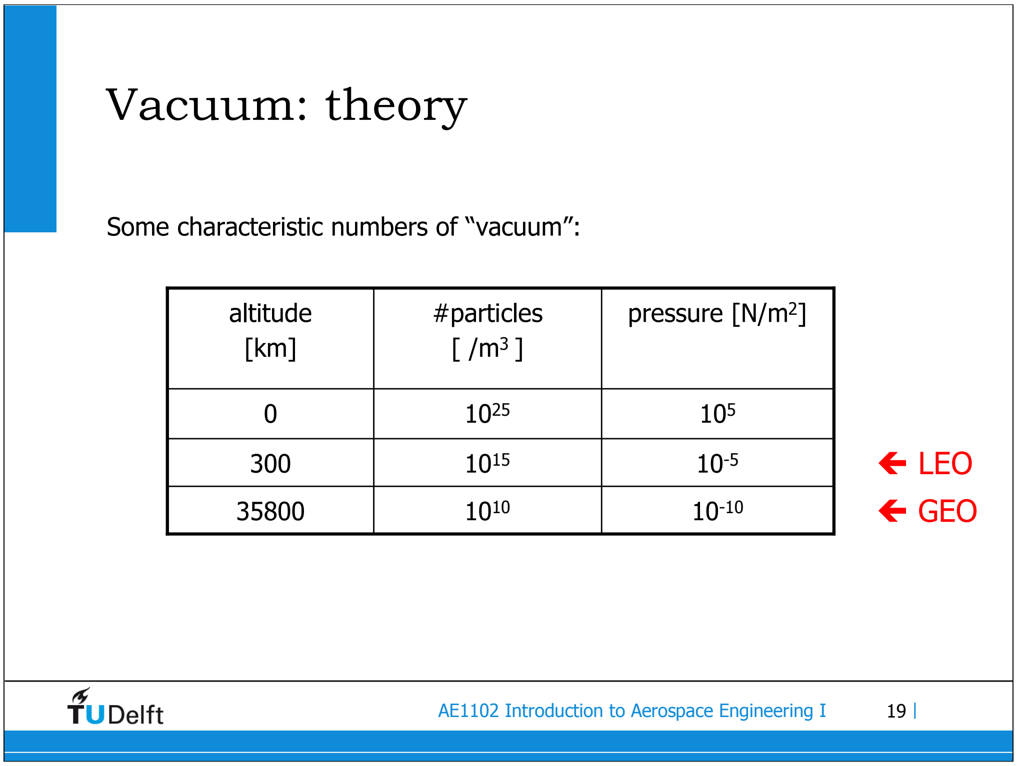
During a solar maximum, the intensity of UV radiation is larger than average. As a consequence, the energy input into the Earth's atmosphere is increased and the atmospheric density is also (much) higher than average. A similar situation occurs on the day-side of the Earth (compared with the dark side). Atmospheric density can yield variations of up to a factor 100, with consequences for the ΔV budget to compensate for drag losses.

Atmosphere: satellites

Atomic oxygen:

- Small molar mass, so present at high altitudes
- Aggressive: organics, metals and composites
- Malfunctioning of sensors



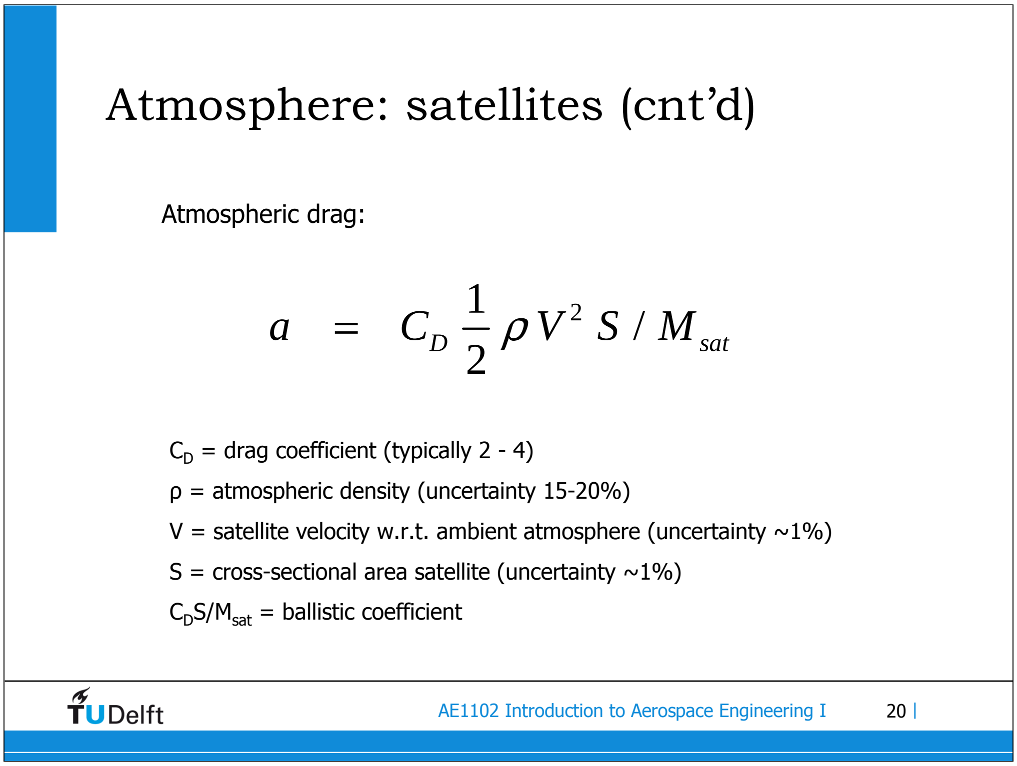


Vacuum: theory

Some characteristic numbers of “vacuum”:

altitude [km]	#particles [/m^3]	pressure [N/m^2]	
0	10^{25}	10^{5}	
300	10^{15}	10^{-5}	← LEO
35800	10^{10}	10^{-10}	← GEO

300 km altitude is ”low-LEO”. 35800 km altitude = GEO.



Atmosphere: satellites (cnt'd)

Atmospheric drag:

$$a = C_D \frac{1}{2} \rho V^2 S / M_{sat}$$

C_D = drag coefficient (typically 2 - 4)

ρ = atmospheric density (uncertainty 15-20%)

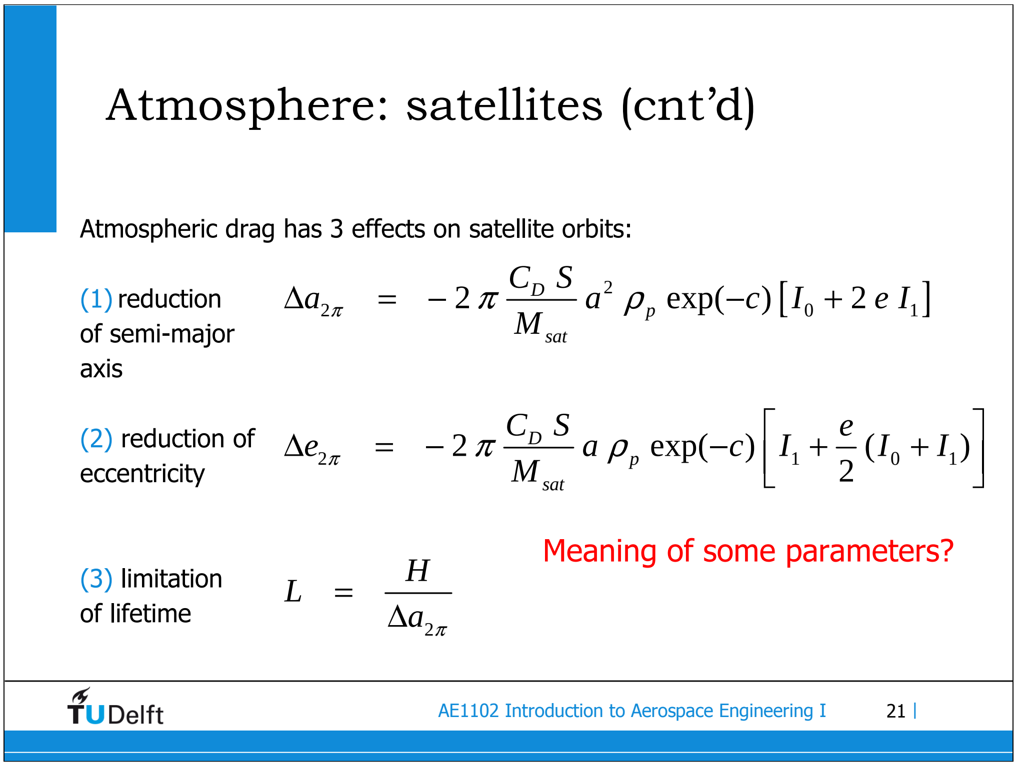
V = satellite velocity w.r.t. ambient atmosphere (uncertainty ~1%)

S = cross-sectional area satellite (uncertainty ~1%)

$C_D S/M_{sat}$ = ballistic coefficient

The variation of atmospheric density with environmental conditions can be a factor 100 or larger (cf. 2 sheets earlier); the uncertainty of the models (knowing these environmental conditions) still is 15-20%.

Similar expressions can be written for the lift and side-force components (as well as torques), but the drag force is by far the most important component.



Atmosphere: satellites (cnt'd)

Atmospheric drag has 3 effects on satellite orbits:

(1) reduction of semi-major axis

$$\Delta a_{2\pi} = -2\,\pi\,\frac{C_D\,S}{M_{sat}}\,a^2\,\rho_p\,\exp(-c)\,[I_0 + 2\,e\,I_1]$$

(2) reduction of eccentricity

$$\Delta e_{2\pi} = -2\,\pi\,\frac{C_D\,S}{M_{sat}}\,a\,\rho_p\,\exp(-c)\left[I_1 + \frac{e}{2}(I_0 + I_1)\right]$$

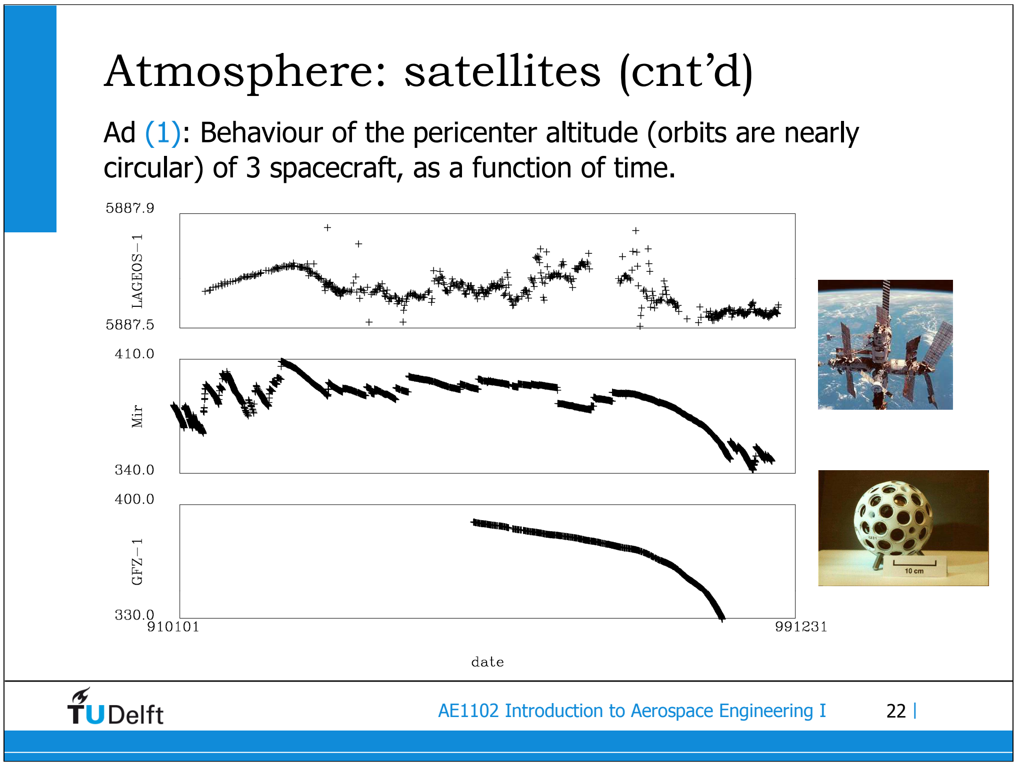
(3) limitation of lifetime

$$L = \frac{H}{\Delta a_{2\pi}}$$

Meaning of some parameters?

The net change (*i.e.* after one complete revolution around the Earth) in semi-major axis "a" and eccentricity "e". Parameter "Msat" represents the mass of the spacecraft, and "ρ_p" the atmospheric density at pericenter (where the drag force is typically largest). For circular orbits (e=0), the value of the part "exp(-c)[…]" is approximately 1. The last equation gives the lifetime L expressed in number of revolutions (so needs to be divided by the orbital period to express this in seconds, minutes, days).

First-order numerical values for density ρ and density scale height H can be found in for instance [Wertz & Larson, 1991].



Atmosphere: satellites (cnt'd)

Ad (1): Behaviour of the pericenter altitude (orbits are nearly circular) of 3 spacecraft, as a function of time.

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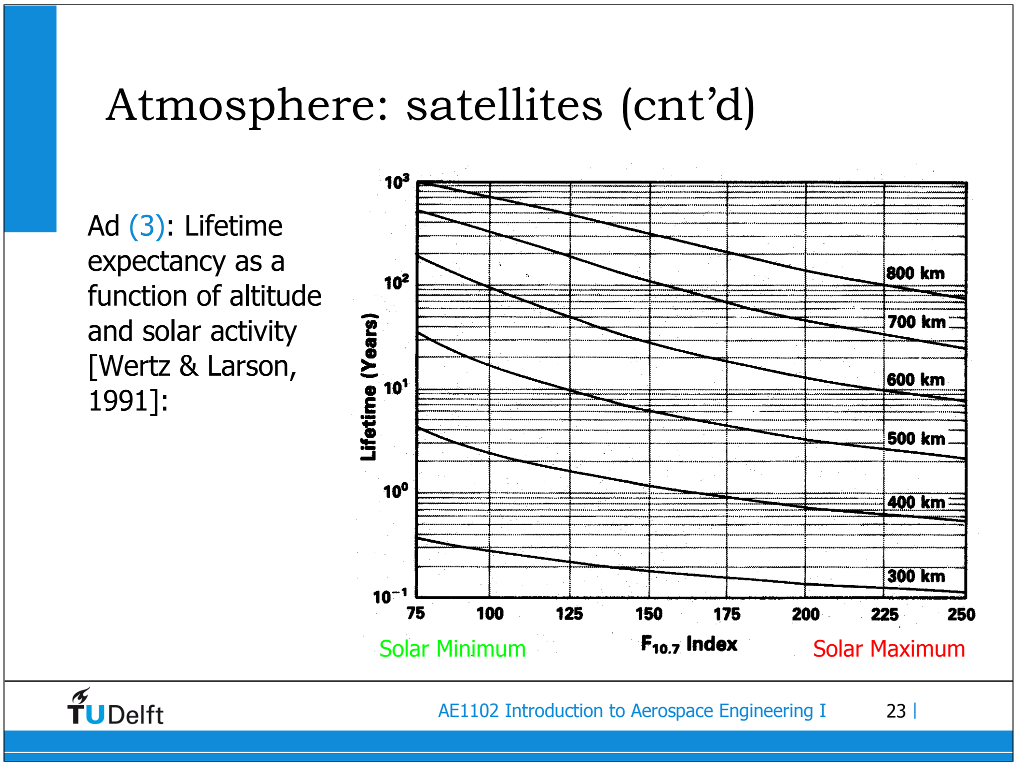
The altitude of LAGEOS-1 (top) is such that it is not affected by atmospheric drag. The Russian space station Mir (middle) and the German satellite GFZ-1 (bottom) orbited the Earth at about 350 km, where drag is dominant. GFZ-1 is fully passive, but Mir was boosted to a higher orbit once every few months. The orbital decay shows a direct correlation with atmospheric density, which in turn is highly correlated with solar activity. Mir and GFZ-1 are completely different spacecraft, but with more-or-less the same rate of orbital decay.

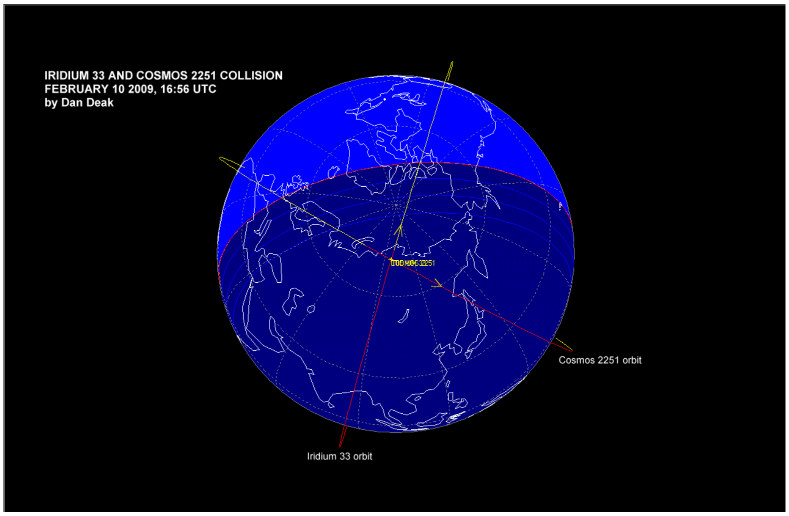


Atmosphere: satellites (cnt'd)

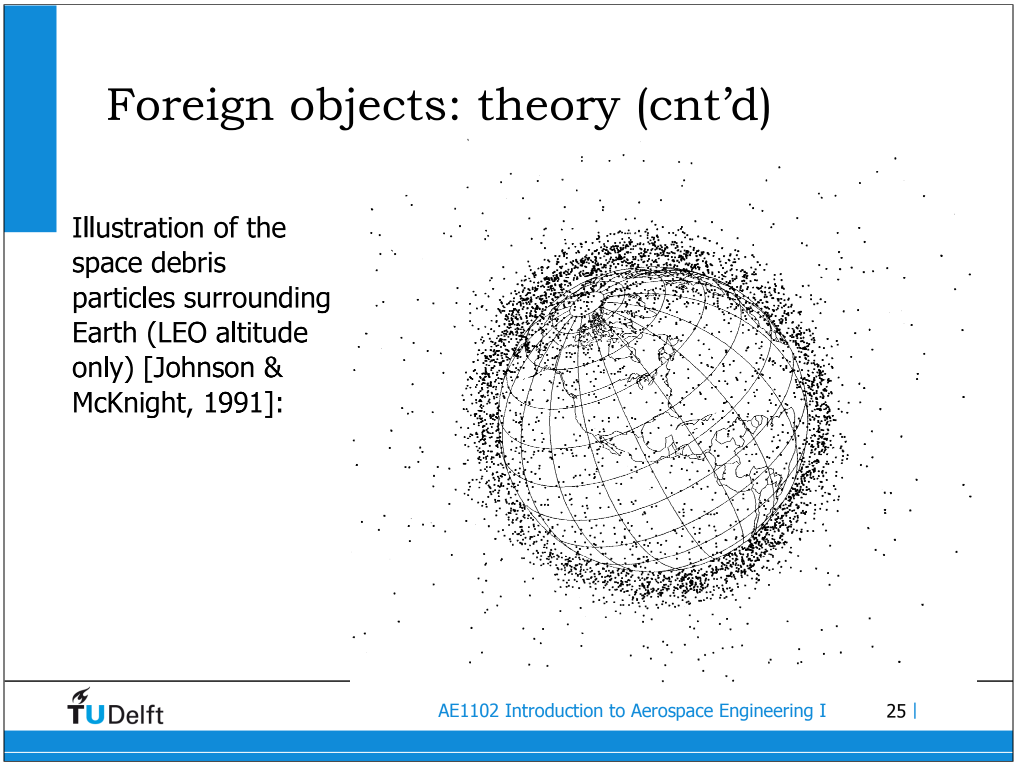
Ad (3): Lifetime expectancy as a function of altitude and solar activity [Wertz & Larson, 1991]:

This is lifetime when no orbital corrections are made. A value of $F_{10.7}$ of 75 corresponds to solar minimum conditions, a value of 250 to solar maximum conditions (cf. sheet 15). Lifetime easily varies by a factor of 10 or more. 800 km is a popular altitude for earth-observing satellites; at 300 km and below orbital lifetime is restricted to a few days or weeks at most.

Foreign objects: introduction



Iridium 33 was still active; Cosmos 2251 stopped functioning in 1995. Since the collision took place at almost right angles, the relative velocity was √2 times the orbital velocity of each satellite (Kepler orbit -> relative velocity 10.5 km/s).



Foreign objects: theory (cnt'd)

Illustration of the space debris particles surrounding Earth (LEO altitude only) [Johnson & McKnight, 1991]:

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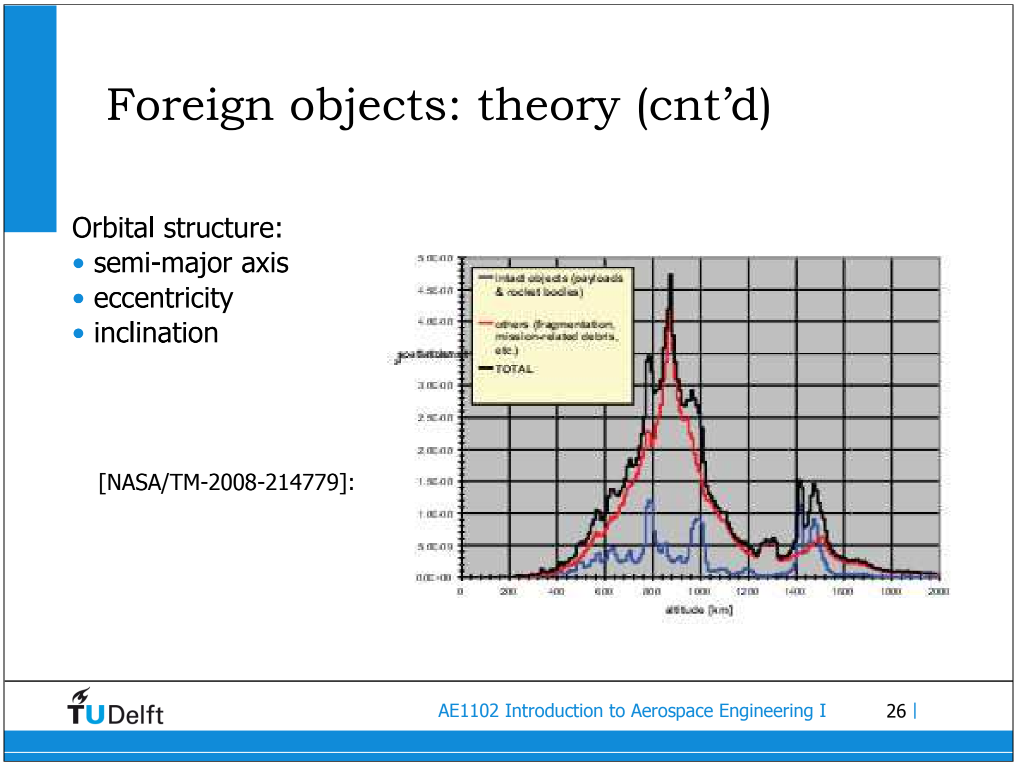
An old plot, only showing the objects that can be tracked; at the beginning of 2009, NORAD's catalog contained about 19000 objects.

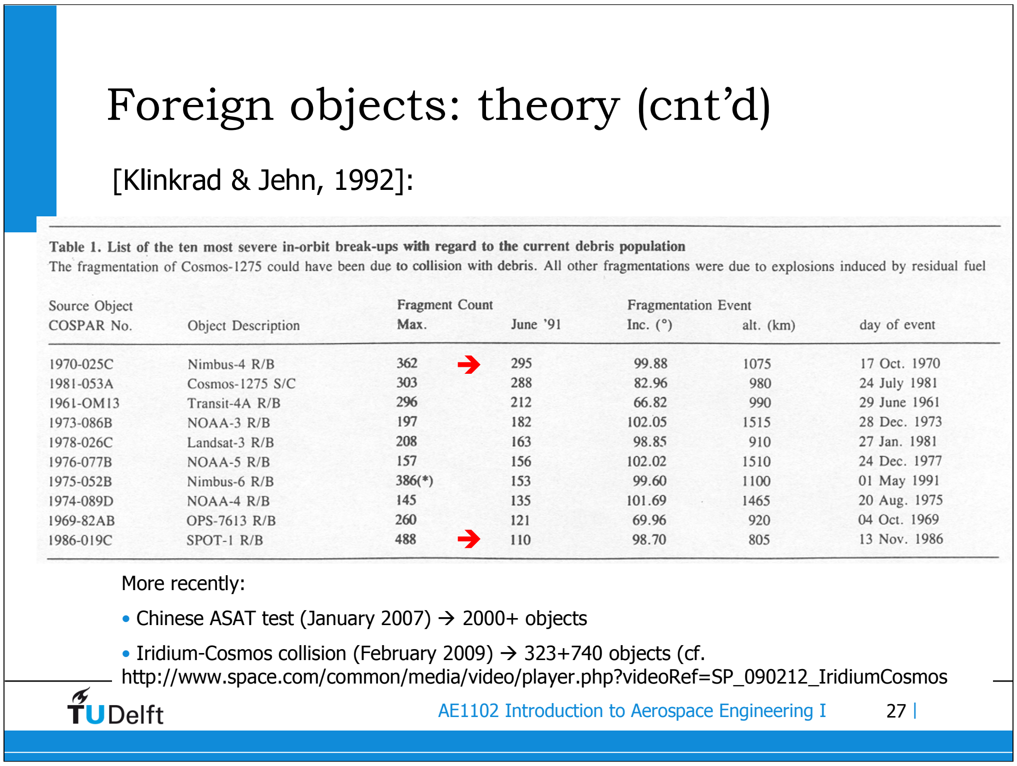


Foreign objects: theory (cnt’d)

Orbital structure:
- semi-major axis
- eccentricity
- inclination

[NASA/TM-2008-214779]:

Intact objects (active satellites, old satellites not fragmented yet) show peak concentrations at 800 and 1000 km; real debris at 800-900 km.



Foreign objects: theory (cnt'd)

[Klinkrad & Jehn, 1992]:

Table 1. List of the ten most severe in-orbit break-ups with regard to the current debris population
The fragmentation of Cosmos-1275 could have been due to collision with debris. All other fragmentations were due to explosions induced by residual fuel

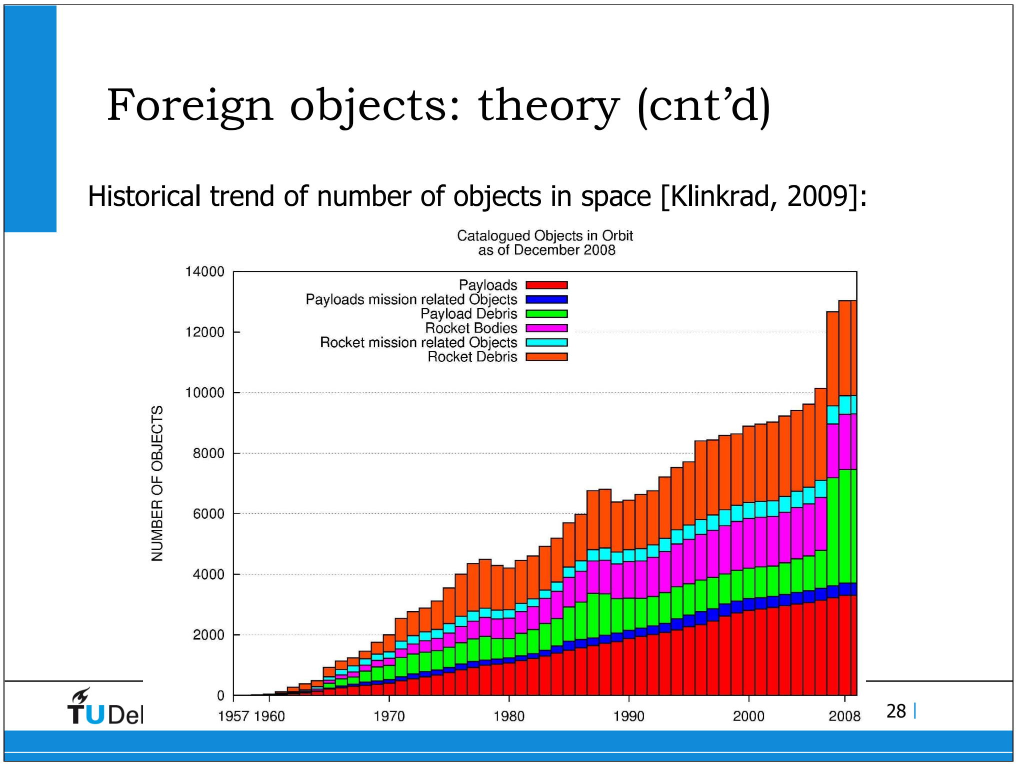
Source Object		Fragment Count		Fragmentation Event		
COSPAR No.	Object Description	Max.	June '91	Inc. (°)	alt. (km)	day of event
1970-025C	Nimbus-4 R/B	362 →	295	99.88	1075	17 Oct. 1970
1981-053A	Cosmos-1275 S/C	303	288	82.96	980	24 July 1981
1961-OM13	Transit-4A R/B	296	212	66.82	990	29 June 1961
1973-086B	NOAA-3 R/B	197	182	102.05	1515	28 Dec. 1973
1978-026C	Landsat-3 R/B	208	163	98.85	910	27 Jan. 1981
1976-077B	NOAA-5 R/B	157	156	102.02	1510	24 Dec. 1977
1975-052B	Nimbus-6 R/B	386(*)	153	99.60	1100	01 May 1991
1974-089D	NOAA-4 R/B	145	135	101.69	1465	20 Aug. 1975
1969-82AB	OPS-7613 R/B	260	121	69.96	920	04 Oct. 1969
1986-019C	SPOT-1 R/B	488 →	110	98.70	805	13 Nov. 1986

More recently:

- Chinese ASAT test (January 2007) → 2000+ objects
- Iridium-Cosmos collision (February 2009) → 323+740 objects (cf. http://www.space.com/common/media/video/player.php?videoRef=SP_090212_IridiumCosmos

Most of the break-ups listed in this table are due to explosions (residual propellant). A few notes: the number of fragments is typically O(100); each fragment is as lethal as the original, intact vehicle; the number of fragments remains high, even decades after the actual breakup.

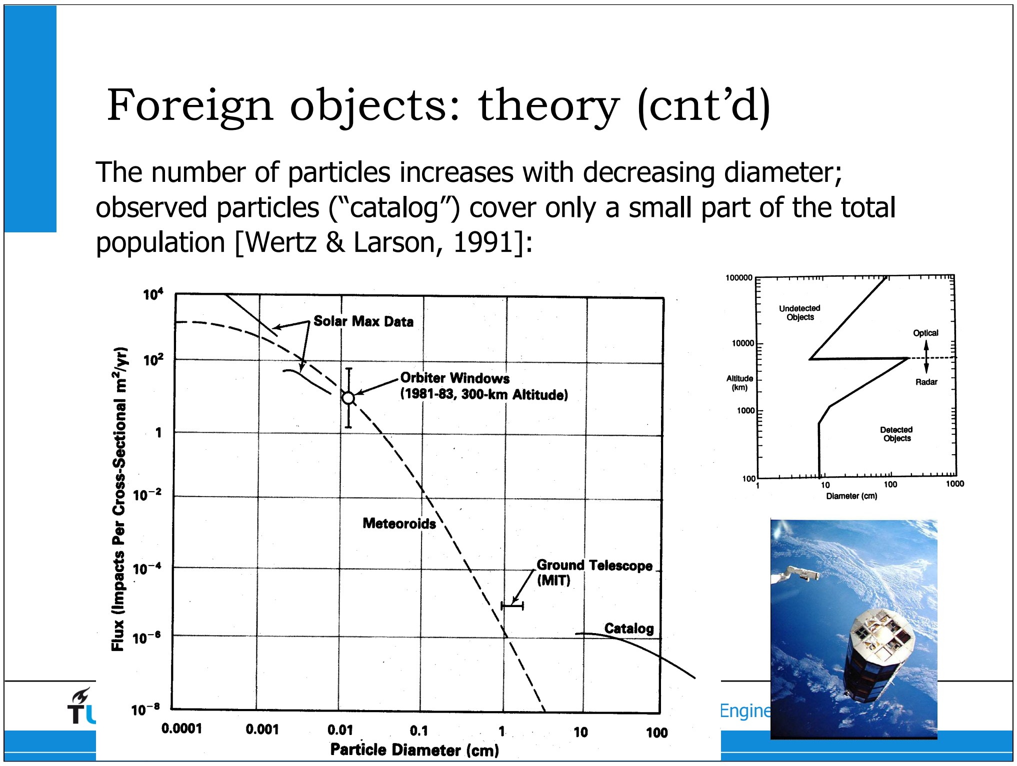
But then: the Chinese ASAT test (January 2007), the Iridium-Cosmos collision (February 2009), ….



Foreign objects: theory (cnt'd)

Historical trend of number of objects in space [Klinkrad, 2009]:

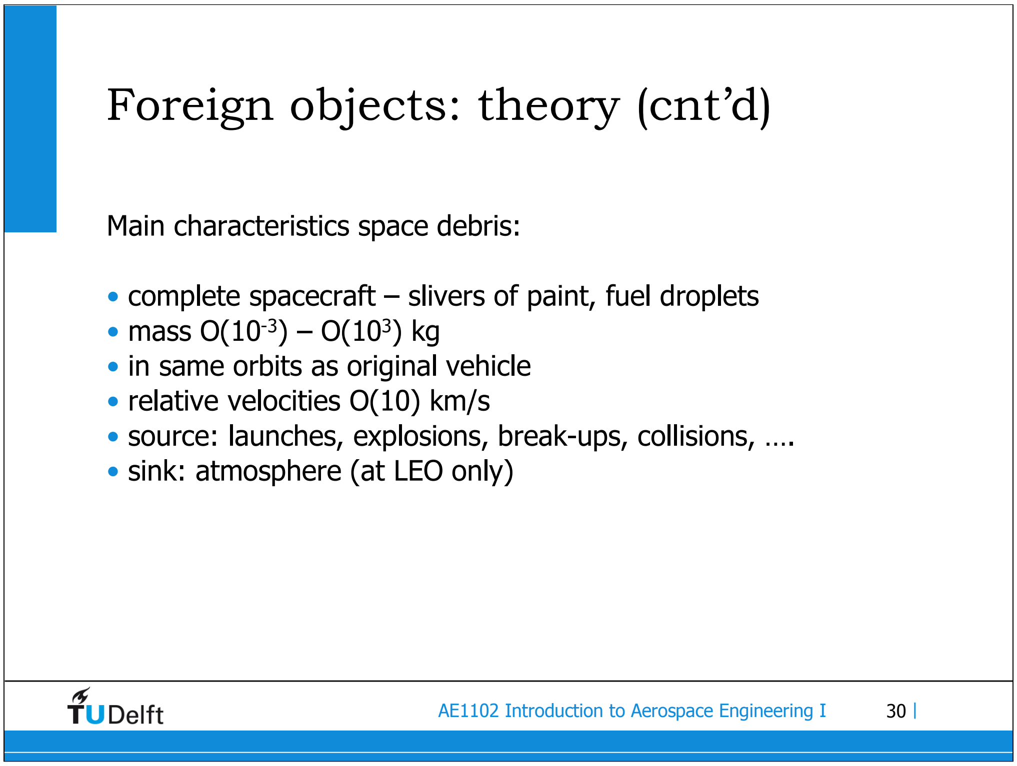
Beginning of 2009: total number of tracked objects is equal to about 19000. The sine-like variation in the curves is due to atmospheric drag (11-year solar cycle), which has a cleaning effect at low altitudes.



Foreign objects: theory (cnt'd)

The number of particles increases with decreasing diameter; observed particles ("catalog") cover only a small part of the total population [Wertz & Larson, 1991]:

Clear correlation between particle size and number of objects. NORAD's catalog is restricted to objects with a diameter of about 10 cm and larger in LEO, and objects with a diameter of about 30 cm in GEO……

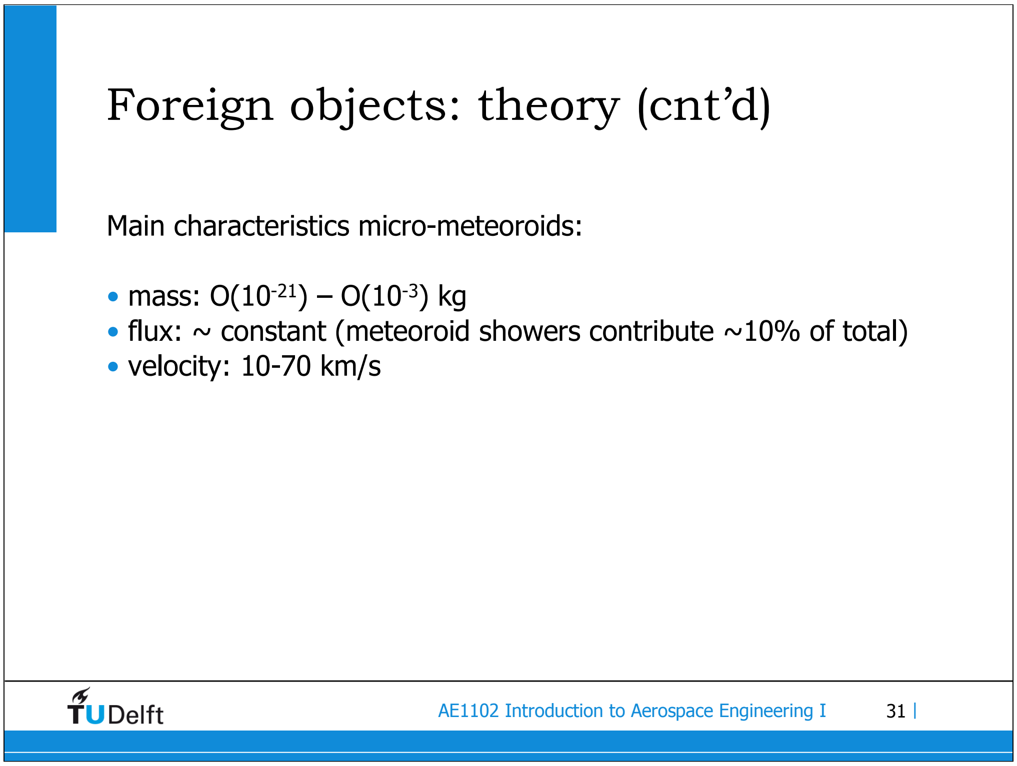


Foreign objects: theory (cnt’d)

Main characteristics space debris:

- complete spacecraft – slivers of paint, fuel droplets
- mass O(10^{-3}) – O(10^{3}) kg
- in same orbits as original vehicle
- relative velocities O(10) km/s
- source: launches, explosions, break-ups, collisions, ….
- sink: atmosphere (at LEO only)

An individual space debris particle is not different from an intact, operational satellite. It follows the laws of nature: it flies 1st order in a Kepler orbit (with semi-major axis, eccentricity, inclination, well-known velocity, etcetera), experiences surface forces (such as atmospheric drag), etcetera.

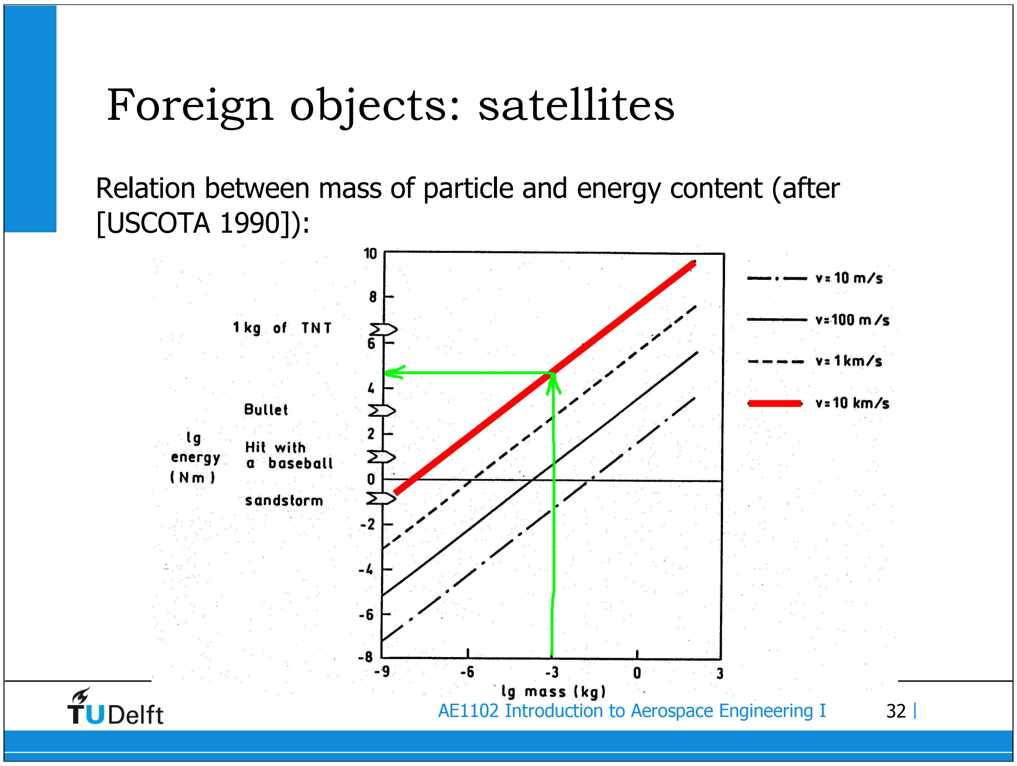


Foreign objects: theory (cnt’d)

Main characteristics micro-meteoroids:

- mass: $O(10^{-21})$ – $O(10^{-3})$ kg
- flux: ~ constant (meteoroid showers contribute ~10% of total)
- velocity: 10-70 km/s

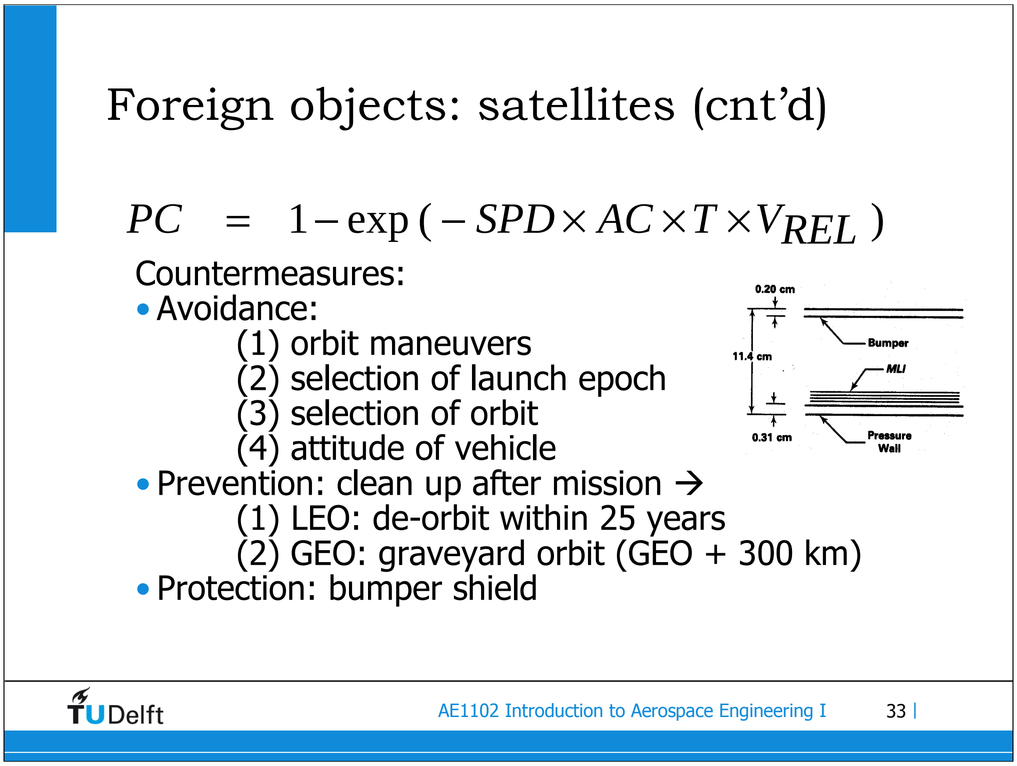
We ignore the big ones…….



Foreign objects: satellites

Relation between mass of particle and energy content (after [USCOTA 1990]):

Log-log scale. In LEO (V_{rel}~10 km/s), a particle with a mass of 1 gram already possesses an energy of something between a bullet and 1 kg of explosives.



Foreign objects: satellites (cnt’d)

$$PC = 1 - \exp\left(-SPD \times AC \times T \times V_{REL}\right)$$

Countermeasures:

- Avoidance:
  - (1) orbit maneuvers
  - (2) selection of launch epoch
  - (3) selection of orbit
  - (4) attitude of vehicle
- Prevention: clean up after mission →
  - (1) LEO: de-orbit within 25 years
  - (2) GEO: graveyard orbit (GEO + 300 km)
- Protection: bumper shield

“PC” = probability of collision; ”SPD” = spatial particle density; “AC” = cross-sectional area; ”T” = mission lifetime; ”V_{REL}” = relative velocity. Make sure that the units of these parameter are consistent!

The chances of being hit during mission lifetime can range up to 10% or even more.

The bumper shield has the impacting particle break up in smaller fragments, or even has it vaporize. Drawbacks: it costs mass and volume, and should be designed according to the expected circumstances in space (which change with time).

Have no false hope: space debris is after your mission…..

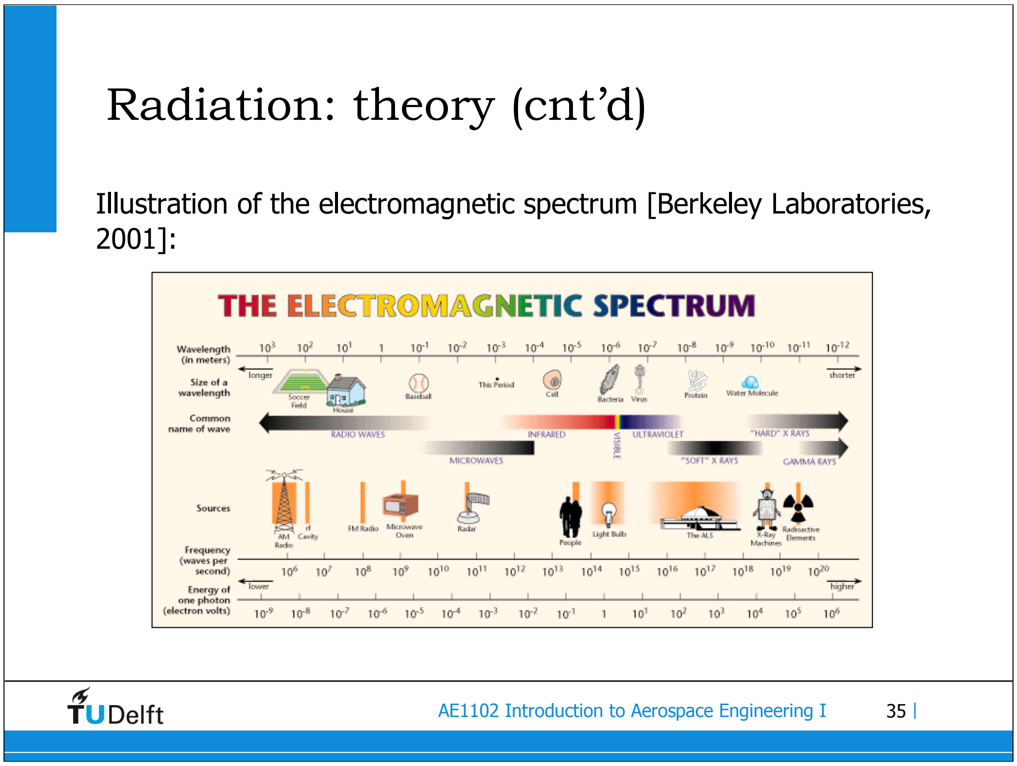
Radiation: theory

2 types:

- electromagnetic radiation
- particle radiation

Electromagnetic radiation: dualistic character: (1) continuous wave, with λ*f=c, and (2) individual photons, each with energy h*f. Source: any object with a temperature different from 0 K. Most prominent for spaceflight: solar radiation, reflected solar radiation (albedo) and thermal radiation from planet(s).

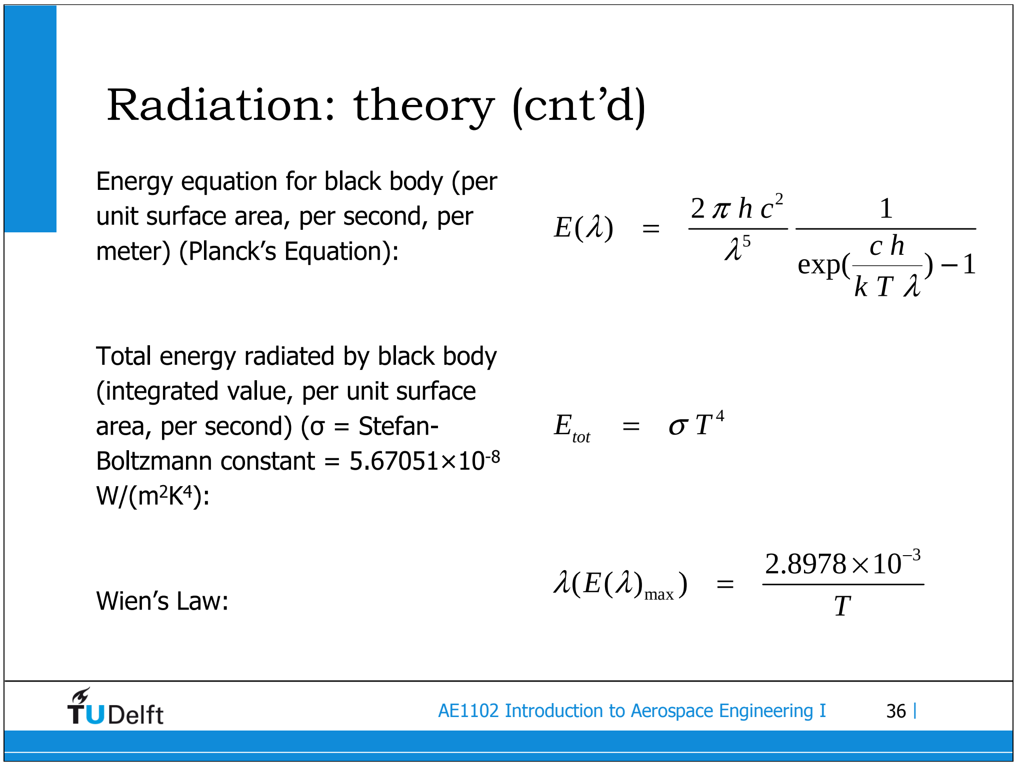
Particle radiation: highly-energetic particles, typically charged. Sources: Sun, other stars, nuclear events, ….



Radiation: theory (cnt'd)

Illustration of the electromagnetic spectrum [Berkeley Laboratories, 2001]:

The electromagnetic spectrum shows a huge variation in wavelength, frequency ($\lambda \times f = c$), and energy ($E = h \times f$). Radiation has a wide variety of sources.



Radiation: theory (cnt'd)

Energy equation for black body (per unit surface area, per second, per meter) (Planck's Equation):

$$E(\lambda) \quad = \quad \frac{2\,\pi\,h\,c^2}{\lambda^5}\,\frac{1}{\exp(\frac{c\,h}{k\,T\,\lambda})-1}$$

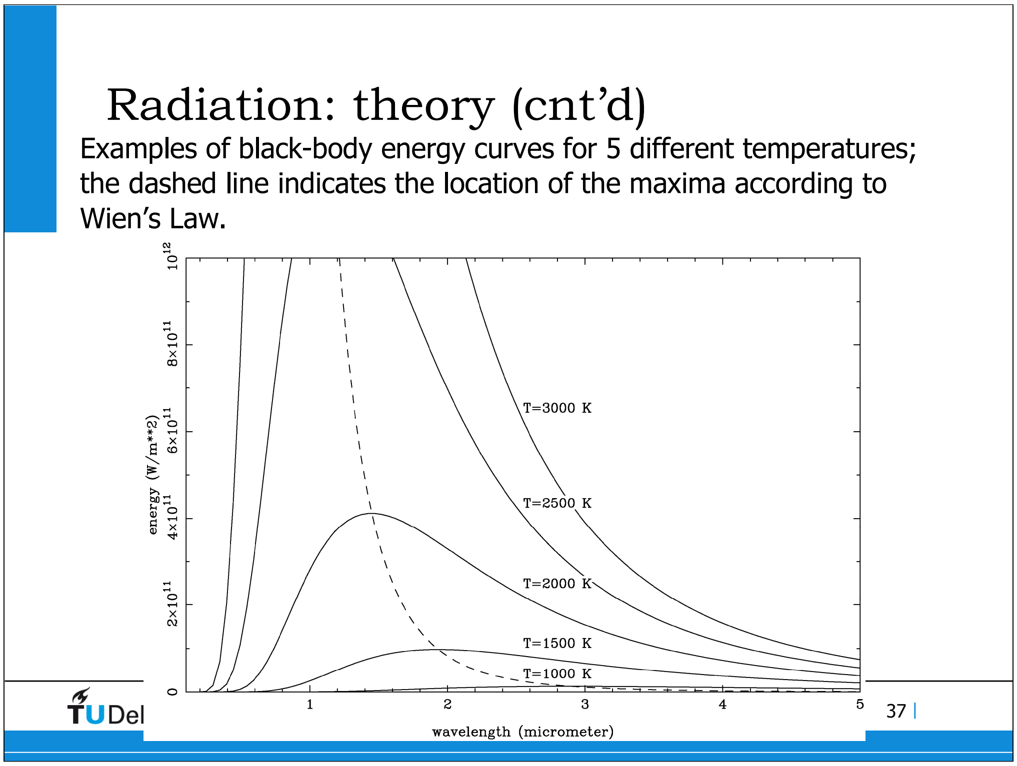
Total energy radiated by black body (integrated value, per unit surface area, per second) (σ = Stefan-Boltzmann constant = 5.67051×10^{-8} $W/(m^2K^4)$):

$$E_{tot} \quad = \quad \sigma\,T^4$$

Wien's Law:

$$\lambda(E(\lambda)_{\max}) \quad = \quad \frac{2.8978\times10^{-3}}{T}$$

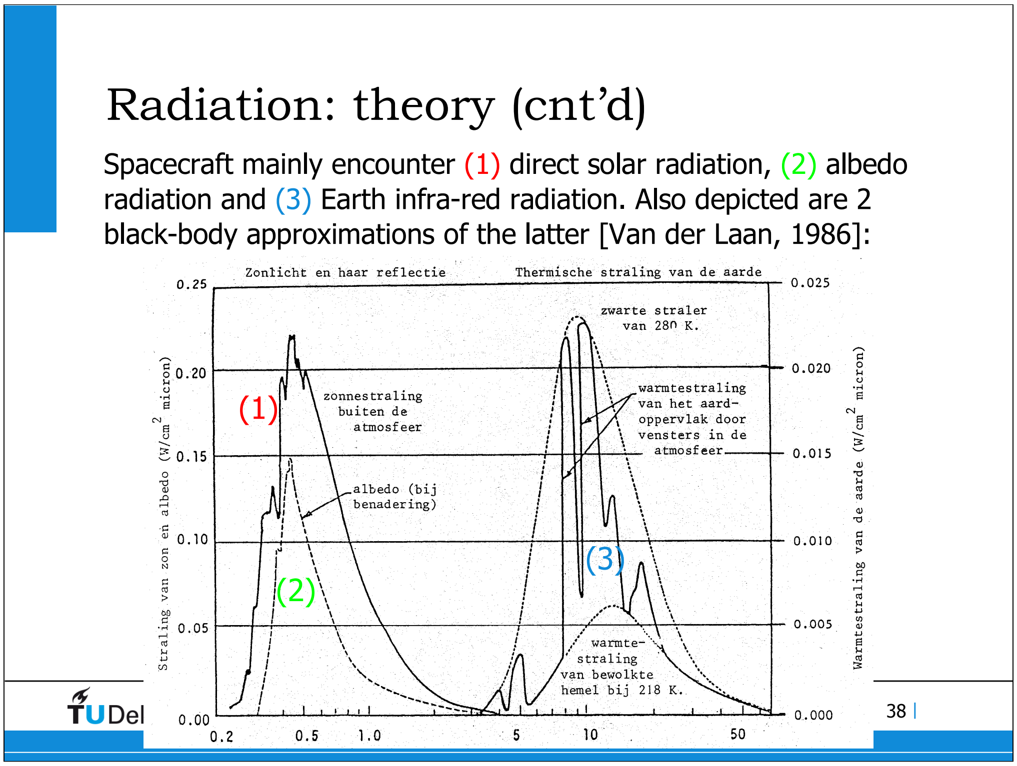
A black body is a hypothetical object, which emits the maximum amount of energy on any given wavelength; this is fully determined by the temperature of the object. It serves as a reference to express radiation and reflectance characteristics of actual objects. Wien's Law gives a simple relation between the temperature of the object and the wavelength at which the radiation intensity is maximum. Temperature "T" is to be expressed in Kelvin.



Radiation: theory (cnt'd)

Examples of black-body energy curves for 5 different temperatures; the dashed line indicates the location of the maxima according to Wien's Law.

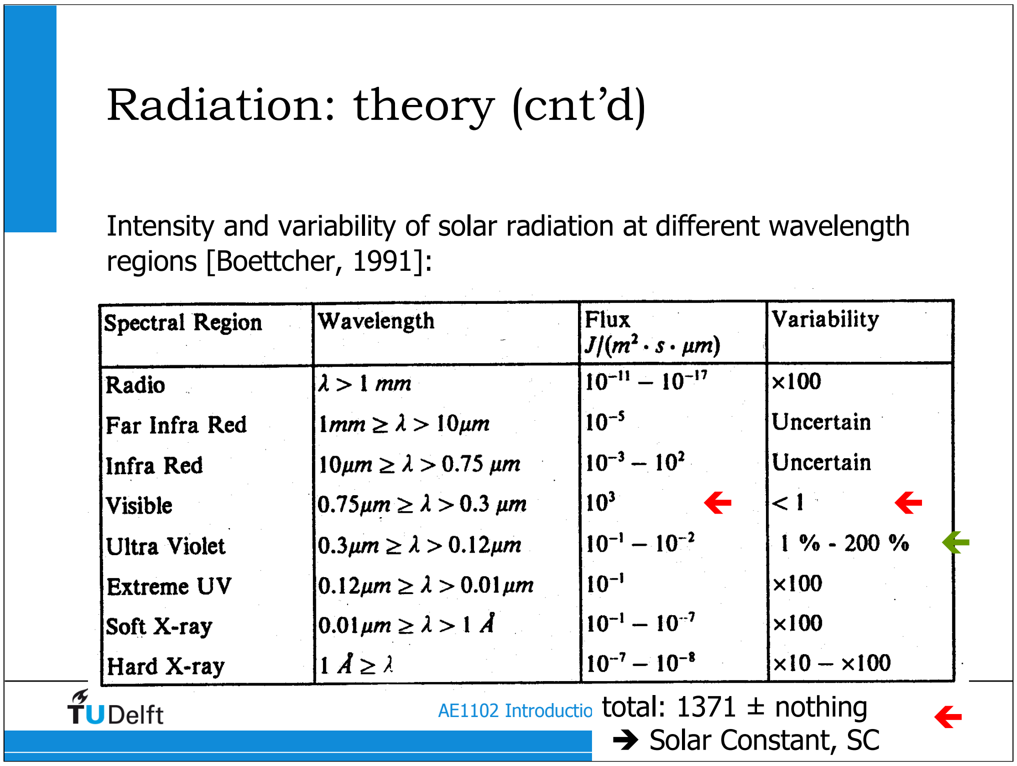
Illustration of the equations given on the previous sheet. For comparison: the Sun has an equivalent black-body temperature of about 5800 K, the Earth of 280 K. According to Wien's Law, the Sun emits the maximum amount of radiation at 0.5 µm (i.e. visible light), whereas the Earth does so at 10.3 µm (i.e. infra-red radiation). Units at y-axis should read W/m^3. AAAA REPLACE PICTURE



Radiation: theory (cnt'd)

Spacecraft mainly encounter (1) direct solar radiation, (2) albedo radiation and (3) Earth infra-red radiation. Also depicted are 2 black-body approximations of the latter [Van der Laan, 1986]:

The fraction of direct solar radiation reflected by the Earth (albedo radiation) depends on wavelength, but a value of about 0.4 can be considered representative for the total effect (left). The infra-red radiation emitted from (not reflected by!) the Earth can be approximated by 2 different black-body curves, which reflect the transparency of the Earth's atmosphere (with 2 wavelength regions with full transparency, at 8 and 11 μm).



Radiation: theory (cnt'd)

Intensity and variability of solar radiation at different wavelength regions [Boettcher, 1991]:

Spectral Region	Wavelength	Flux $J/(m^2 \cdot s \cdot \mu m)$	Variability
Radio	$\lambda > 1\ mm$	$10^{-11} - 10^{-17}$	×100
Far Infra Red	$1mm \geq \lambda > 10\mu m$	10^{-5}	Uncertain
Infra Red	$10\mu m \geq \lambda > 0.75\ \mu m$	$10^{-3} - 10^{2}$	Uncertain
Visible	$0.75\mu m \geq \lambda > 0.3\ \mu m$	10^{3} ←	< 1 ←
Ultra Violet	$0.3\mu m \geq \lambda > 0.12\mu m$	$10^{-1} - 10^{-2}$	1 % - 200 % ←
Extreme UV	$0.12\mu m \geq \lambda > 0.01\mu m$	10^{-1}	×100
Soft X-ray	$0.01\mu m \geq \lambda > 1\ \mathring{A}$	$10^{-1} - 10^{-7}$	×100
Hard X-ray	$1\ \mathring{A} \geq \lambda$	$10^{-7} - 10^{-8}$	×10 – ×100

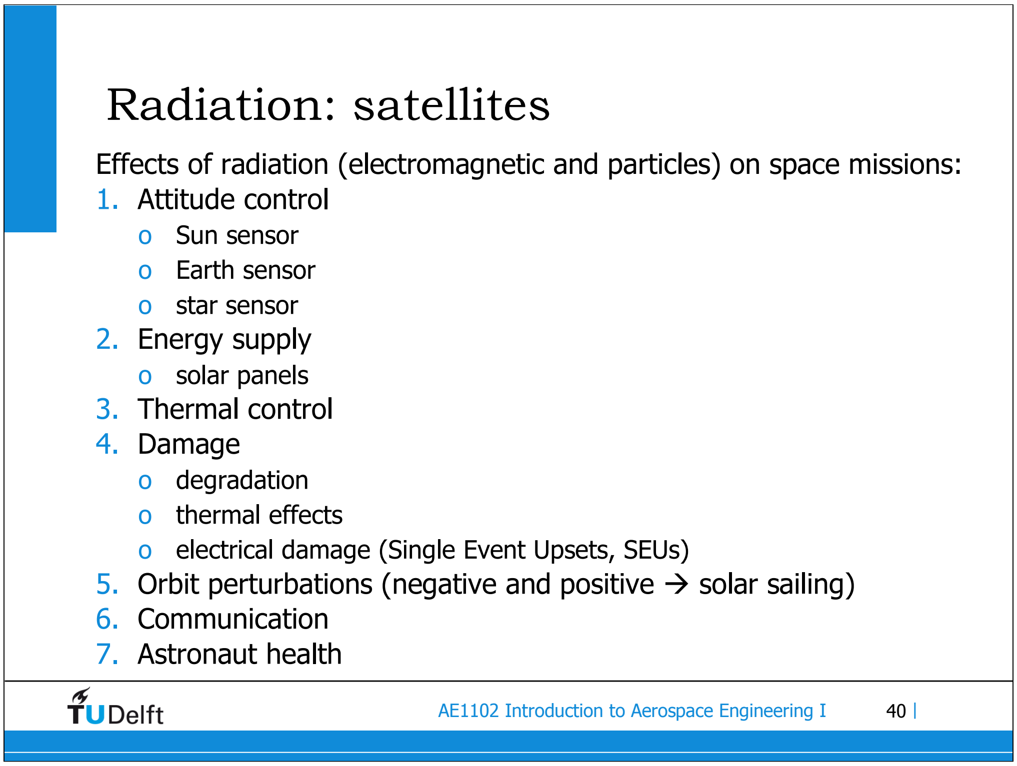
total: 1371 ± nothing ←

➔ Solar Constant, SC

Two main messages here:

(1) the majority of solar radiation can be found in the visible spectrum (1000 J/m^2.s.µm) (cf. previous two sheets).

(2) The variability in this part of the spectrum is very small, and in regions where variability is large the intensity itself is very small -> total solar radiation intensity is more-or-less constant at a given distance -> the Solar Constant (1371 W/m^2) at 1 AU.



Radiation: satellites

Effects of radiation (electromagnetic and particles) on space missions:

1. Attitude control
   - Sun sensor
   - Earth sensor
   - star sensor
2. Energy supply
   - solar panels
3. Thermal control
4. Damage
   - degradation
   - thermal effects
   - electrical damage (Single Event Upsets, SEUs)
5. Orbit perturbations (negative and positive → solar sailing)
6. Communication
7. Astronaut health

Attitude control: accuracy depends on dimension of target, type of radiation, and requirements.

Energy supply: Si and GaAs cells; efficiencies of up to 30% can be obtained (experimentally).

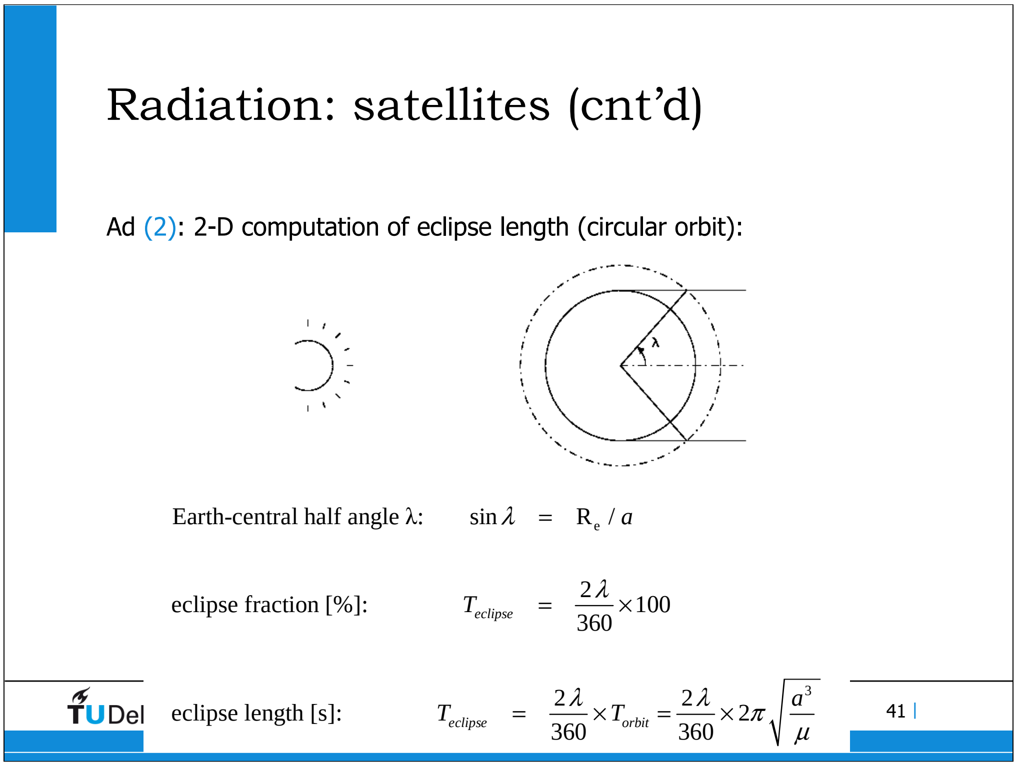
Thermal control: heat transfer to and from surroundings mostly by radiation (except in (re)entry).

Damage: properties of paint slowly differ, structural strength, electrical shorts, …..

Orbit perturbations: solar radiation pressure is one of the dominant forces in GEO satellites.

Communication can be blocked by ionization of the atmosphere.

Astronaut health: nausea, orientation problems, but also increased chances of developing cancer.



Radiation: satellites (cnt'd)

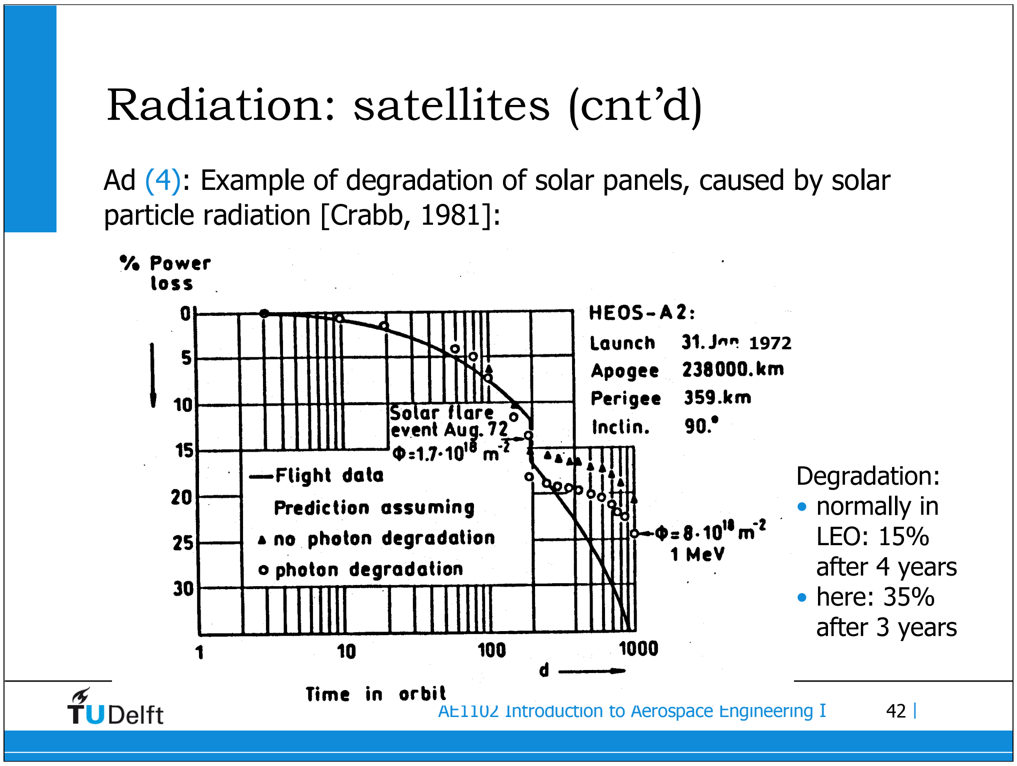
Ad (2): 2-D computation of eclipse length (circular orbit):

Earth-central half angle λ: $\sin\lambda = R_e / a$

eclipse fraction [%]: $T_{eclipse} = \frac{2\lambda}{360} \times 100$

eclipse length [s]: $T_{eclipse} = \frac{2\lambda}{360} \times T_{orbit} = \frac{2\lambda}{360} \times 2\pi \sqrt{\frac{a^3}{\mu}}$

As usual, ”a” represents the semi-major axis and ”Re” the Earth radius.



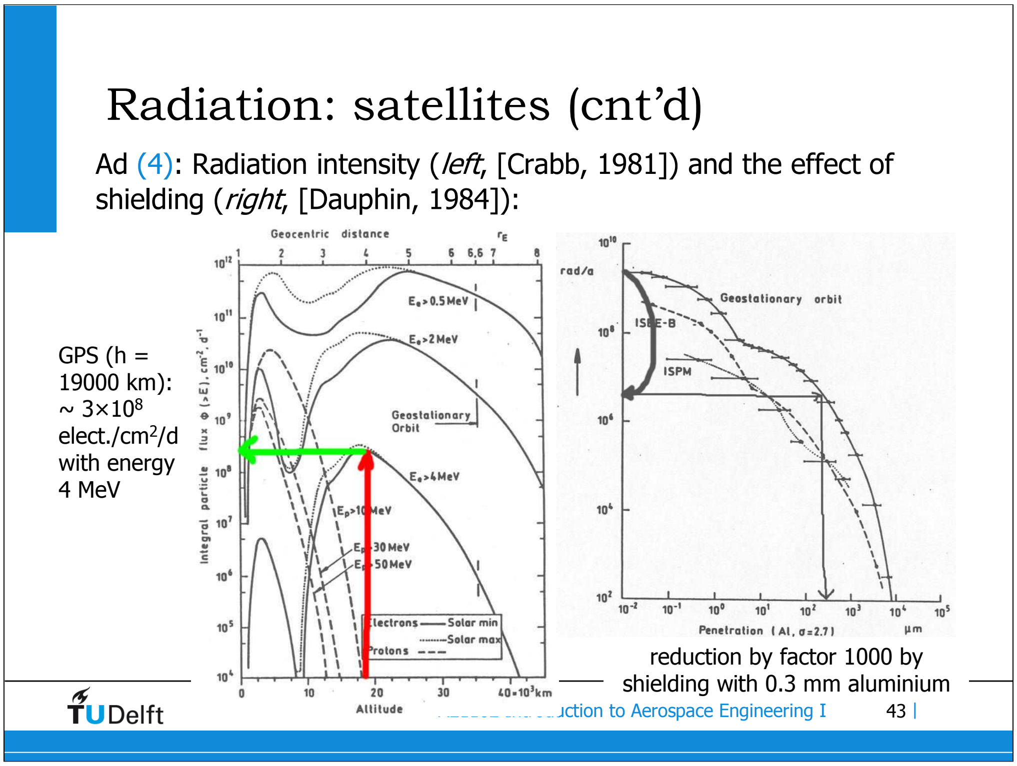
Radiation: satellites (cnt'd)

Ad (4): Example of degradation of solar panels, caused by solar particle radiation [Crabb, 1981]:

Degradation:

- normally in LEO: 15% after 4 years
- here: 35% after 3 years

A total reduction of 35% after 3 years is excessive (but a direct consequence of the chosen orbit: going through the Van Allen Belts every single revolution). The situation is aggrevated by two instantaneous solar flares. The correct launch epoch is January 31, 1972.



Radiation: satellites (cnt’d)

Ad (4): Radiation intensity (*left*, [Crabb, 1981]) and the effect of shielding (*right*, [Dauphin, 1984]):

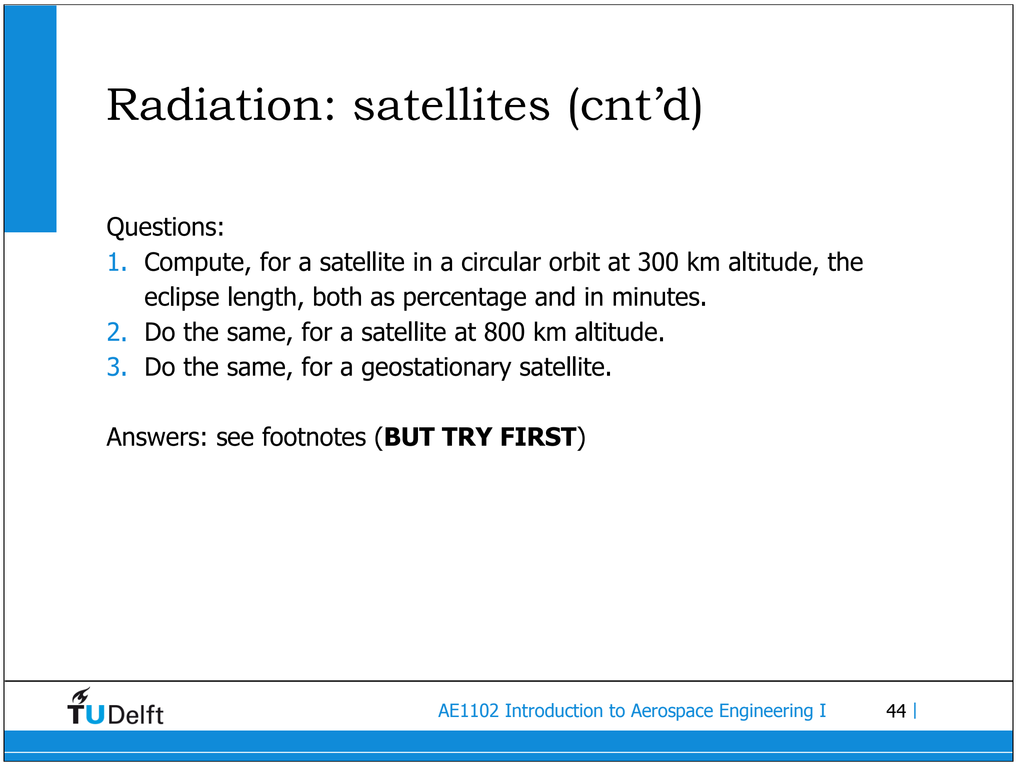
GPS (h = 19000 km): ~ 3×10^8 elect./cm^2/d with energy 4 MeV

reduction by factor 1000 by shielding with 0.3 mm aluminium

Left plot: at a given altitude (*e.g.* at GEO) one can identify the concentration of particles with a certain energy content. Integration (or summing up) gives a 1st order estimate of the total radiation dose.

Right plot: units given in “rad/year”; no specification of exposed area. Left extreme of x-scale can be considered as representative of unblocked exposure in space, other x-values are at given penetration depth ➔ use for determination of shielding thickness for required reduction factor.

Note: both plots are in log-scale.



Radiation: satellites (cnt’d)

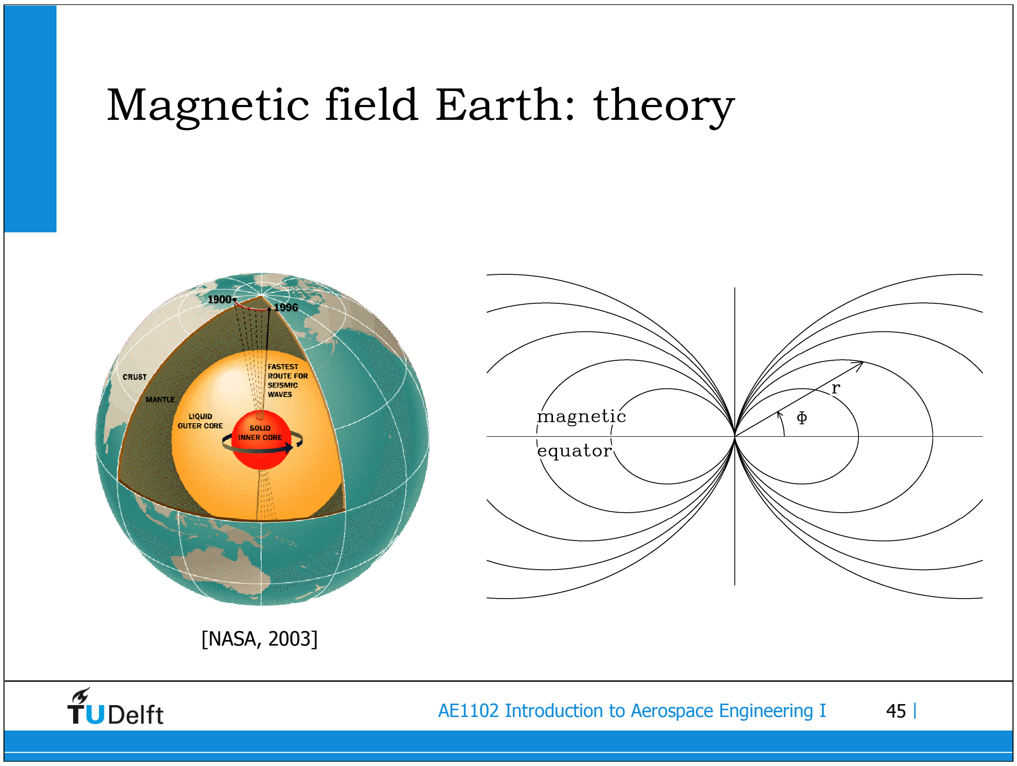
Questions:

1. Compute, for a satellite in a circular orbit at 300 km altitude, the eclipse length, both as percentage and in minutes.
2. Do the same, for a satellite at 800 km altitude.
3. Do the same, for a geostationary satellite.

Answers: see footnotes (**BUT TRY FIRST**)

Answers (**DID YOU TRY?**):

1) $T_{eclipse}$ = 40.4%, or 36.6 min. 2) $T_{eclipse}$ = 34.8%, or 35.1 min. 3) $T_{eclipse}$ = 4.8%, or 69.4 min.

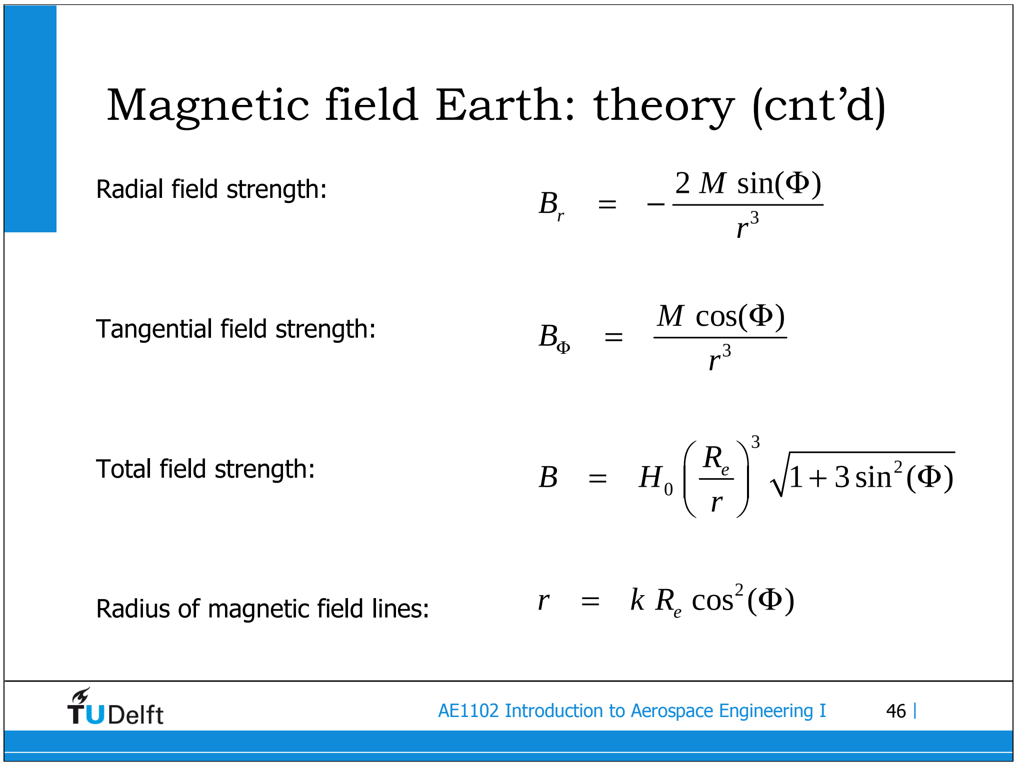


Magnetic field Earth: theory

[NASA, 2003]

The rotation of molten, charged metals in the Earth's outer core is responsible for the creation of a magnetic moment (left). First order, a dipole magnetic field is created (right).

It is believed that a planet, or a star, can generate a magnetic field if its core contains both magnetic material and currents. In our solar system, planets that qualify and that are known to have a magnetosphere include Mercury, Earth, Mars (perhaps), Jupiter, Saturn, Uranus and Neptune [UCAR, 2009].



Magnetic field Earth: theory (cnt'd)

Radial field strength: $$B_r = -\frac{2\,M\,\sin(\Phi)}{r^3}$$

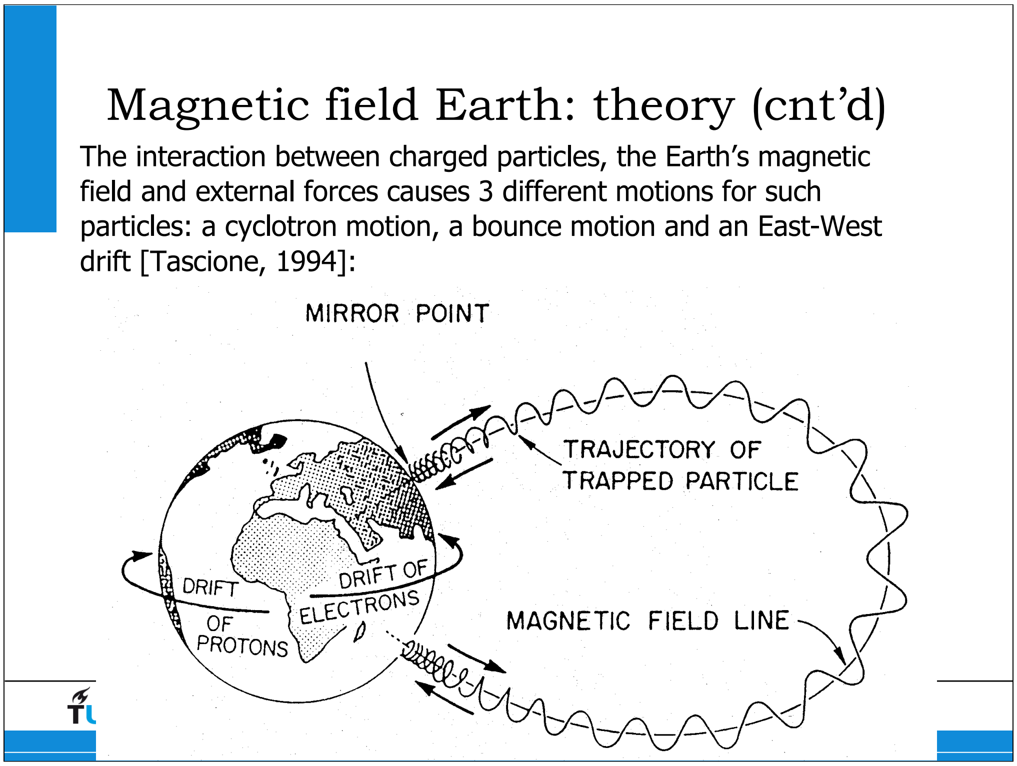
Tangential field strength: $$B_\Phi = \frac{M\,\cos(\Phi)}{r^3}$$

Total field strength: $$B = H_0 \left(\frac{R_e}{r}\right)^3 \sqrt{1+3\sin^2(\Phi)}$$

Radius of magnetic field lines: $$r = k\,R_e\,\cos^2(\Phi)$$

Position of interest in space is expressed by radius "r" (w.r.t. the center of the dipole) and the geomagnetic latitude Φ; both are different from the normal geocentric coordinates. M is the dipole moment (vector). H_0 is the tangential field strength at the equator (the radial component is zero).

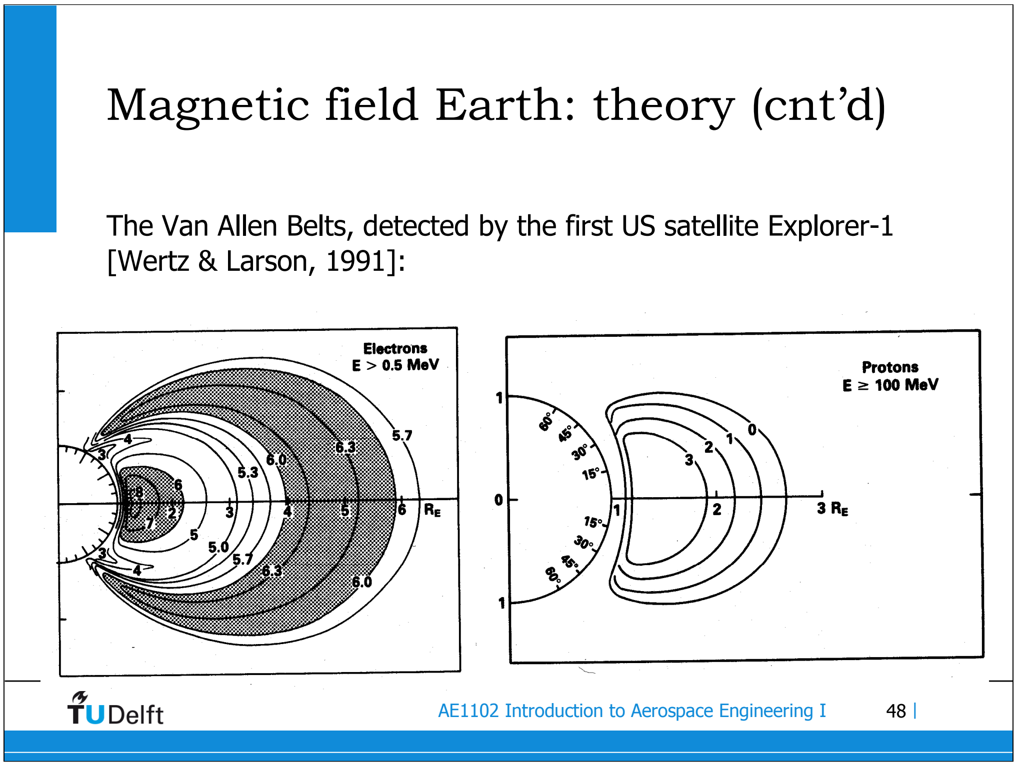
The dipole term is the most important one. In reality, an infinite series expansion is used to model the real magnetic field (comparable with the modeling of the potential of the gravity field, where the main term –μ/r is dominant by at least a factor 1000 for the Earth).



Magnetic field Earth: theory (cnt'd)

The interaction between charged particles, the Earth's magnetic field and external forces causes 3 different motions for such particles: a cyclotron motion, a bounce motion and an East-West drift [Tascione, 1994]:

Cyclotron motion is spinning motion of charged particle around field line. Bounce motion is North-South-North motion along field line.

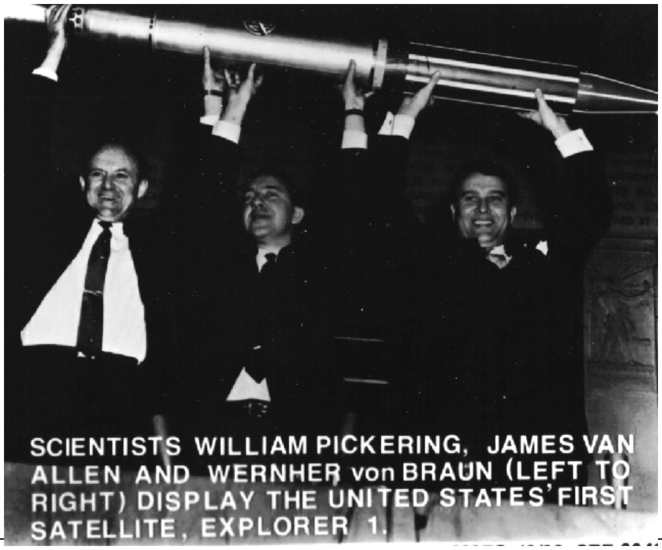


Magnetic field Earth: theory (cnt'd)

The Van Allen Belts, detected by the first US satellite Explorer-1 [Wertz & Larson, 1991]:

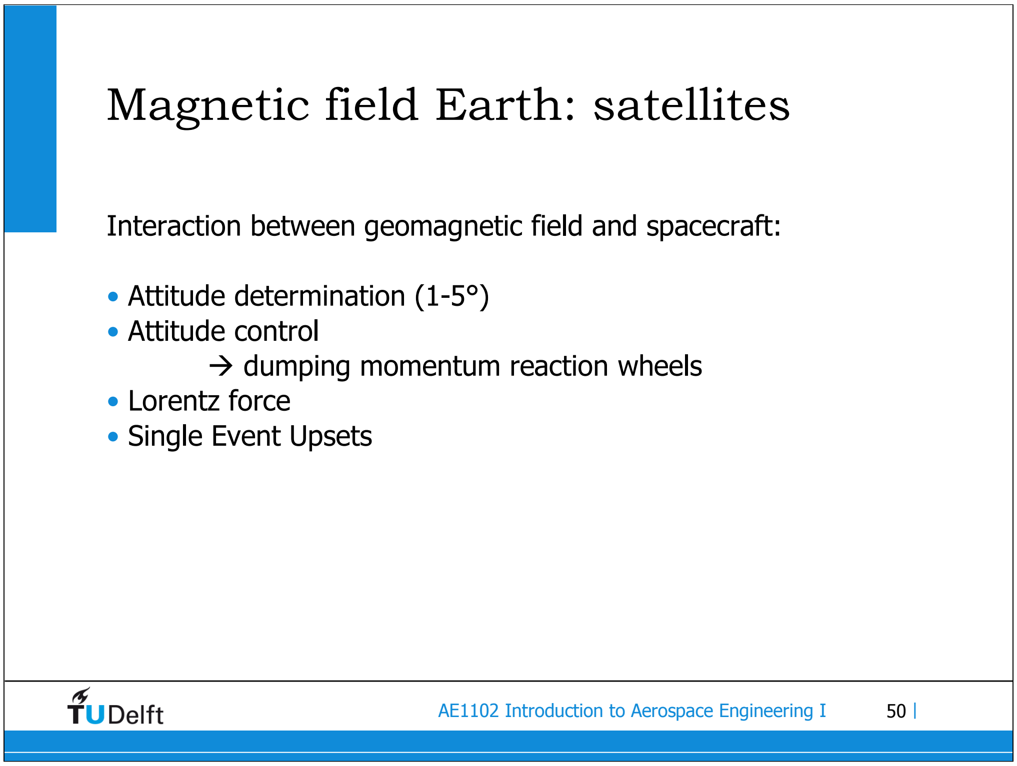
Regions with high concentrations of harmful, high-energy particles. Regions are different fro electrons and protons. Actual location depends on charge of particles, solar activity, and others.

Magnetic field Earth: theory (cnt’d)



SCIENTISTS WILLIAM PICKERING, JAMES VAN ALLEN AND WERNHER von BRAUN (LEFT TO RIGHT) DISPLAY THE UNITED STATES’ FIRST SATELLITE, EXPLORER 1.

Three proud men, before the launch of the spacecraft. History!



Magnetic field Earth: satellites

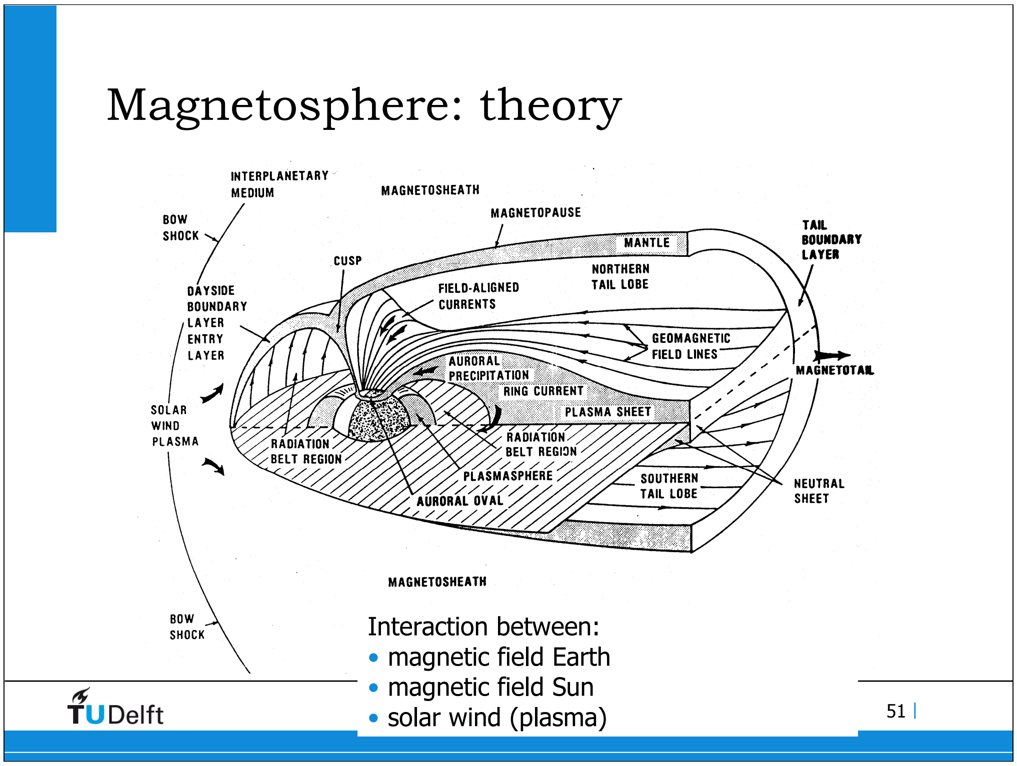
Interaction between geomagnetic field and spacecraft:

- Attitude determination (1-5°)
- Attitude control
  → dumping momentum reaction wheels
- Lorentz force
- Single Event Upsets

Dumping momentum: of reaction wheels, when saturized.

Lorentz force: $\mathbf{F}_L = \mathbf{B} \times \mathbf{I}$.

Single Event Upsets (SEUs): impacts of high-energetic, charged particles in satellite, and consequences.

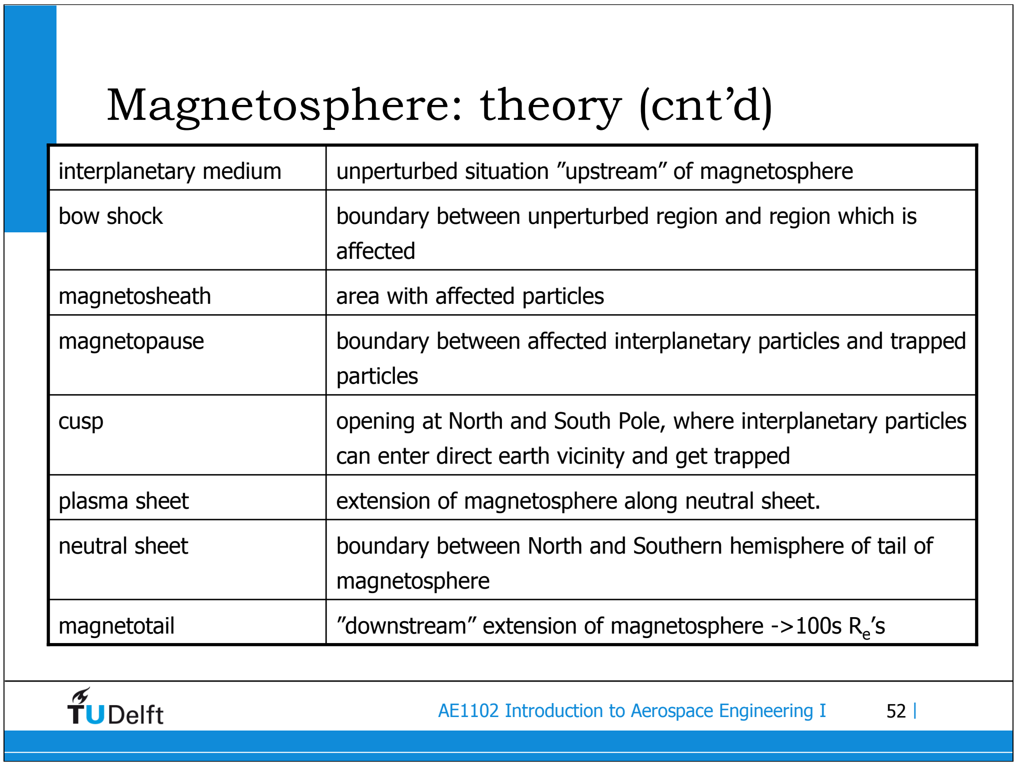


Magnetosphere: theory

Interaction between:

- magnetic field Earth
- magnetic field Sun
- solar wind (plasma)

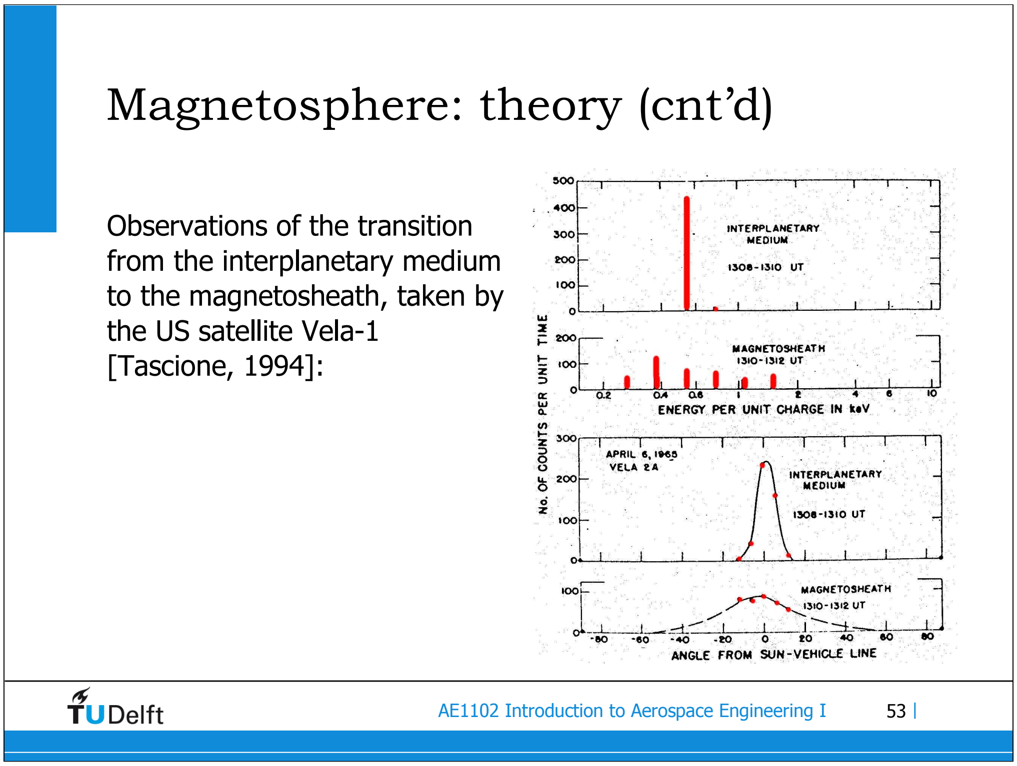
See next sheet for further explanation. Locations and distances are highly variable, since dependent on solar activity.



Magnetosphere: theory (cnt’d)

interplanetary medium	unperturbed situation ”upstream” of magnetosphere
bow shock	boundary between unperturbed region and region which is affected
magnetosheath	area with affected particles
magnetopause	boundary between affected interplanetary particles and trapped particles
cusp	opening at North and South Pole, where interplanetary particles can enter direct earth vicinity and get trapped
plasma sheet	extension of magnetosphere along neutral sheet.
neutral sheet	boundary between North and Southern hemisphere of tail of magnetosphere
magnetotail	”downstream” extension of magnetosphere ->100s R_e’s

See previous sheet.



Magnetosphere: theory (cnt’d)

Observations of the transition from the interplanetary medium to the magnetosheath, taken by the US satellite Vela-1 [Tascione, 1994]:

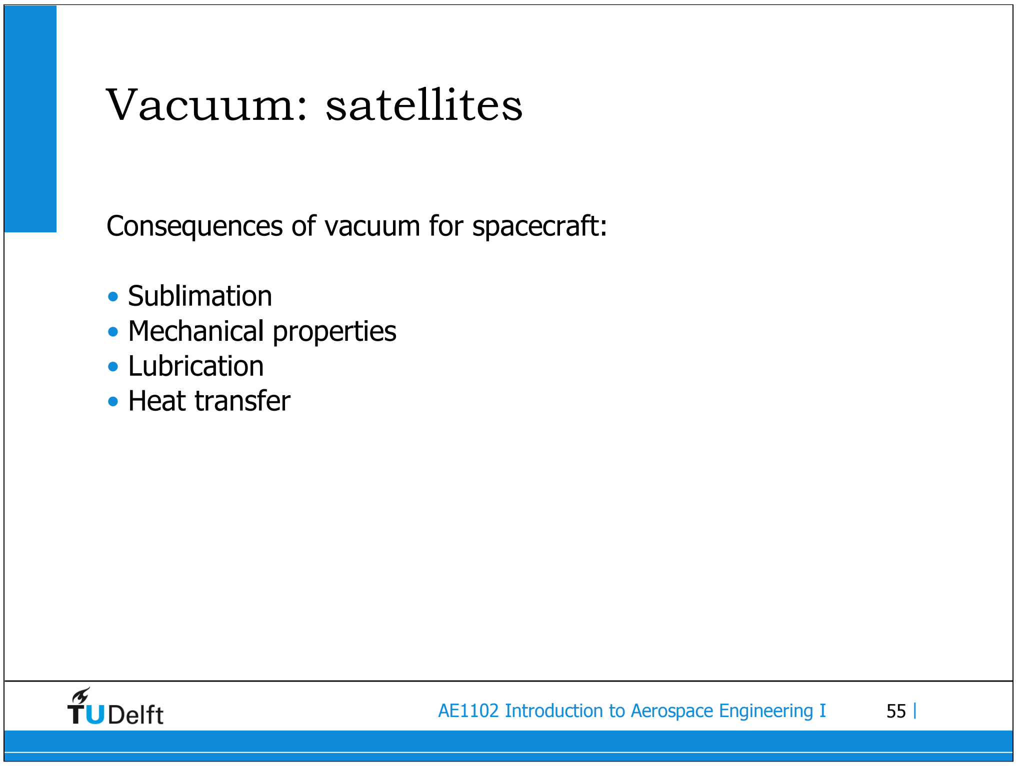
TU Delft

Note the short time over which the transition takes place. Yes the shock is there!

Magnetosphere: satellites

Radiation protection:

- Shielding
- Duplication of components
- Space qualified components
- Avoidance



Vacuum: satellites

Consequences of vacuum for spacecraft:

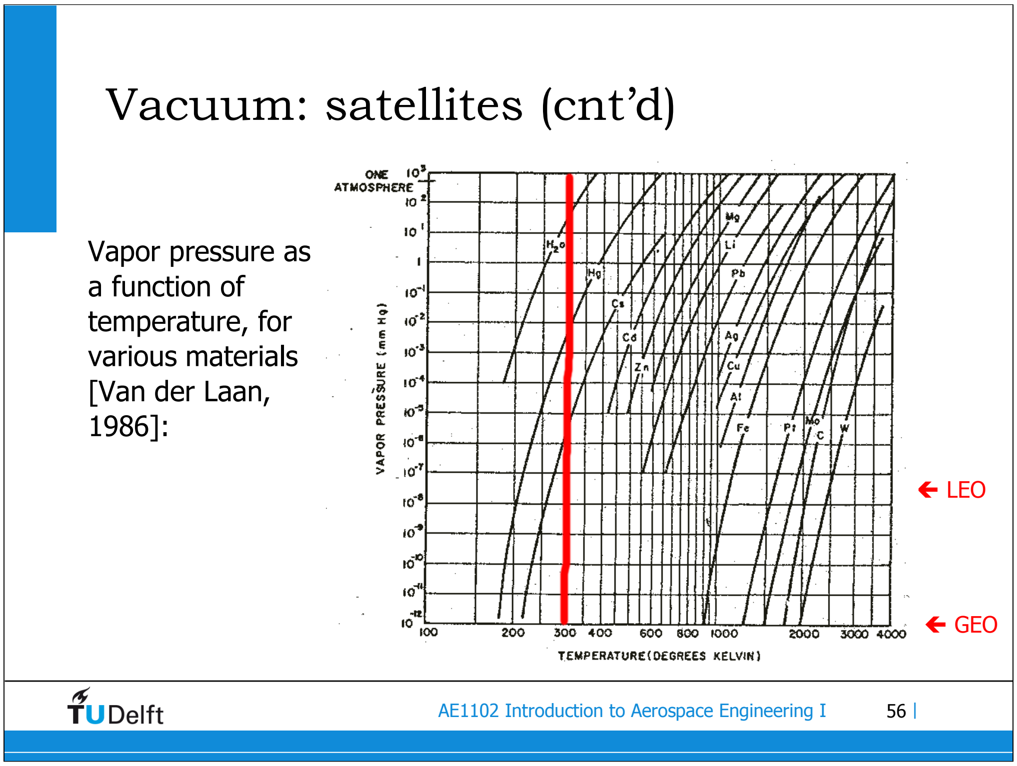
- Sublimation
- Mechanical properties
- Lubrication
- Heat transfer

Sublimation: construction materials dissolve, disappear, outgas.

Mechanical properties: strength, fatigue life, friction (may worsen, may improve).

Lubrication: may disappear.

Heat transfer: mainly through radiation.



Vacuum: satellites (cnt'd)

Vapor pressure as a function of temperature, for various materials [Van der Laan, 1986]:

If the environmental pressure falls below the vapor pressure for a specific construction material, the material will slowly disappear -> proper selection; operations procedures.

Hg stands for the element mercury ("kwik"). Example: cesium (Cs). At 300 K, it has a vapor pressure of about 3×10^{-5} mm Hg, whereas the environmental pressure at LEO is smaller than that (about 3×10^{-7} mm Hg). So: the material will slowly dissolve.