



# EE-585 – Space Mission Design and Operations

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## Today's outline

The Sun's activity and space weather

Orbital regimes & ground track

Non-keplerian perturbations I: Atmospheric drag and orbital lifetime

Non-keplerian perturbations II: Earth non-circularity and sun-synchronous orbits

Non-keplerian perturbations III: Other massive bodies

Non-keplerian perturbations IV: Solar radiation pressure

# **The Sun's activity and space weather**

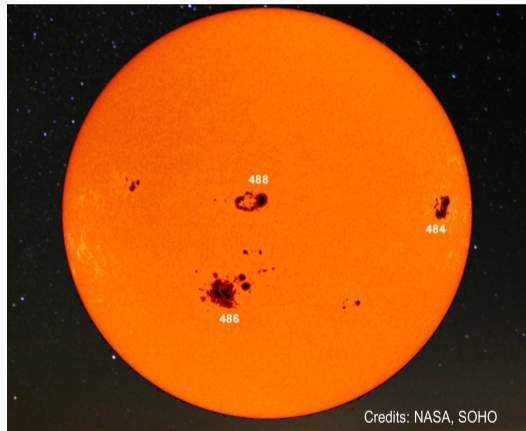
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# Sunspot groups on the surface of the Sun

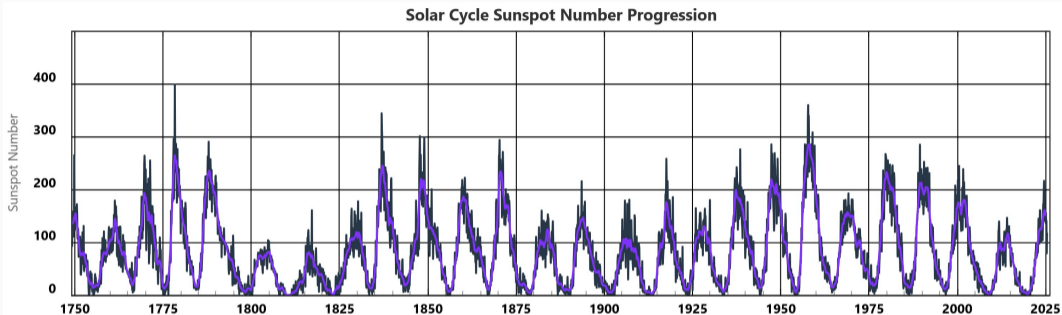
The Sun is a G-type dwarf star. It rotates every 27 days. Its appearance and radiation varies with time in various parts of the electromagnetic spectrum.

They are created by changes in the magnetic flux of the Sun.

Sunspots have been observed (visually) since 800 BC. Annual values series go back to 1700. Daily values since 1818.



# Solar cycle



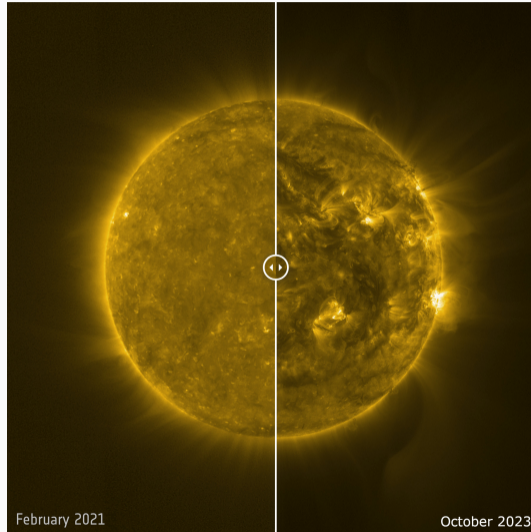
Credits: Space Weather Prediction Center, NOAA

There is a solar cycle of the sunspot numbers with a period of  $\sim 11$  yr.

Not symmetrical rise and fall. min  $\rightarrow$  max takes  $\sim 4.8$  yr and max  $\rightarrow$  min  $\sim 6.2$  yr.

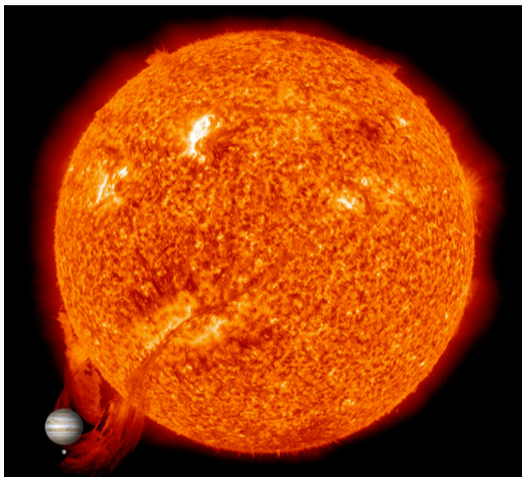
Solar cycle	21	22	23	24	25	26
Sunspot Maximum	1979	1990	2001	2012	2024	$\sim 2035$
Sunspot Minimum	1985	1996	2007	2018	2029?	$\sim 2041$

# The active sun



Credits: ESA & NASA/Solar Orbiter/EUI Team

# Solar prominences



Credits: NASA

The Sun is an active star. Its surface is granular with prominences: flares and coronal mass ejections.

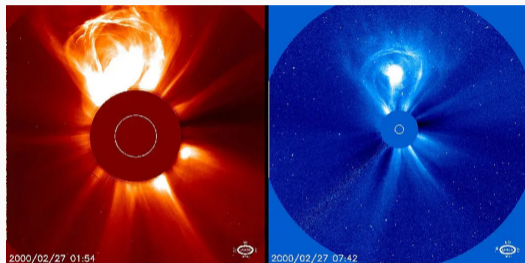
A solar prominence is a large, bright feature extending outward from the Sun's surface, often in a loop shape. While the corona consists of extremely hot ionised gases, which do not emit much visible light, prominences contain much cooler plasma, similar in composition to that of the lower chromosphere.

The image represents solar prominences with images of Jupiter and the Earth for size comparison.

# Space weather

Solar wind continuously flows outward from the Sun and consists mainly of protons and electrons. Density and speed vary.

Coronal Mass Ejections (CMEs) are large expulsions of plasma and magnetic field from the Sun's corona. If they are Earth-directed, they arrive in from 15-18h to several days.



Credits: SOHO ESA & NASA

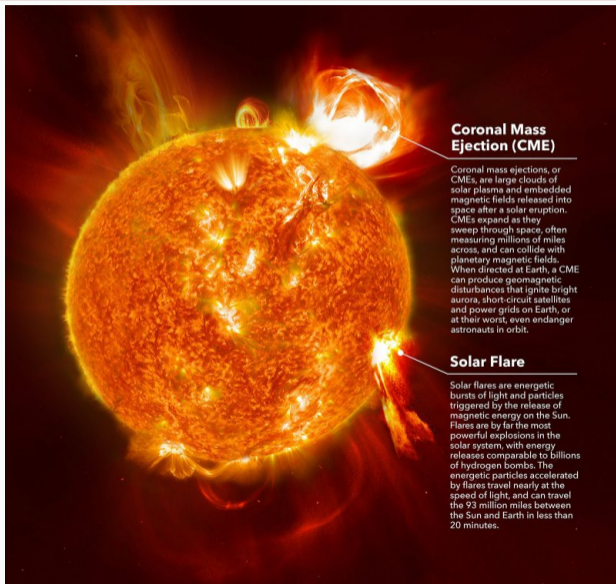
Solar flares are large eruptions of electromagnetic radiation (X-ray and UV radiation) from the Sun lasting from minutes to hours.

The intensity and speed of solar wind and CMEs depend on the solar activity.

→ This is creates space weather.

(Much more information on NOAA's Space Weather Prediction Center → [spaceweather.gov](http://spaceweather.gov))

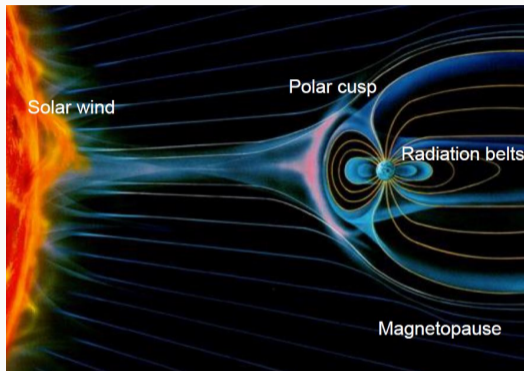
# CMEs vs solar flares



Credits: NASA

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## Interaction of the solar wind with the geomagnetic field



The geomagnetic field is significantly distorted due to the solar wind, made of charged particles flowing in all directions from the Sun.

The magnetopause is the boundary between the magnetosphere and the flow of particles from the solar wind, which is mainly protons and electrons.

The charged particles follow the Earth's magnetic field lines in the equatorial regions of the Earth. In the region of the magnetic poles, these particles can get into the low atmosphere and produce Northern Lights and Southern Lights. In the anti-Sun direction, the geomagnetic field lines are open to the interplanetary medium. Credits: NASA

# Impact of space weather

- Electrical power transmission → geomagnetic induced current
- High Frequency Radio + satellite Communications → variability of the ionosphere can block the propagation of radio waves (ionosphere = 80-600 km where UV + solar radiation ionize molecules → lots of electrons)
- GNSS → ionosphere propagation perturbation
- Satellite drag → see next slides
- Satellite electronics → see next slides
- Auroras → see next slides
- Climate → solar activity affect the total solar irradiance, but this change in total solar irradiance (TSI) is too small to have a major impact on the Earth's climate.

## Indicators of space weather

- **Geomagnetic Storms (G)** major disturbance of Earth's magnetosphere result in shocks with long periods high solar wind → induced currents, increased drag, surface charging, HF radio blackouts, auroras.  
 $K_p$  index measures disturbance of Earth's magnetic field.
- **Solar Radiation Storms (S)** → CME + flare eject accelerate protons which ionizes the atmosphere → radiations levels harmful to high-altitude humans, satellite electronics + solar array damages, HF radio blackouts.  
Measure is proton flux.
- **Radio Blackouts (R)** → Large solar X-ray flares change Earth's ionosphere → high and low frequency blackouts, GNSS errors. Measure is X-ray flux.

The US NOAA scale ranges from 0 (none) to 5 (extreme)

# Northern/Southern lights



Northern and Southern Lights – auroras – are produced by solar wind electrons interacting with the atmosphere.

Green light comes from atomic oxygen at  $\lesssim 200$  km.

Red light from oxygen at 200 – 500 km.

Nitrogen generates other colours like blue and purple.

Credits: NASA

# Aurora geographic distribution



Auroras are usually only visible at high latitudes  $\gtrsim 50 - 55^\circ$ .

Solar wind changes in intensity with time. Extreme events can generate auroras visible down to  $\sim 35^\circ$ .

Credits: K. Chay

## Reminder: Radiation effects on spacecraft systems

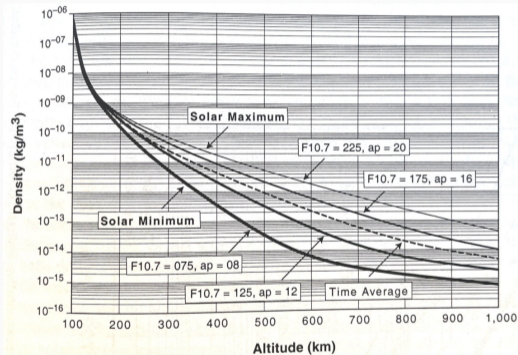
- Single event effects (SEE)
  - High energy particle travelling through a semiconductor leaves an ionised track behind.
  - May cause a highly localised effect.
- Single Event Upset (SEU) is a change of state caused by one single ionizing particle → bit flip → reboot
- Single Event Latchup (SEL) is 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?

# Effects on the atmospheric density

The solar activity also has a significant effect on the density of the Earth's atmosphere at a given altitude.

This effect is large for the altitudes  $\lesssim 1,000$  km  $\rightarrow$  it has an effect on the lifetime of satellites in LEO.

At solar maximum, for a given altitude, the density will be higher  $\rightarrow$  the drag more important  $\rightarrow$  lifetime reduced.



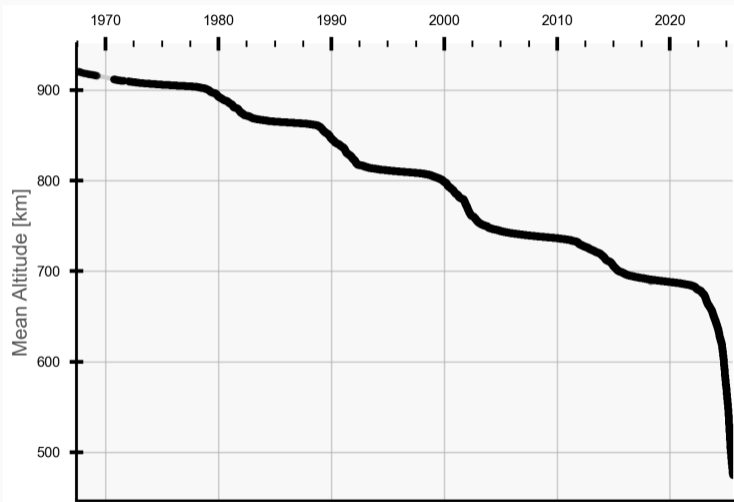
Credits: J. R. Wertz & W. J. Larson, *SMAD*, 3rd Edition, 2010

# Effects of the solar activity on the drag

Surcal 150B was launched on 31 May 1967. It is a 41-cm diameter calibration sphere.

Periods of high solar activity are clearly identifiable, as the decay rates are much higher.

Data: Space-Track.org

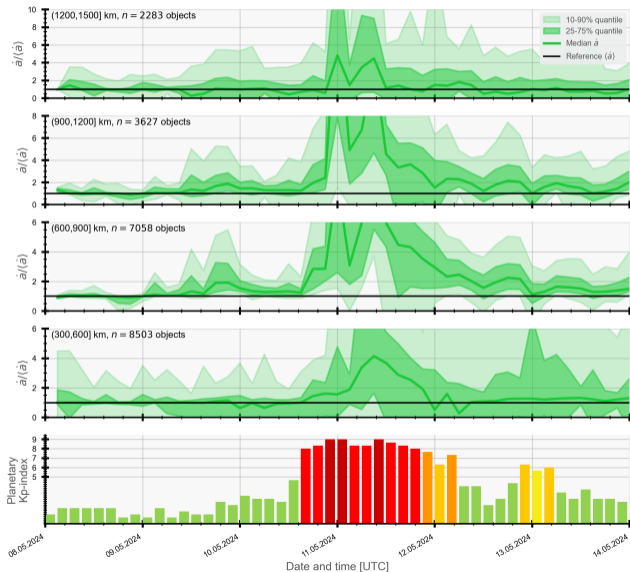


# Extreme solar storm and the atmospheric drag

G5 event on the 11 May 2024 changed the mean decay rate  $\dot{a}$  on LEO objects by a factor of  $\sim 2 - 5$  for  $\approx 12 - 24$ h with respect to the typical decay rate  $\langle \dot{a} \rangle$ .  $n$  is the number of objects taken into account (satellites + debris).

Prediction of trajectory is difficult.

Credits: APCO / Swiss govt SSA report, 2024; Data from Space-Track.org

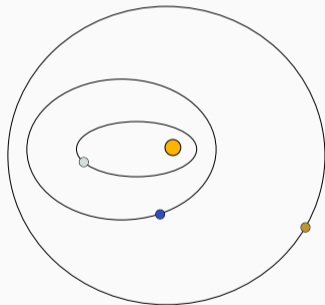


## **Orbital regimes & ground track**

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## Reminder: Kepler's laws

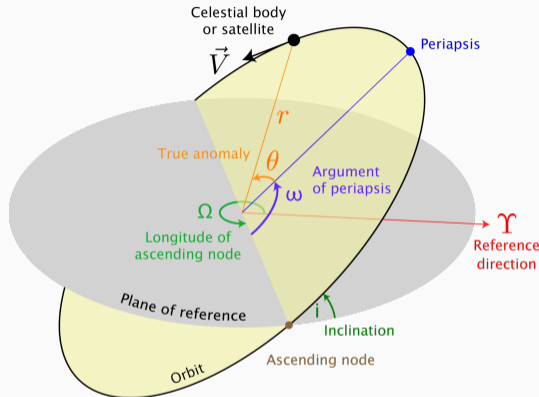
Two-body system, with  $M \gg m_{S/C}$ ,  $\implies F = G \frac{Mm}{r^2} = \frac{\mu m}{r^2}$



1. Orbits are sections of conics.
2. Equal area are swept in equal times (velocity at perigee  $>$  at apogee).

3.  $T = 2\pi \sqrt{\frac{a^3}{\mu}}$

# Reminder: classical orbital elements



$e$  eccentricity,  $a$  semi-major axis

$i$  inclination of the orbital plane

$\Omega$  longitude or Right Ascension of the Ascending Node (RAAN) in the plane of reference

$\omega$  argument of periapsis

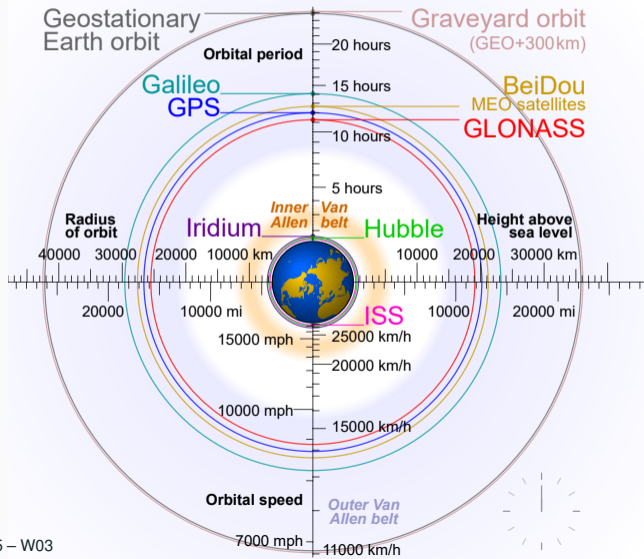
$\theta$  True anomaly

Current time  $t$  allowing for a determination of the exact position of the object.

Credits: Adapted from Wikipedia, Lasunnkty

The spacecraft is passing from the southern celestial hemisphere to the northern on a point on the plane of reference called the ascending node. The descending node is on the other side, when going from N to S.

# Mostly used orbits



**LEO** Low Earth orbit

**MEO** Medium Earth orbit

**GEO** Geostationary Earth orbit

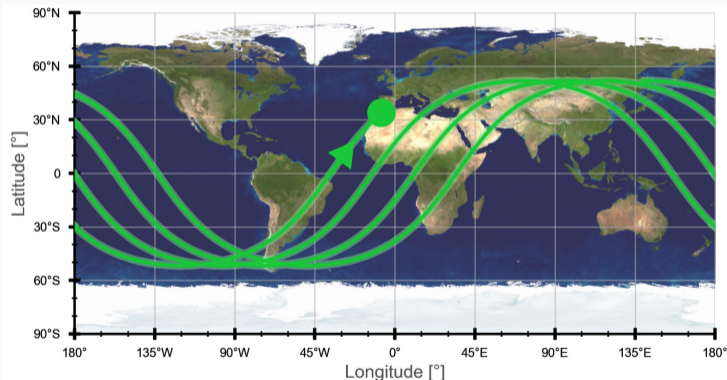
Credits: Wikipedia

## Low Earth orbit (LEO)

- Low Earth orbit (LEO) are orbits at altitudes below 2000 km ( $T \lesssim 127$  min) and low eccentricity.
- Typical altitudes are  $z \sim 400 - 500$  km  $\rightarrow T \sim 90$  min and  $v \sim 7.7$  km/s
- Orbits at  $\lesssim 350$  km altitude are called very low Earth orbit (VLEO)
- Uses: all, including human space flight. Most common use is satellite telecommunication (SATCOM).
- Relatively easy to reach, small altitude (low latency, high optical resolution)
- Main perturbations: atmospheric drag, Earth's non-sphericity

# Satellite ground track

The ground track is the projection of the satellite's trajectory on the surface of the Earth.



For LEO, the successive equatorial crossings (at the ascending nodes)  $\sim 22.5^\circ$  apart ( $= T = 90 \text{ min} \times \frac{360^\circ}{24\text{h}} = 1.5\text{h} \times 15^\circ/\text{h}$ )

Each equatorial crossing moves to the west.

The satellite is moving to the east (for  $i < 90^\circ$ )  
→ prograde orbit.

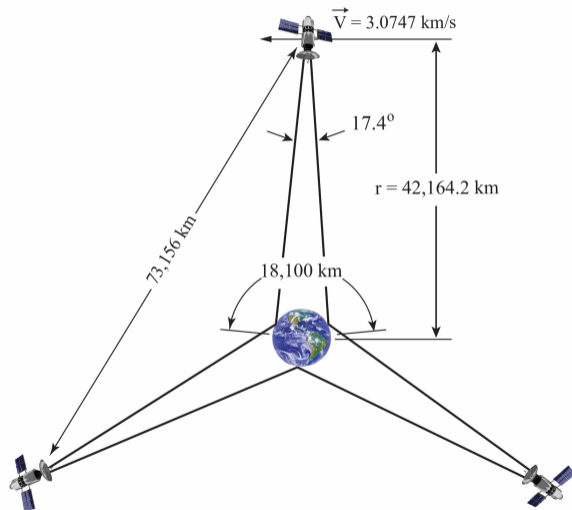
International Space Station, alt  $\sim 415 \text{ km}$ ,  $i = 51.64^\circ$ .

The dot shows the current position and the arrow the direction of motion.

## Medium Earth orbit (MEO)

- Medium Earth orbit (MEO) are orbits at altitudes  $2000 < z < 35786$  km ( $T < 1$  day) and low eccentricity.
- Typical altitudes are  $z \sim 20'000$  km  $\rightarrow T \sim 1/2$  day and  $v \sim 3.7$  km/s.
- Uses: Mostly global navigation satellite services (GNSS: GPS, GLONASS, Galileo) and SATCOM.
- Main perturbations: solar radiation, radiation belts

## Geosynchronous and geostationary orbits (GEO, GSO)



From a SATCOM and weather perspective, a satellite that is fixed in the sky is very interesting.

$T = 1$  sidereal day = 23h 56min 4.09s = 1436 minutes,  $T = 2\pi \sqrt{\frac{r^3}{\mu}}$

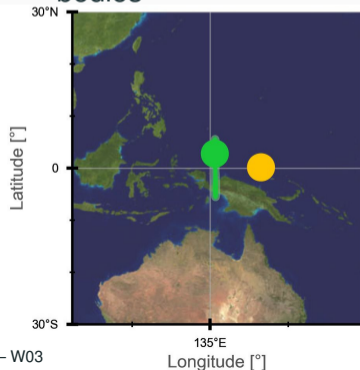
$\Rightarrow r_{\text{GEO}} = 42'164.2$  km or altitude 35'786 km ( $\sim 36'000$  km),  
 $v \sim 3.1$  km/s.

Geostationary is  $e = 0, i = 0$

Geosynchronous,  $a = r_{\text{GEO}}, i \neq 0$

## Geosynchronous and geostationary orbits (GEO, GSO)

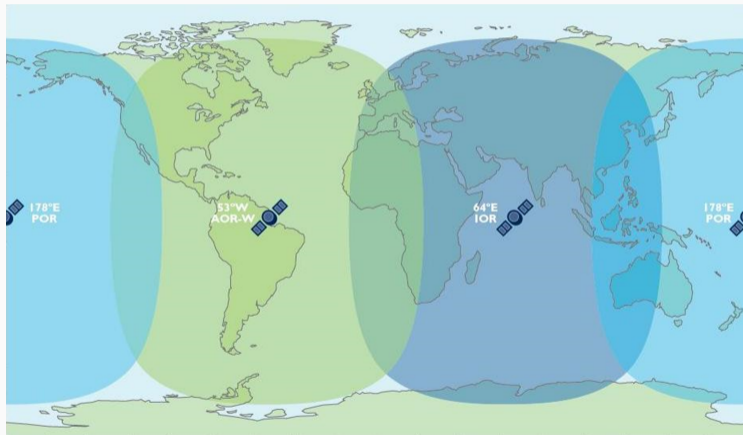
- Uses: SATCOM, broadband (TV, radio), weather
- Coverage is limited to impossible at high latitudes.
- To increase coverage, inclination is increased ( $i < 15^\circ$ )
- Main perturbations: solar radiation, gravitational perturbations from other bodies



The ground track for a geostationary orbiting satellite is a point on the equator.

If  $i > 0$  (here  $i = 5.7^\circ$ ), the object makes small figure of 8.

## Example coverage for GEO

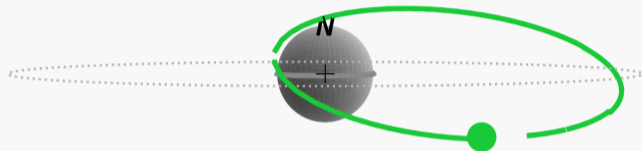


Credits: Inmarsat

The Inmarsat system blankets the Earth, connecting geostationary satellites for near total coverage.

This is a simplified picture. SATCOM satellites have beams that cover much smaller regions. E.g. Europe, Middle East, Southern Africa, ...

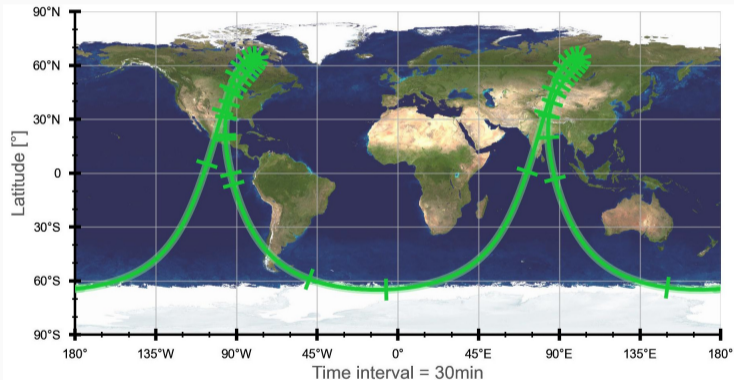
## Highly elliptical orbits (HEO) and geostationary transfer orbit



- Typically low perigee and very high apogee.
- Uses: SATCOM and transfer to GEO.
- Main perturbations: solar radiation, radiation belts, gravitational perturbations from other bodies

# HEO example: Molniya

Molniya orbits were first used by USSR to guarantee SATCOM links at high latitudes



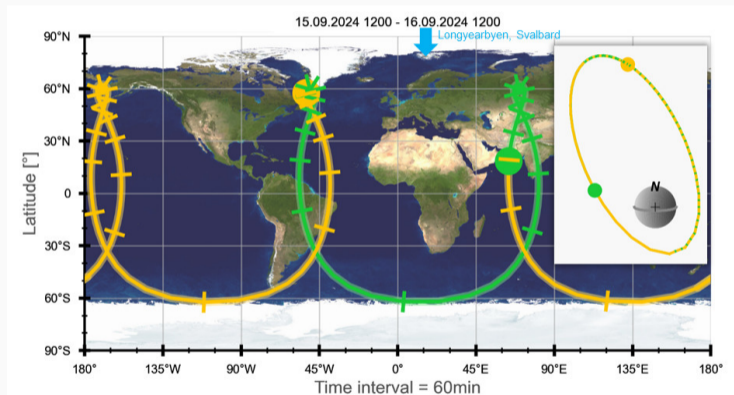
2nd Kepler law  $\rightarrow$  more time is spent at apogee than perigee (30 minutes between each tick on the plot).

A constellation (= several satellites operated as a group) of  $\geq 3$  satellites with well chosen orbital parameters ensures constant coverage.

Typical orbits:  $i = 63.4^\circ$ ,  $T = 1/2$  sidereal day,  $e \sim 0.7 \implies$  low perigee/high apogee.

# HEO example: Molniya-like (1/2)

Two satellites in HEO guarantee coverage in the Arctic.



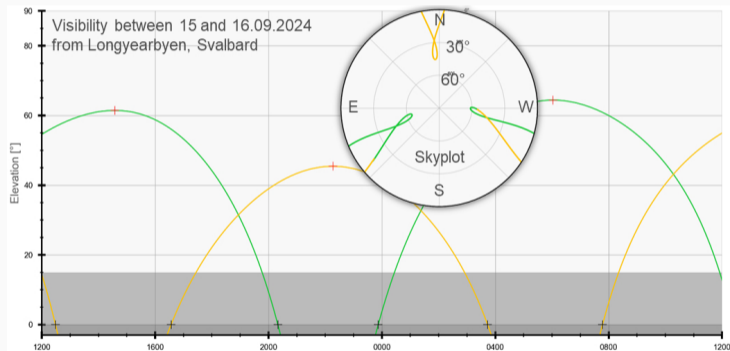
$i = 62.4^\circ$ ,  $T = 2/3$  sidereal day,  $e \sim 0.53 \implies$  low perigee/high apogee.

2nd Kepler law  $\rightarrow$  more time is spent at apogee than perigee.

The ground antenna must follow the satellites.

## HEO example: Molniya-like (2/2)

Two satellites in HEO to guarantee coverage in the Arctic.



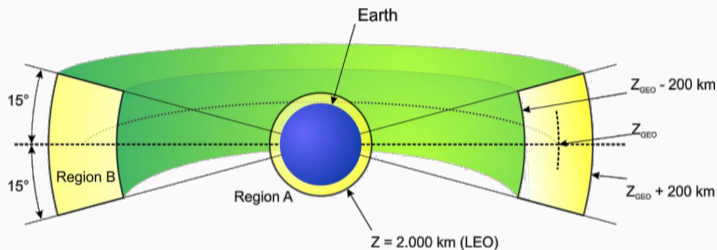
$i = 62.4^\circ$ ,  $T = 2/3$  sidereal day,  $e \sim 0.53 \implies$  low perigee/high apogee.

2nd Kepler law  $\rightarrow$  more time is spent at apogee than perigee.

The ground antenna must follow the satellites.

- Graveyard orbit:  $r_{\text{GEO}} + \sim 300$  km, end-of-life satellites are raised there to be passivated and disposed of ( $\rightarrow$  mostly non-operational satellites).
- xGEO (or far Earth orbit) are orbits around the Earth at higher altitude than GEO. Mostly for scientific uses (e.g. TESS searching for exoplanet).
- Cis-lunar: around the Moon, not bound gravitationally to the Earth.

# Protected regions



Credits: IADC

There are 2 protected regions around the Earth:

A LEO,  $z < 2000$  km

B GEO,  $z \pm 200$  km

Defined by the Inter-Agency Space Debris Coordination (IADC).

Protected = no (as little as possible) debris generation.

# There are perturbations around the Earth

Kepler's assumptions no longer hold, because. . .

- the residual atmosphere is generating a drag force which lowers the altitude;
- the Earth is non-spherical which creates non-uniform gravitational potential;
- there are other significant objects that exert a non-negligible gravitational force on satellites close to the Earth (Moon, Sun);
- the solar radiation induces a non-central perturbing force.

# **Non-keplerian perturbations I: Atmospheric drag and orbital lifetime**

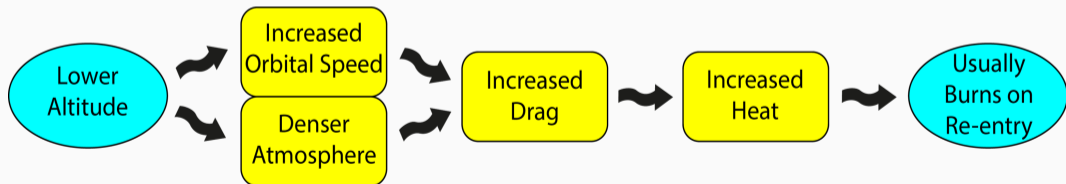
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## Orbit decay and limitation of orbital lifetime

The orbital decay is the reduction of the satellite's semi-major axis  $a$ .

This occurs up to altitudes of  $\sim 600 - 700$  km.

Orbital decay is caused by the drag in Earth's residual atmosphere,  
 $\rho_{\text{upper atmosphere}} \neq 0 \text{ kg/m}^3$ .



## Drag equations and deceleration

The force due to the drag is

$$F_{\text{drag}} = \frac{1}{2} \rho V^2 C_D A_n$$

where

- $\rho$  is the atmospheric density ( $\text{kg/m}^3$ )
- $V$  is the velocity ( $\text{m/s}$ )
- $C_D$  is the drag coefficient (-)
- $A_n$  is the cross section ( $\text{m}^2$ )

The acceleration is

$$a_{\text{drag}} = \frac{1}{2} \rho V^2 \frac{C_D A_n}{m} = \frac{1}{2} \rho V^2 \times \frac{1}{BC}$$

where

- $BC$  is the ballistic coefficient ( $\text{kg/m}^2$ )

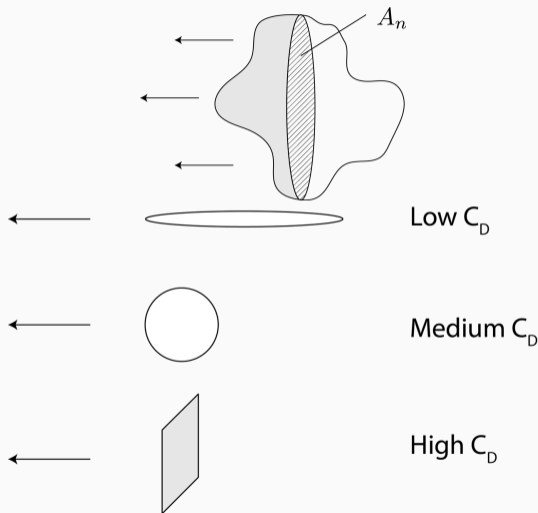
# Ballistic coefficient

The ballistic coefficient measures the resistance to orbit decay caused by atmospheric drag.

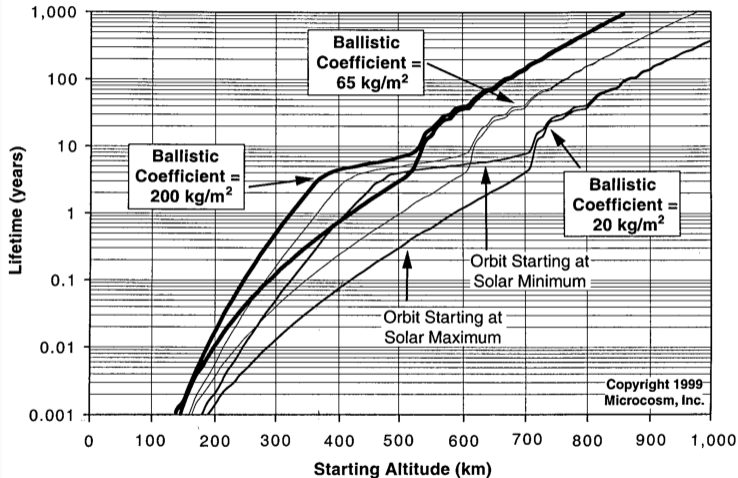
$$BC = \frac{m}{C_D A_n} \quad \text{in kg/m}^2$$

The drag coefficient depends on shape, attitude and surface condition (specular and diffuse reflection, absorption).

Typically,  $C_D \sim 2.2$ , but can vary from 2 – 4



# Lifetime and ballistic coefficient

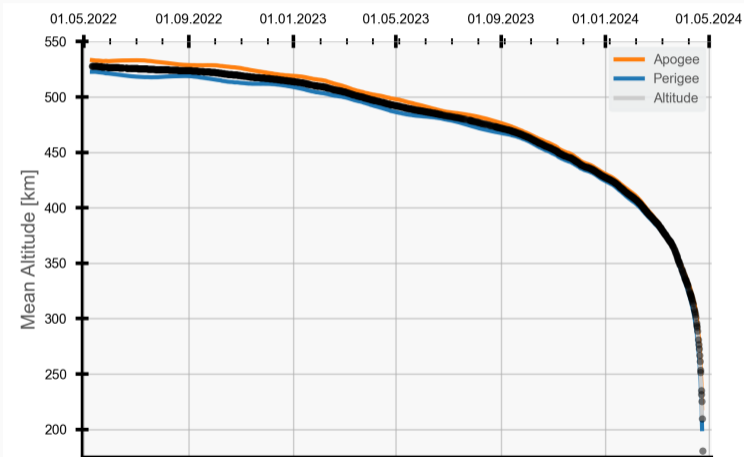


Credits: J. R. Wertz & W. J. Larson, *SMAD*, 1992

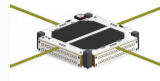
*BC* is inversely proportional to the drag deceleration.

A high *BC* indicates a small value of the deceleration and consequently a long lifetime

# Orbital lifetime of SpaceBEE 146



Data: Space-Track.org



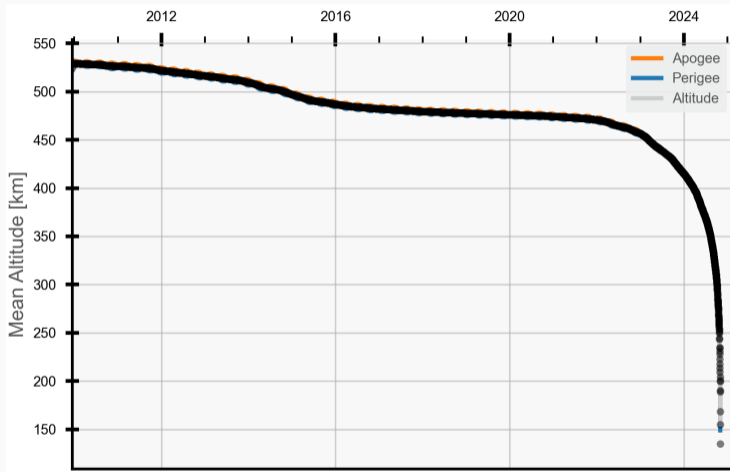
Credits: Swarm Technologies

SpaceBEE is a picosatellite (0.25U cubesat,  $10 \times 10 \times 2.5$  cm; 450 gr) to provide two-way satellite communications and data relay. The operator, Swarm Technologies, is owned by SpaceX.

Launched 02 MAY 2022 on an Electron rocket (Rocket-Lab) from New Zealand, re-entered 23 APR 2024.

Orbital lifetime:  $\sim 2$  years,  
 $BC \sim 50 - 55 \text{ kg/m}^2$ .

# Orbital lifetime of the Wide-field Infrared Survey Explorer (WISE)



Data: Space-Track.org



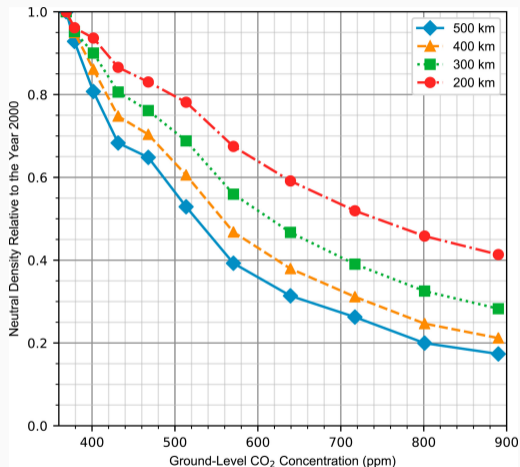
Credits: NASA/JPL-Caltech

NASA infrared astronomy space telescope ( $2.9 \times 2 \times 1.7$  m, 661 kg)

Launched 14 DEC 2009 on an Delta II (ULA) from Vandenberg, California, decommissioned 01 AUG 2024, re-entered 02 NOV 2024.

Orbital lifetime:  $\sim 14$  years,  $BC \sim 150 - 250 \text{ kg/m}^2$ .

# Effect of climate change on the upper atmosphere



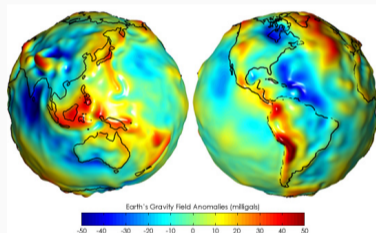
Credits: Brown, M. K., Lewis, H. G., Kavanagh, A. J., & Crossen, I. (2021).

- Increasing CO<sub>2</sub> causes cooling in the upper atmosphere and a decrease in atmospheric density over time.
- Neutral density at 500 km altitude lowers by over 80% with a high ground-level carbon dioxide concentration of 890 ppm (RCP8.5 model).
- Meeting the 1.5°C Paris Agreement target would limit the reduction in neutral density at 400 km since the year 2000 to around 28%.
  - Objects in LEO will have 30% longer lifetimes (1.5°C assumption) compared to the year 2000.
  - Less manoeuvres to remain on orbit ("station-keeping") but debris will linger for longer.
  - *Space Sustainability Course EE-587.*

## **Non-keplerian perturbations II: Earth non-circularity and sun-synchronous orbits**

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# Earth gravitational potential



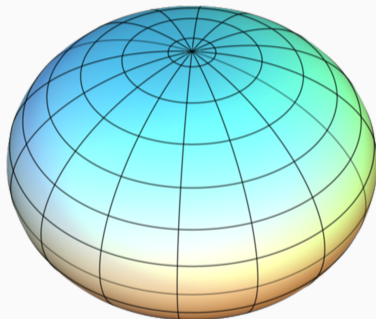
Credits: Grace mission, NASA/DLR

Earth is not a perfect sphere.

A first approximation ( $n = 2$ ) is an oblate sphere. The model can be improved by additional geopotential coefficients.

The rotation of the Earth's on its axis bulges the equator. This is modelled by the  $J_2$  coefficient.

## Equatorial bulge – $J_2$ perturbation



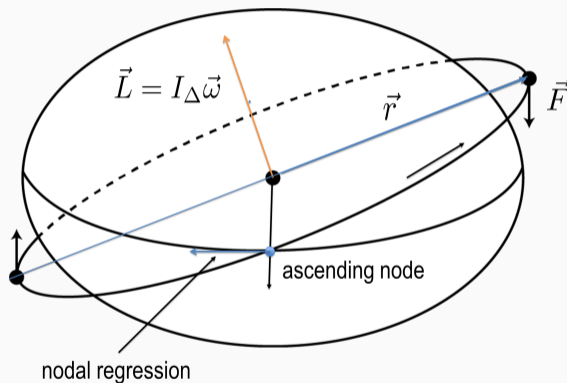
Credits: Wikipedia

The flattening of the Earth's surface is 1:298 (which corresponds to a radius difference of 21.38 km of the Earth radius 6378.13 - 6356.75 km).

This has two impacts on the orbit:

1. Nodal regression (RAAN drift)
2. Rotation of the line of apsides (argument of perigee  $\omega$ )

## Nodal regression for LEO – Forces and torques



The equatorial bulge causes the gravitational force on a satellite to deviate from a purely central force, except at equator crossings, and for purely equatorial or polar orbits.

$$\begin{aligned}\vec{T} &= \vec{r} \times \vec{F} \\ &= \vec{r} \times \ddot{\vec{r}} \\ &= \frac{d\vec{h}}{dt}\end{aligned}$$

## Nodal regression rate for low Earth orbits

The rate of changes of  $\Omega$  and  $\omega$  due to zonal coefficient  $J_2$  are

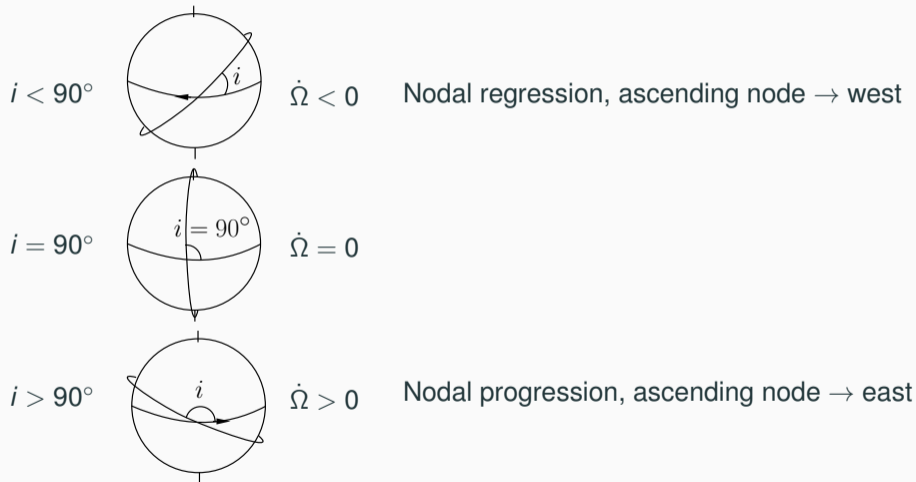
$$\dot{\Omega}_{J_2} \approx -2.06474 \times 10^{14} \frac{\cos i}{a^{3.5}(1-e^2)^2} \quad \text{RAAN drift}$$

$$\boxed{\dot{\Omega}_{J_2} \approx -\text{cst} \cdot \frac{\cos i}{a^{3.5}}} \quad \text{RAAN drift for circular orbit}$$

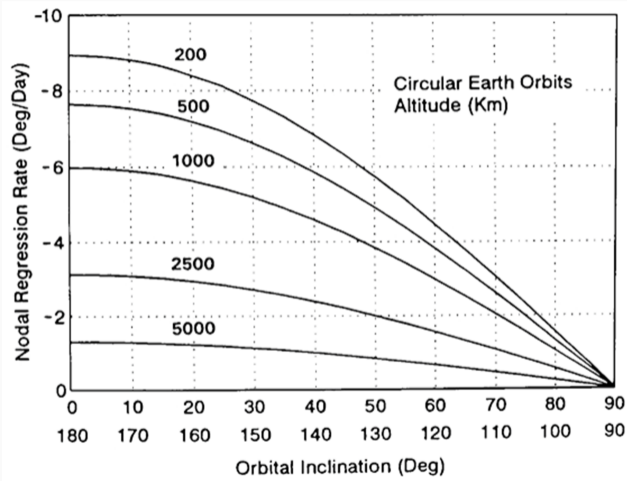
$$\dot{\omega}_{J_2} \approx 1.03237 \times 10^{14} \frac{4 - 5 \sin^2 i}{a^{3.5}(1-e^2)^2} \quad \text{Argument of perigee drift}$$

where  $\dot{\Omega}$  and  $\dot{\omega}$  are in degrees per mean solar day with  $a$  in kilometers.

# Visualisation of the nodal regression and progression



# Nodal regression rate for low Earth orbits



Credits: J. R. Wertz & W. J. Larson, *SMAD*, 1992

The line of nodes drifts...

- westwards for  $i < 90^\circ$   
(posigrade or direct orbit)  
→ nodal regression
- eastwards for  $i > 90^\circ$   
(retrograde orbit) → nodal progression

# Sun-synchronous orbit

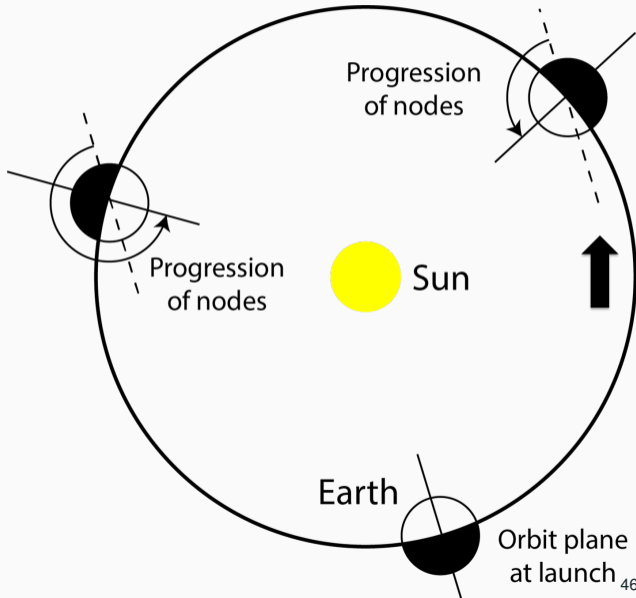
A Sun-synchronous orbit (SSO) is an Earth centred orbit which maintains a constant orientation with respect to the Sun during the year.

⇒ that the line of nodes rotates to keep a constant angle to the vector of the Sun.

Requirements on  $\dot{\Omega}$  for SSO:

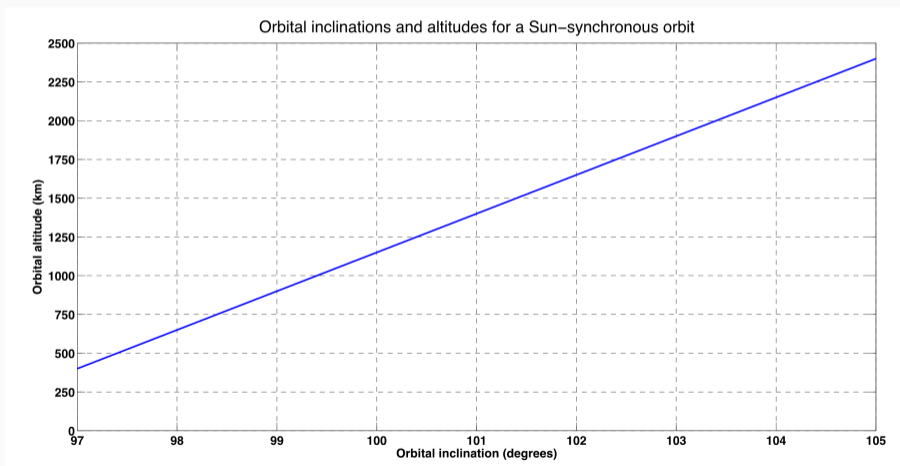
$$\dot{\Omega} = \frac{360^\circ}{365.242 \text{ days}} = 0.9856 \frac{\text{deg}}{\text{day}}$$

→ nodal progression ⇒  $i > 90^\circ$



# Orbital inclinations and altitudes for a Sun-synchronous orbit

The blue line shows the possible orbital parameters ( $e = 0$ ) such that the SSO condition is fulfilled.



Typical SSO parameters:  $97^\circ < i < 99.5^\circ$ ,  $300 < z < 1000\text{km}$ ,  $e \sim 0$

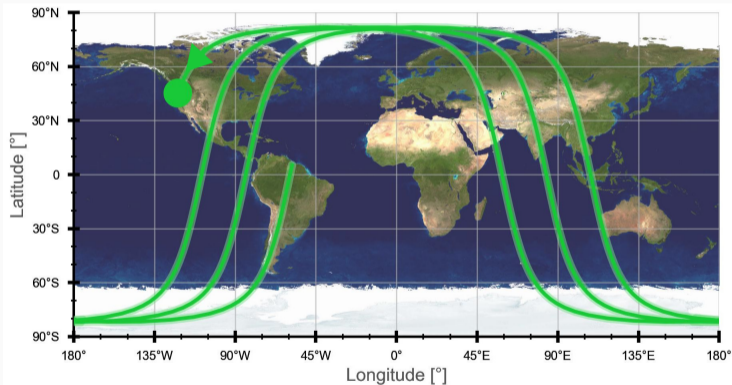
## Use Cases for SSO

A satellite in a Sun-synchronous orbit passes the equator at the same (solar) time each day (e.g. a satellite's sun-synchronous orbit might cross the equator  $\sim 15$  times a day each time at 3:00 pm and 3:00 am local time). This is the equatorial crossing time (ECT).

SSO orbits are interesting because. . .

- satellites pass over the same region on the equator at the same illumination angle, however the solar illumination varies at non-zero latitudes;
- similar argument but for non-Earth observations: the angle between the plane of the orbit and the direction of the Sun is constant yielding a large field of view;
- the coverage is global;
- 6:00 am/6:00 pm ECT (i.e. dawn/dusk) SSO minimises the time spent in eclipses.

# SSO ground track

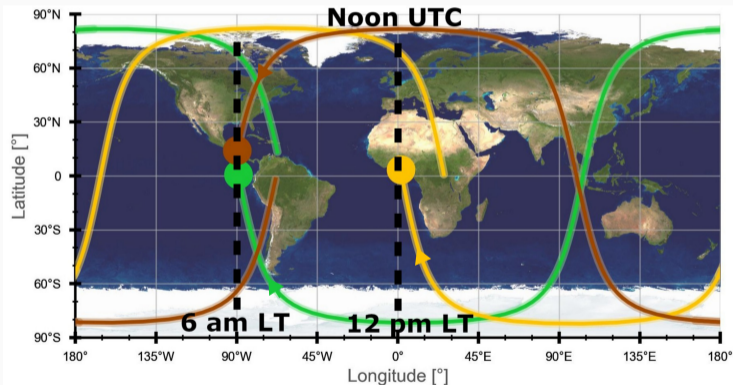


$i > 90^\circ \rightarrow$  retrograde motion.

Example: alt,  $z \sim 700$  km,  $i = 98.2^\circ$ , ECT  $\uparrow 6\text{am}/\downarrow 6\text{pm}$ .

# SSO Equatorial Crossing Time

Satellites on SSO cross the equator always at the same local solar time (LT).



$i > 90^\circ \rightarrow$  retrograde motion.

↑ crossing ascending node  
↓ crossing descend. node

Green: ↑6am/↓6pm

Brown: ↑6pm/↓6am

Yellow: ↑noon/↓12am

*Example: when yellow object crossed the equator 1 orbit before, it was 12pm LT at Lake Victoria.*

## **Non-keplerian perturbations III: Other massive bodies**

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## Other sources of gravitational forces

Body	Acceleration [ $g_0$ ]
Earth	$\sim 0.9$
Sun	$6 \times 10^{-4}$
Moon	$3 \times 10^{-6}$
Jupiter	$3 \times 10^{-8}$
Venus	$2 \times 10^{-8}$

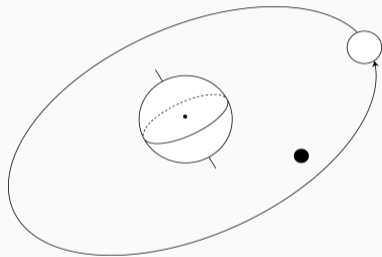
These bodies might not always be neglected, especially in regions higher than MEO.

## Restricted three-body problem

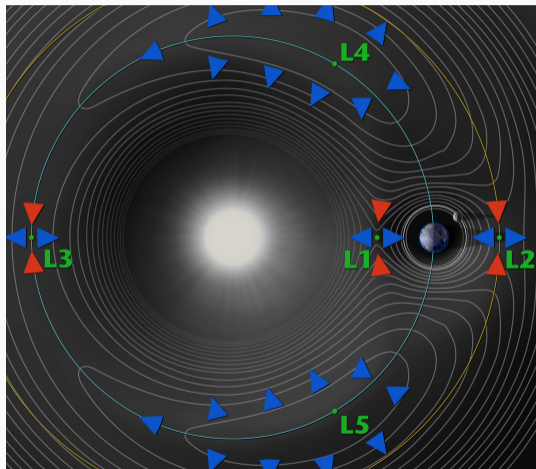
The assumption of only one significant massive object is relaxed. The restricted three-body problem describes the trajectory of a small mass in a system with two large bodies with the following assumptions:

1. The two main bodies (of mass  $m_1$  and  $m_2$ ) are on circular orbits around the centre of mass of the system.
2. The mass of the third body  $m$  is  $m \ll m_1, m_2$ .
3. The third body is in the plane of the orbit of the two main bodies.

This is valid for the Earth-Moon or Sun-Earth, Sun-Jupiter system.



# Lagrange points



Credits: NASA, WMAP Science Team

There are 5 points at which the third mass  $m$  where the gravitational forces and the satellite's inertial acceleration are at equilibrium → Lagrange points.

The L4 or L5 points form an equilateral triangle with the two other masses. They are locally stable if  $m_1$  is massive enough ( $m_1/m_2 \gtrsim 25$ ). Stability arises from coriolis force despite being maximas.

L1, L2, L3 are on a line. They are on saddle points of equilibrium. If perturbed, objects at these points will move away over time.

Red arrows indicate stability, blue arrows instability.

## Interest of Lagrange points

- In the Sun-Earth system, the distance to the Earth of the L1 Lagrange point is about 1.5 million km, or 1% of the Sun-Earth distance = 0.01 astronomical unit (AU). The Lagrange point L2 is 1.5 million km away from the Earth in the anti-Sun direction.
- In the Sun-Jupiter system, there are asteroids trapped around L4 and L5, the so called Trojans (respectively the Trojan and Greek camps).
- In the Earth-Moon system, there are no objects around L4 or L5, because of the perturbation by the gravitational force of the Sun.
- Orbits can be achieved around L1, L2 or L3. They require limited station-keeping (Lissajous or halo).
- Sun-observation missions can be placed in L1, like SOHO.
- Astronomical observatories are at L2 like James Webb Space Telescope or Euclid. They can continuously observe in the anti-sun direction.
- Space weather mission at L5. Vigil (ESA, 2031) will look at the sunspots moving in the view of Earth.

## **Non-keplerian perturbations IV: Solar radiation pressure**

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## Solar radiation pressure

- The total solar irradiance (recall: total energy of the photons emitted by the Sun integrated over the electromagnetic spectrum) at Earth's distance is  $S_0 \sim 1368 \text{ W/m}^2$ .
- The momentum of a photon is its energy divided by the speed of light  $c$ .
- The perturbing acceleration is

$$\vec{p} = -\frac{S_0}{c} \frac{C_R A_n}{m} \hat{u}$$

where  $C_R$  is the radiation pressure coefficient (1 if the surface is a blackbody, 2 if the incident radiation is reflected),  $m$  is the mass of the object and  $A_n$  is the absorbing cross-section and  $\hat{u}$  the unit vector pointing towards the Sun.

- The solar radiation pressure dominates the drag deceleration at  $\sim 800 \text{ km}$  altitude  $\rightarrow$  important for GEO orbits.

### → 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