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Space Quantum Communications

How to use FSO (Free Space Optical) communications to implement QKD (Quantum Key Distribution)

Learning Outcomes

By the end of this unit, you will be able to:

- Describe how the QKD system in space works
- Explain all the required subsystems that are part of the system
- Understand the trade-offs between different engineering decisions

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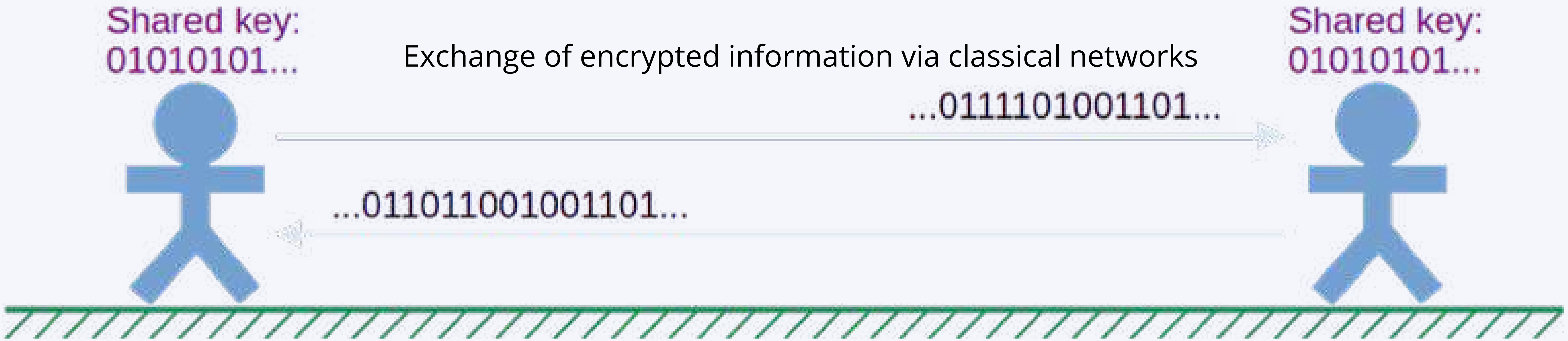
The Challenge

- Quantum Key Distribution (QKD) is a secure communication method that uses the principles of quantum mechanics to enable two parties to share a secret key. This key can then be used to encrypt and decrypt messages, ensuring that the communication is secure against eavesdropping.
- After Alice and Bob got the shared key, they can use symmetric encryption algorithms
- Why symmetrical encryption? Because it is strong against quantum computing
- The challenge is: How could both Alice and Bob exchange the key, before the actual data exchange, without anyone else tampering?



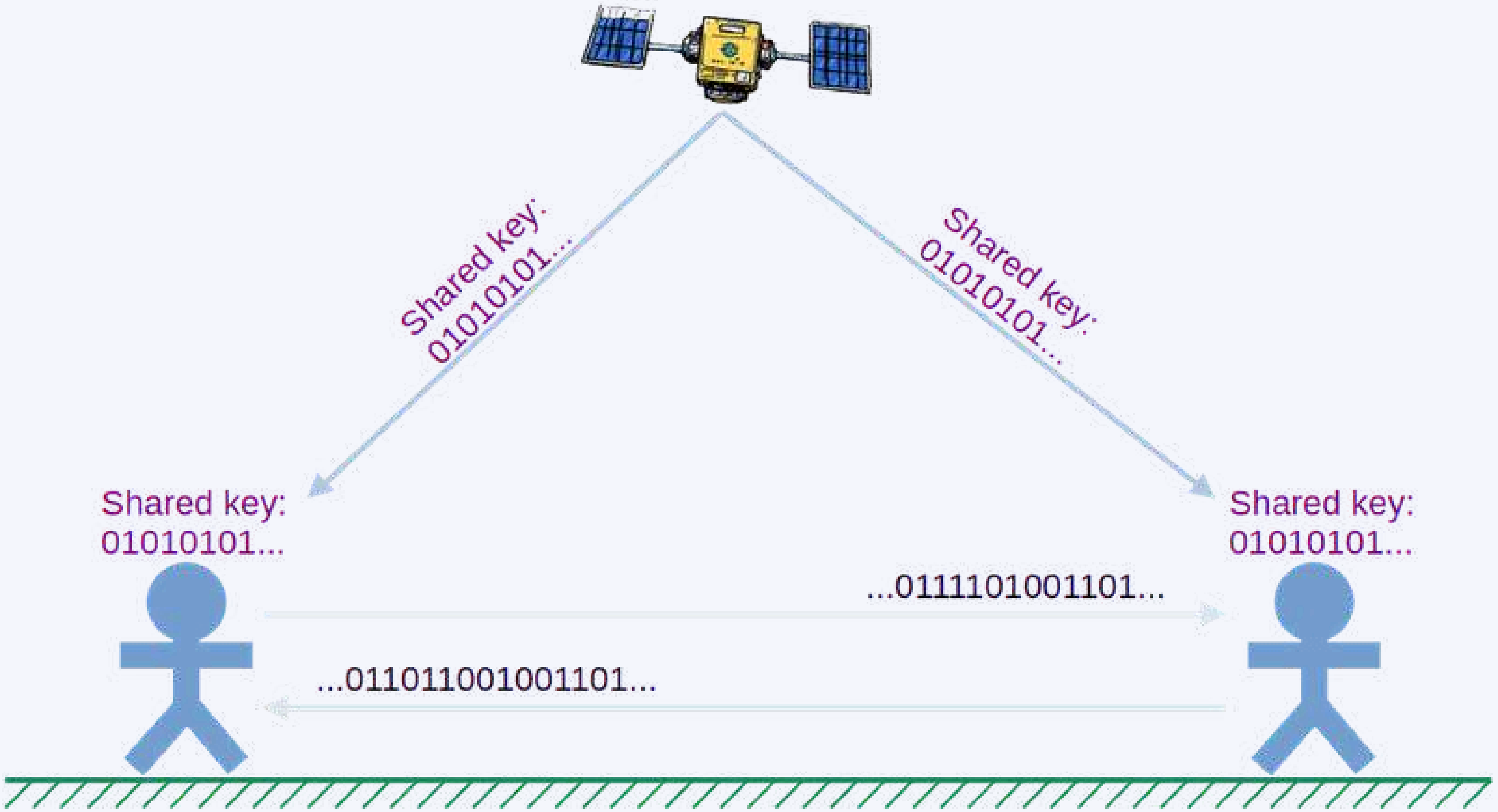
The Solution

A satellite in space generates the key using a Quantum Random Number Generator (QRNG).

Then the satellite sends the key to both Alice and Bob via optical quantum communications using Free Space Optical (FSO) communications (light beams through free space, such as air, outer space, or vacuum, without the need for physical cables like optical fiber).

Note: The satellite does not have to send the key simultaneously. The Micius satellite (500 km orbit altitude) sent the key to Beijing (China) and Vienna (Austria), separated by 7600 km.

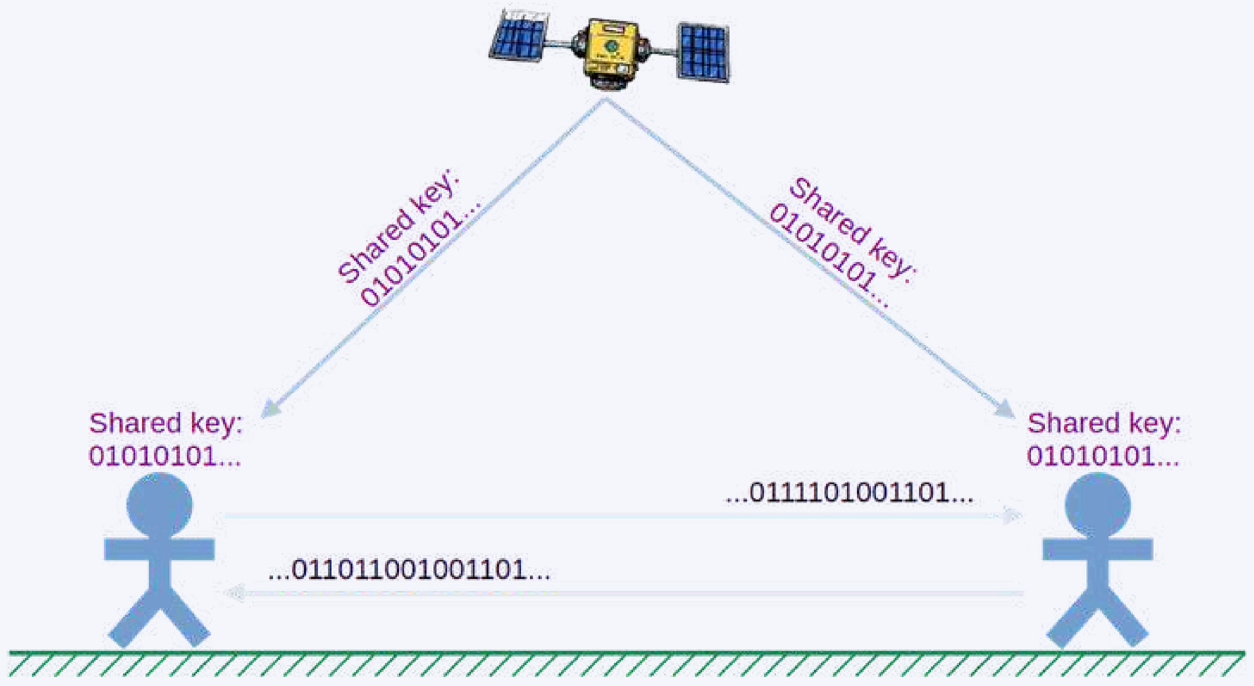
https://phys.org/news/2018-01-real-world-intercontinental-quantum-enabled-micius.html



Advantage of FSO vs Optical Fiber

For terrestrial QKD via optical fibers, the signal attenuation scales exponentially with the fiber length, the maximum link distance is currently limited to a few hundred kilometers. This is sufficient to establish secure key exchange in local networks but a global communication architecture mandates key generation over significantly longer distances.

Optical satellite-to-ground links feature significantly lower propagation losses than fiber links. Under good weather conditions, losses scale quadratically with distance which facilitates significantly longer QKD link distances when compared to fiber links.



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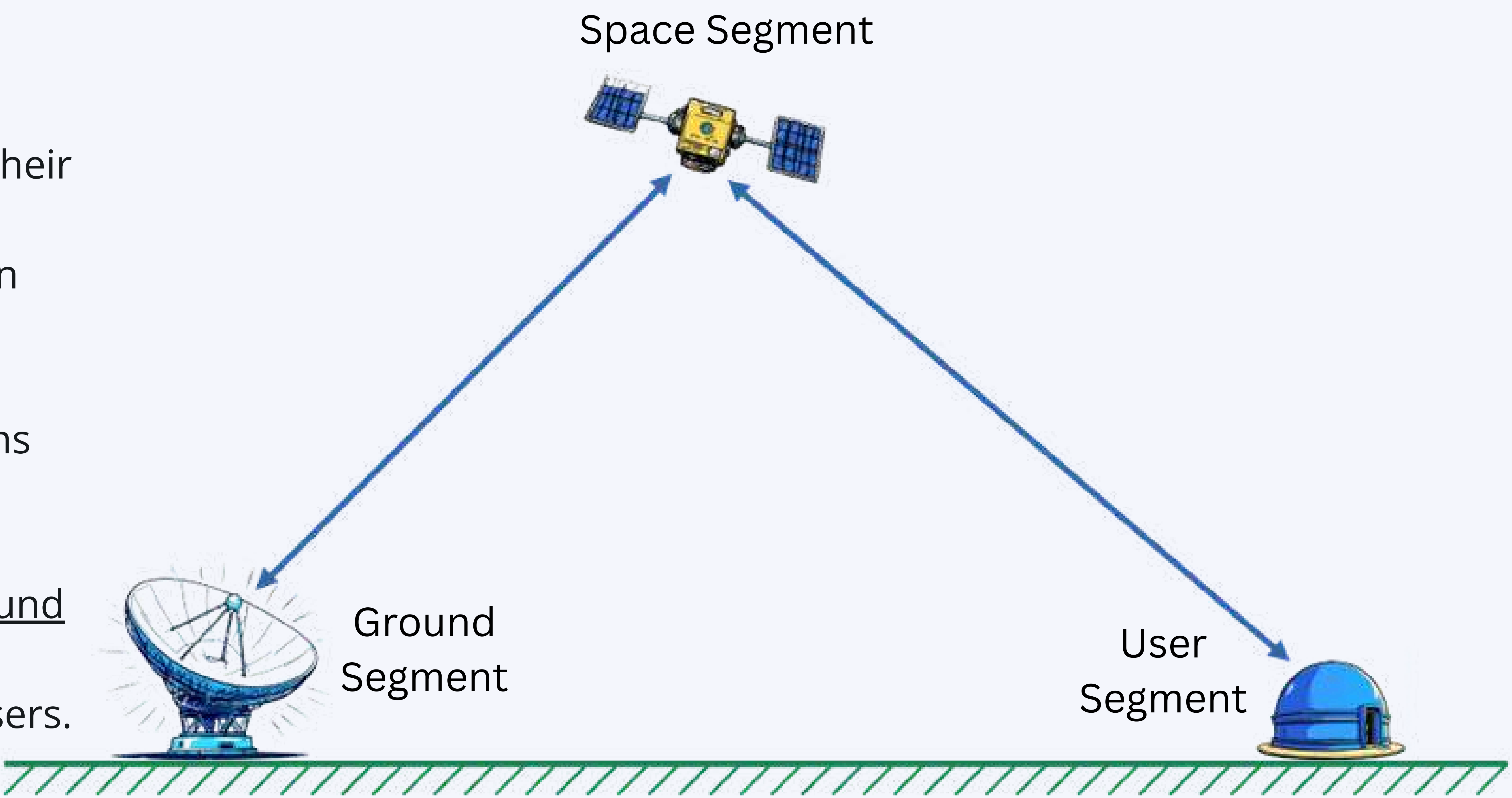
The Implementation

In space engineering vocabulary: the System is composed of three parts (segments).

- Space Segment: The satellite or constellation of satellites. And their payloads.
- Ground Segment: The operation control for the satellite (orbit, attitude) and its payload (key generator). This communications are typically done with radio antennas.
- User Segment: The Optical Ground Station (OGS) that receives the secret key and interacts with users.



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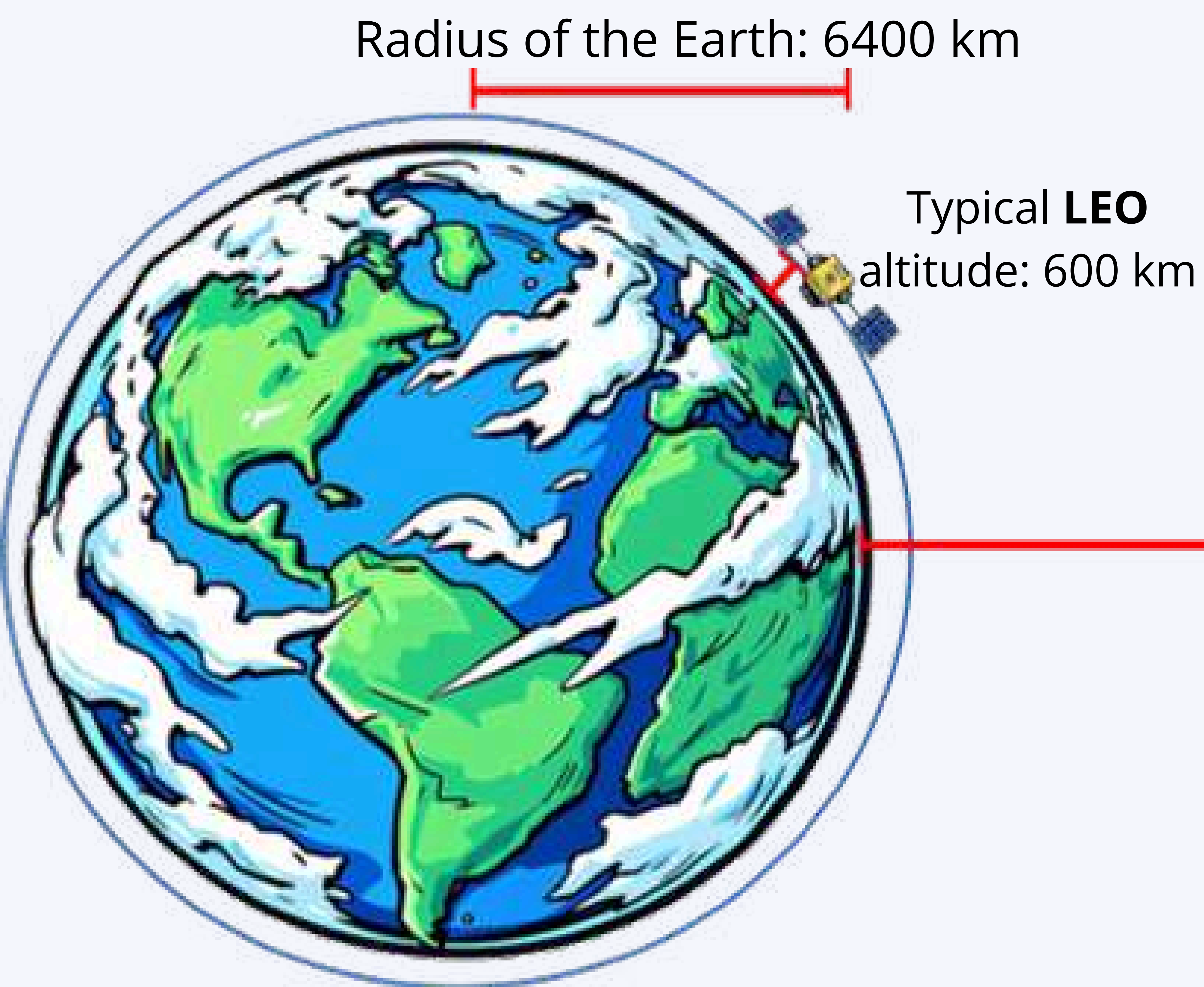
Satellite Orbits

There are two typical orbits for communication satellites around the Earth:

- **<u>LEO</u>** (Low Earth Orbit), at about 500-1000 km altitude (about 10% or Earth radius)
- **<u>GEO</u>** (GEostationary Orbit), at about 36000 km altitude



Effect of LEO Altitude

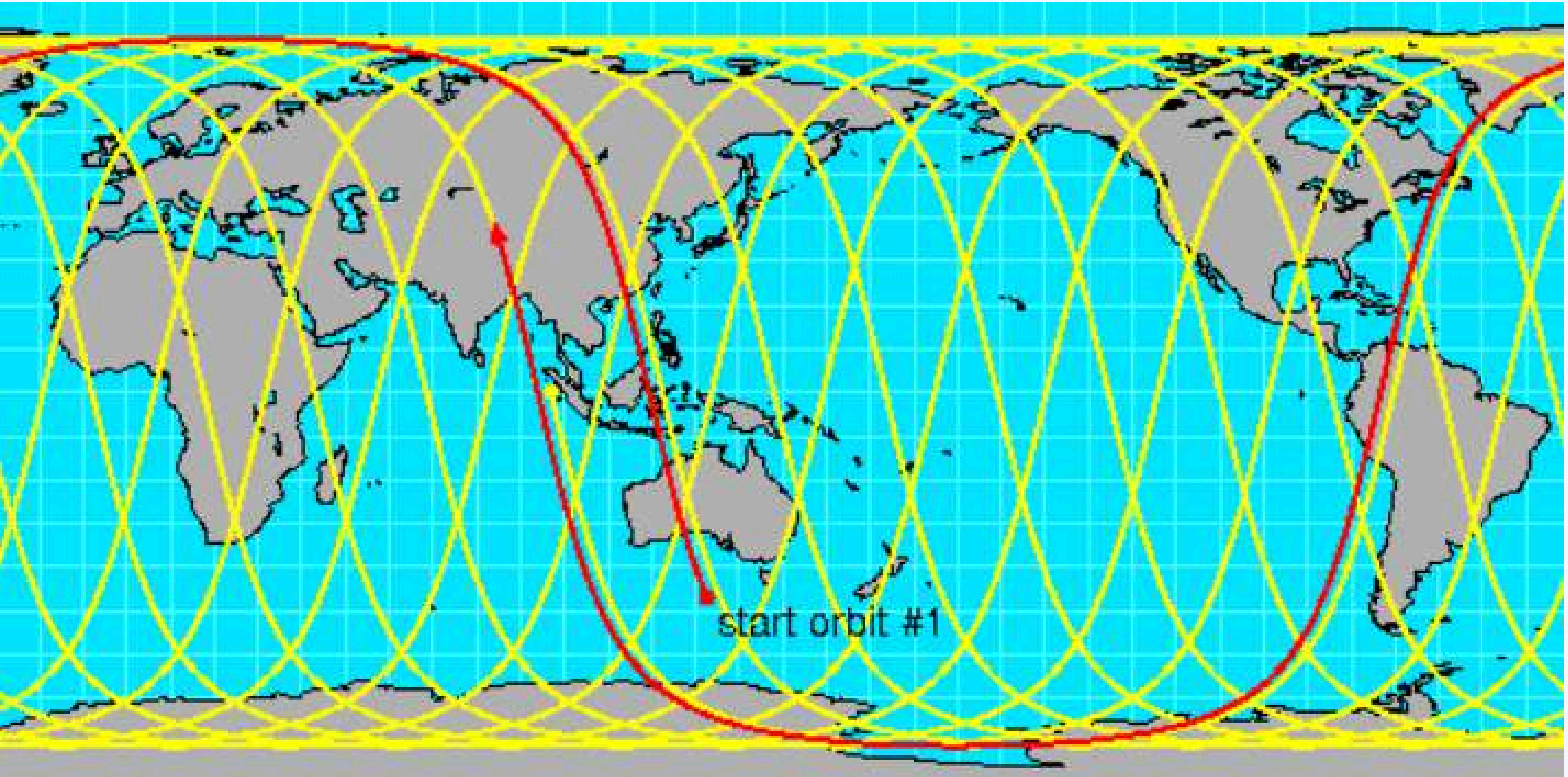
The visibility of a **LEO** satellite from ground is limited.

See on the right an example with a Sentinel-1 satellite (about Earth Observation, not quantum related).

Note the polar orbit (North-South scans), and that two consecutive orbits (orbital period: 98 minutes) are quite far away from each other. Many orbits are needed to fly above any point on the Earth.

Sentinel-1 orbit altitude is about 700 km. Note that 700 km is the distance between Monaco and Luxembourg, both visible in the map.

Typical track on Earth surface of satellite on LEO



Note the drift in the first orbit.

Orbits do not overlap, unless we choose the orbital parameters carefully (see SSOs in a moment)

SSO, a very special LEO

A special group of LEOs, very commonly used, is the Sun Synchronous Orbit (SSO)

https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#SSO

A SSO is a nearly polar orbit around a planet, in which the satellite passes over any given point of the planet's surface at the same local mean solar time.

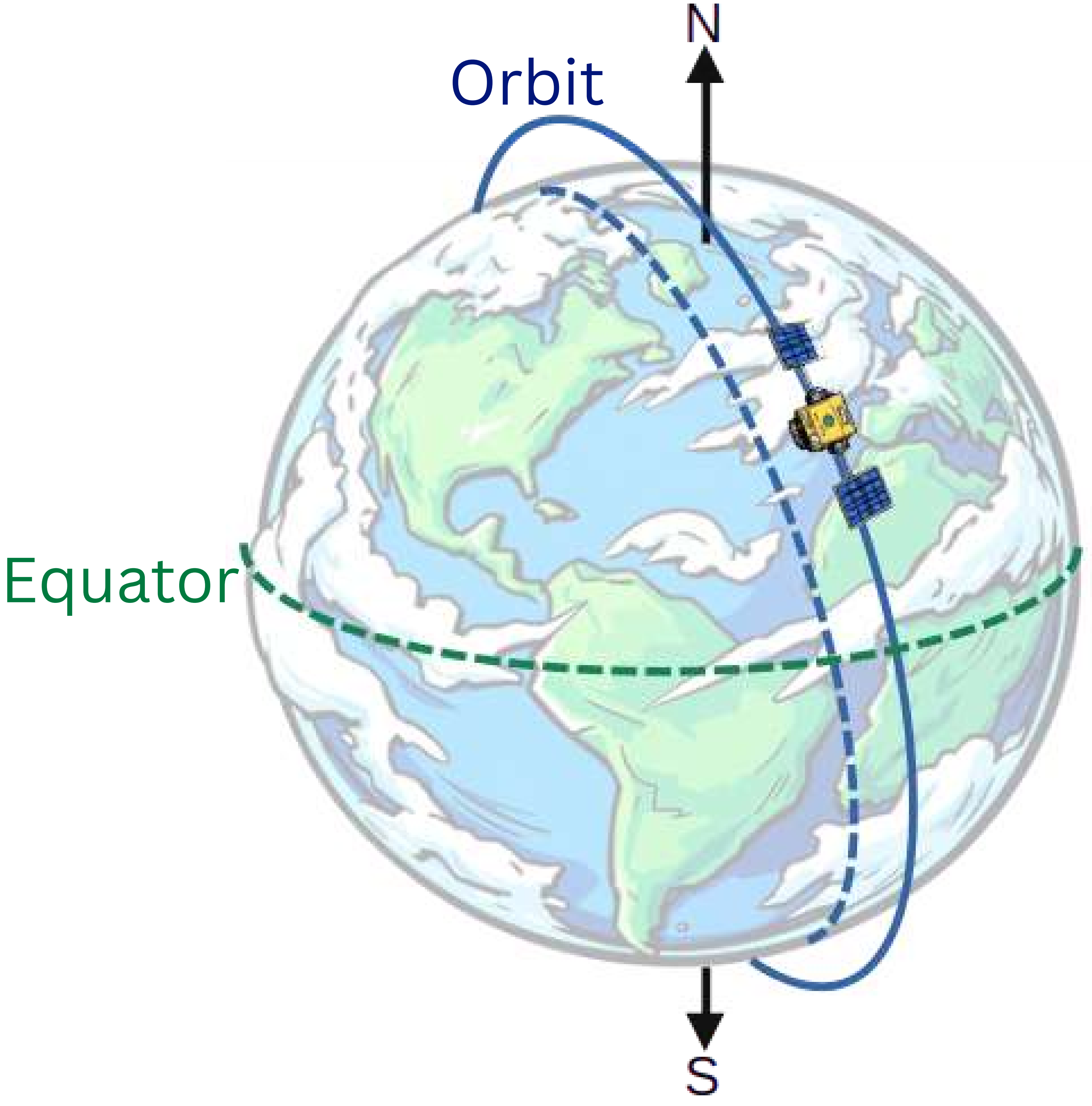
It is useful because the user knows in advance at what time the satellite will fly over, always at the same (solar) time (for example, always midnight over Cyprus).

And thanks to be fact that it is nearly polar orbit, the satellite eventually passes over all points of the Earth.

Both Micius and Eagle-1 are satellites in SSO.

https://arxiv.org/html/2505.20838v1

https://www.eoportal.org/satellite-missions/quess#launch

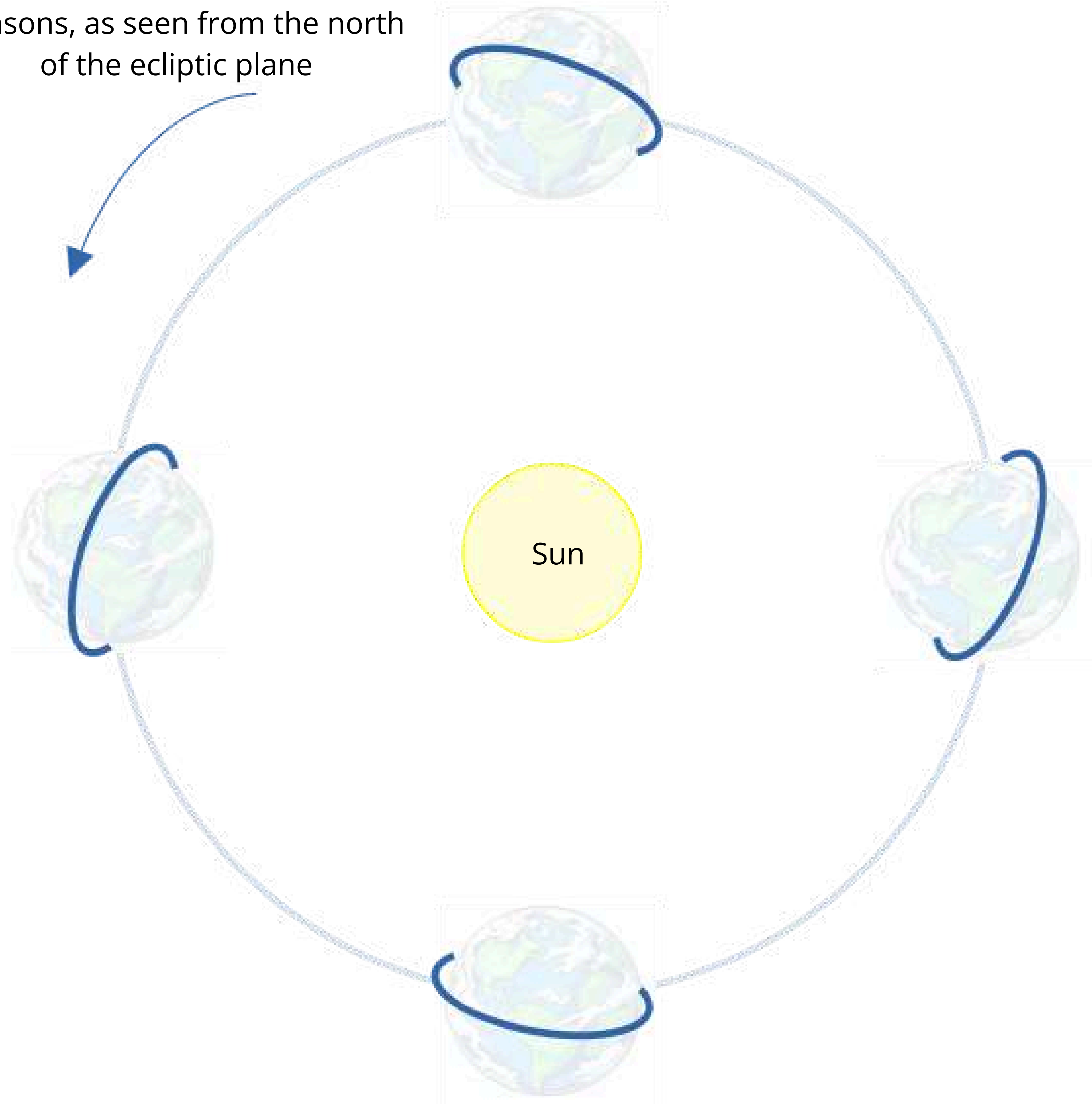


The geometry of a SSO

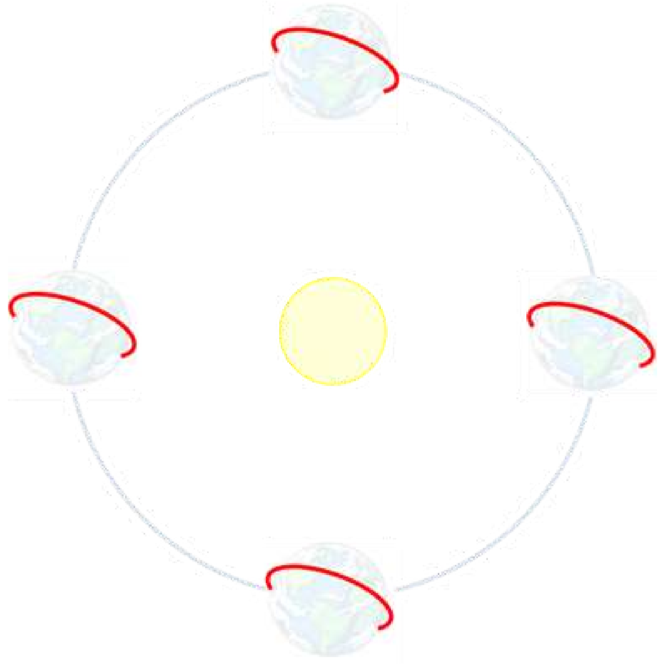
The Earth is not spherical → Systematic perturbation in orbit

Technically, a generic SSO is an orbit arranged so that it precesses through one complete revolution each year, so it always maintains the same angle with the Sun. Taking advantage of the perturbation!

Motion of the Earth in its orbit around the Sun, during the four seasons, as seen from the north of the ecliptic plane



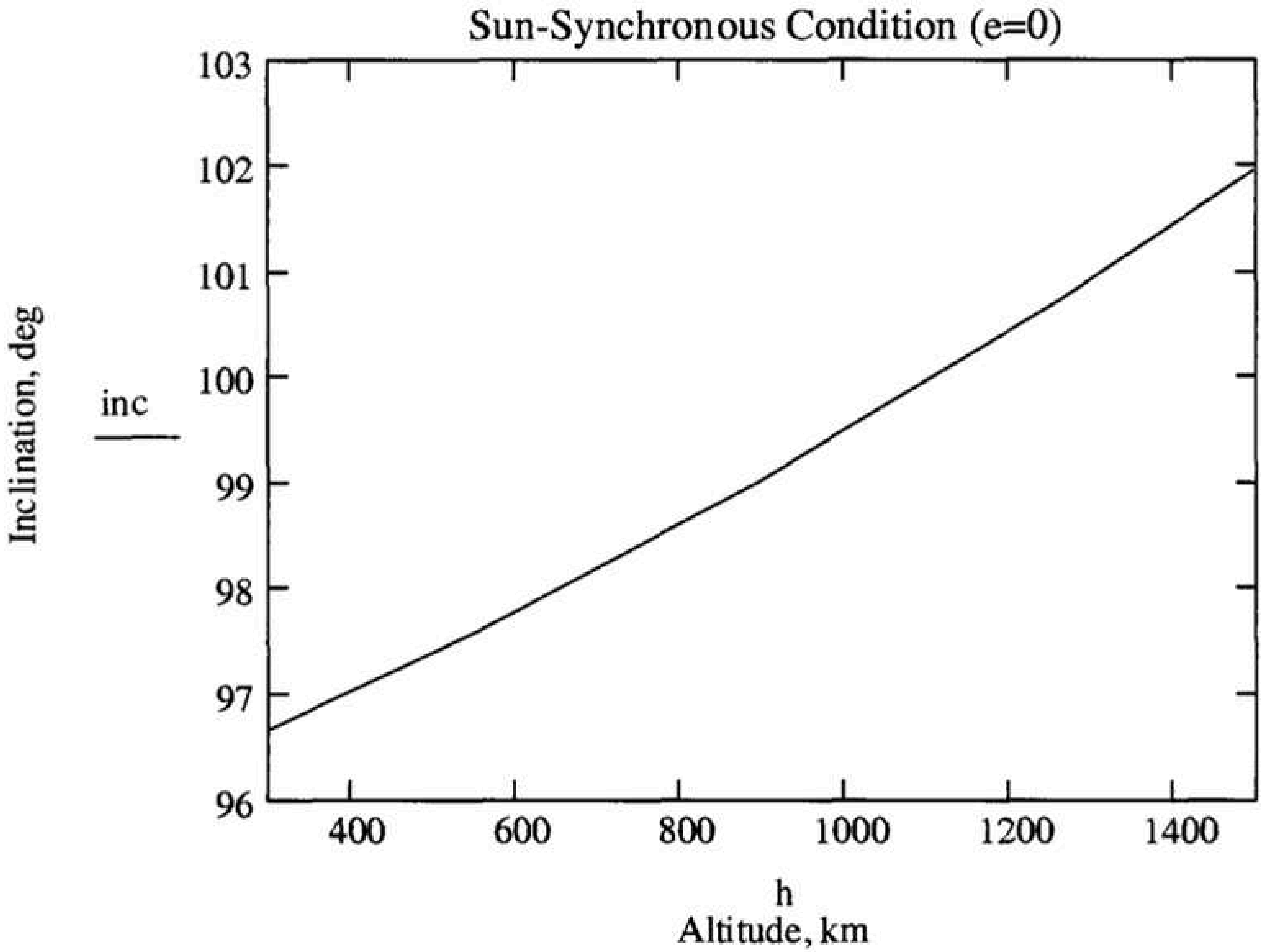
For comparison purposes, this is the equivalent diagram for a typical orbit. In absence of perturbations, the orbit keeps its orientation constant in an inertial frame. The orbit does not rotate, only the Sun and the Earth move.



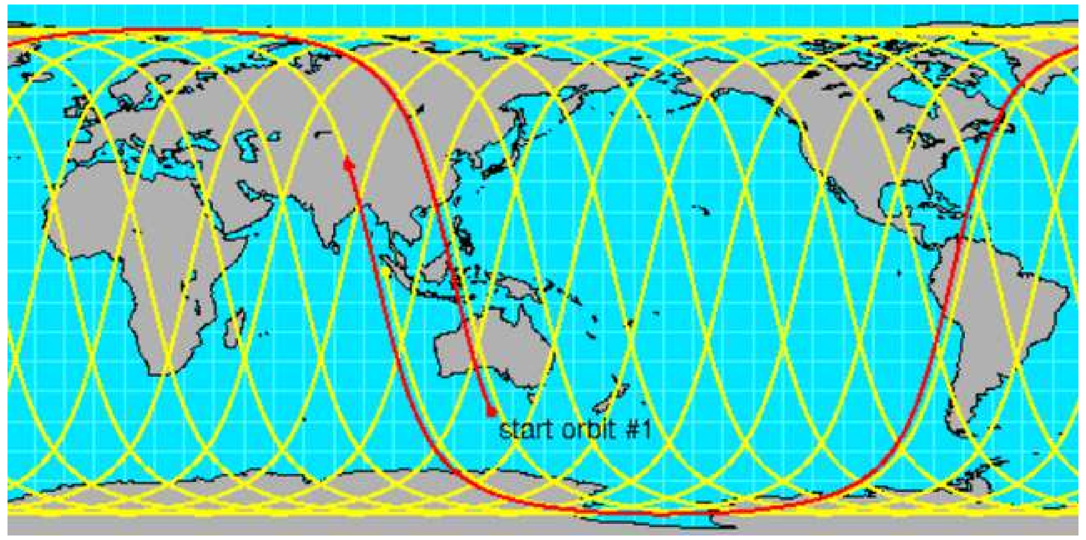
SSO: altitude vs inclination

SSO are defined by altitude and orbit inclination (both are linked, knowing one fixes the other). With this combination there is precession in the orbit at exactly the same angular speed as the apparent motion of the sun in the sky.

More info: “A-B-Cs of Sun-Synchronous Orbit Mission Design”, Ronald J. Boain. https://ntrs.nasa.gov/citations/20210001902



Special Subset of SSOs



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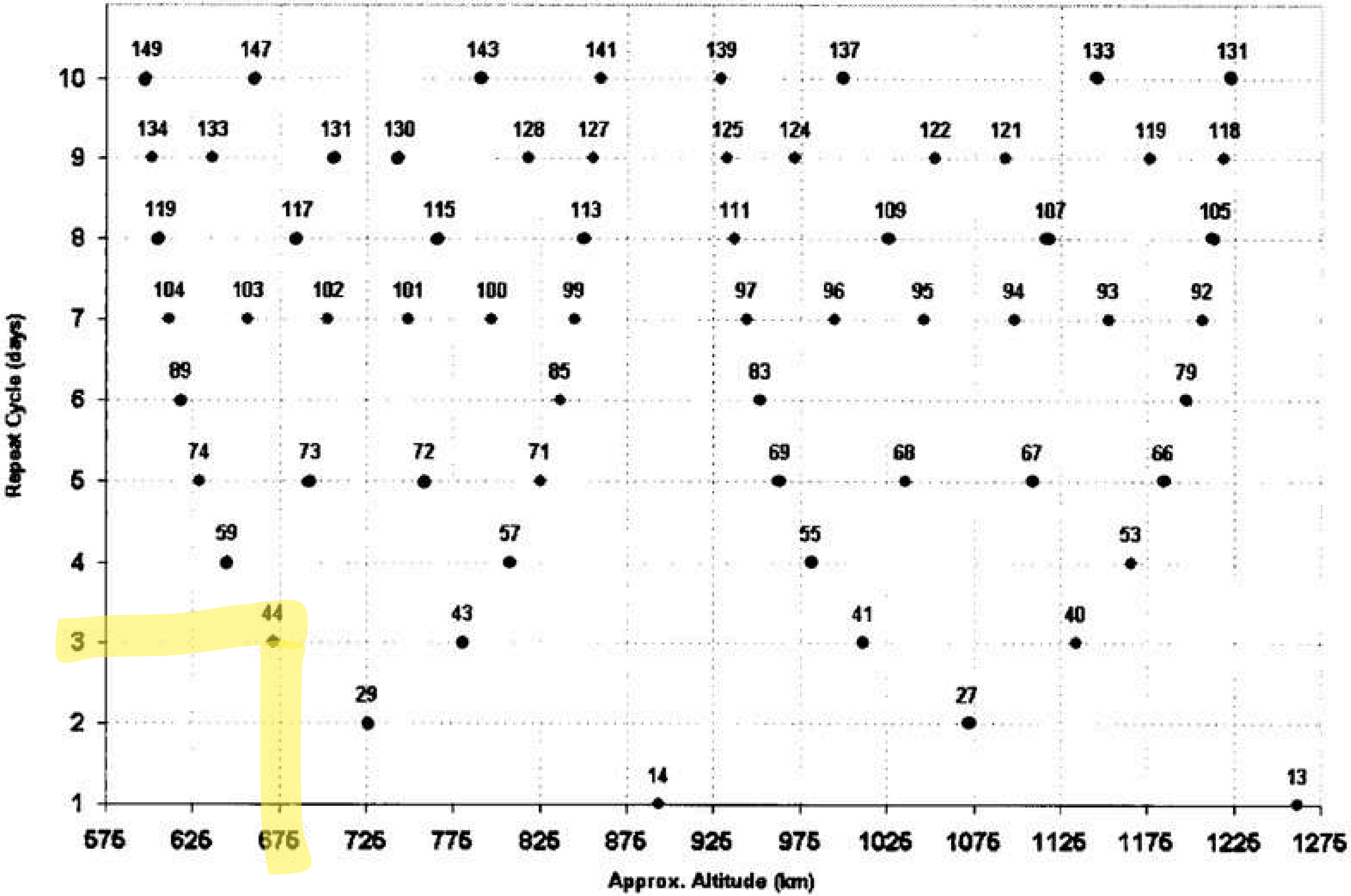
Taking into account the Earth rotation (day & night cycle) some special SSO altitude & inclination combinations generate orbits that repeat themselves <u>with respect to an observer on the Earth</u> (like electron orbits and their quantum numbers!).

Example: At **675 km** altitude, the orbit repeats itself after **44 orbits** (~98 min/orbit), that corresponds to **3 days.**



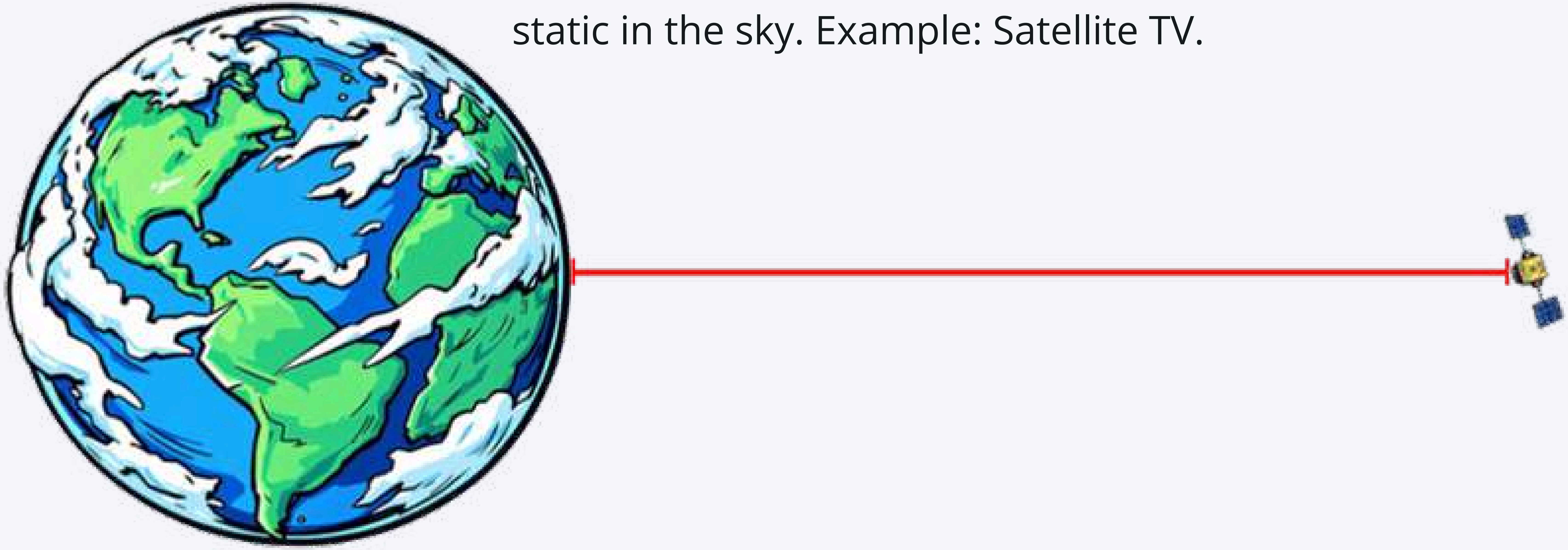
More info: "A-B-Cs of Sun-Synchronous Orbit Mission Design", Ronald J. Boain.
https://ntrs.nasa.gov/citations/20210001902

LEO (Low Earth Orbit)

- Pros
  - Lower cost of launch (lower EUR/kg)
  - Global coverage. In a polar LEO orbit, a satellite could fly above any point of the Earth
- Cons
  - Operational complexity. Although it takes the satellite about 90 minutes to orbit the Earth, it takes many orbits to be above the same place on the Earth, therefore at mid latitudes there could be communications between satellite and ground station only once or twice per week → Many satellites are needed for continuous coverage
  - Limited time for communications. The satellite crosses the sky above the ground station in less than 5 minutes

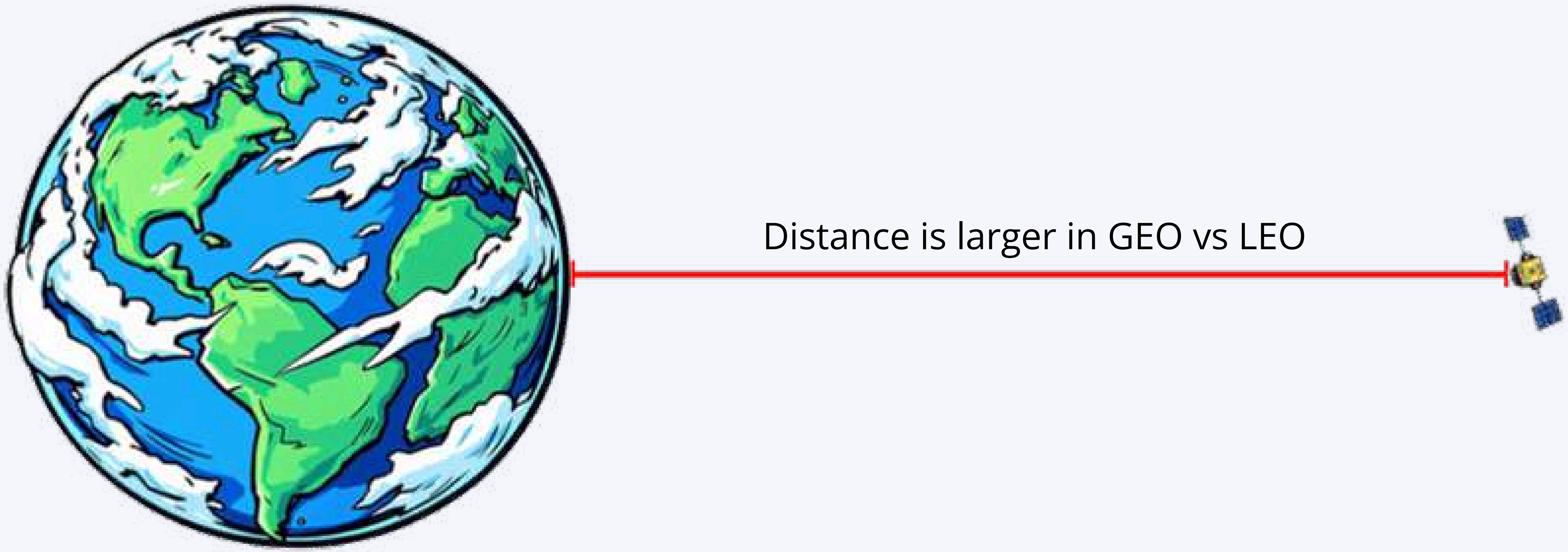
Satellites in GEO

GEO are very popular orbits for telecommunications because the satellite orbits the Earth at an angular velocity exactly equal to the rotation of the Earth. In other words: The satellite is apparently static in the sky. Example: Satellite TV.



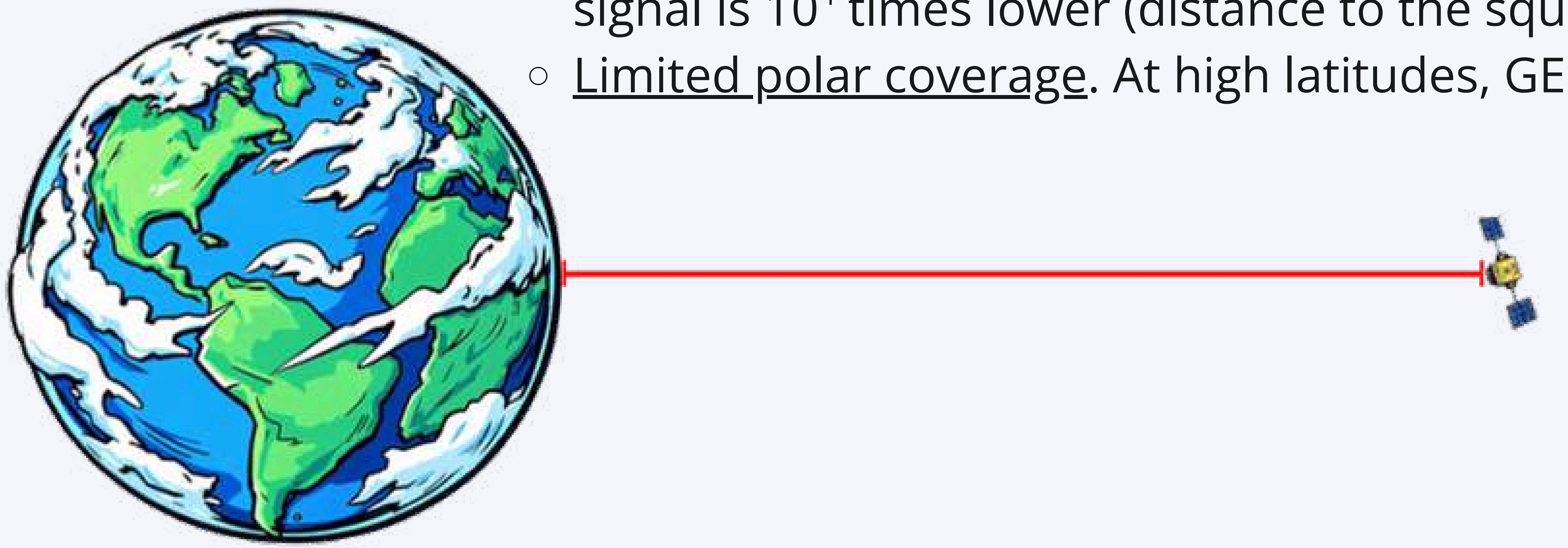
Effect of the distance to a GEO satellite

Satellites in GEO are about 60 times farther away from the Earth than satellites in LEO (36000 km vs 500-1000 km). And signal decreases with the square of the distance. Therefore, 60 times more distance (36000 vs 600 km) means 60^2 (=3600) lower signal (~36 dB).



GEO (GEostationary Orbit)

- Pros
  - Continuous operations. A satellite at an equatorial orbit at 36000 km altitude orbits the Earth at an angular velocity exactly equal to the rotation of the Earth → The satellite is apparently static in the sky
  - Few satellites are needed: One satellite covers continuosly ⅓ of the Earth
- Cons
  - High cost of launch (high EUR/Kg)
  - Worse signal to noise: The satellite is 100 time farther away than LEO, therefore signal is 10^4 times lower (distance to the square) → Larger telescope on ground
  - Limited polar coverage. At high latitudes, GEO satellite are near or below the horizon



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Ground Segment

A Ground Segment consists of all the ground-based elements of a space system used by operators and support personnel. It is composed of:

- Ground Station (radio interface with satellites)
- Mission Control Center (MCC, from which satellites are managed)
- Spacecraft integration and test facilities
- Launch facilities
- and other facilities

Cyta Ground Station in Cyprus.
Cyprus Mail, Cyta enters partnership with international satellite provider

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Optical Ground Station (OGS)

The OGS is composed of the dome that contains the telescope, the adaptive optics (see more later), the mount for pointing it, the electronics for optical communications, a control room, and the system for sharing the keys with the users.

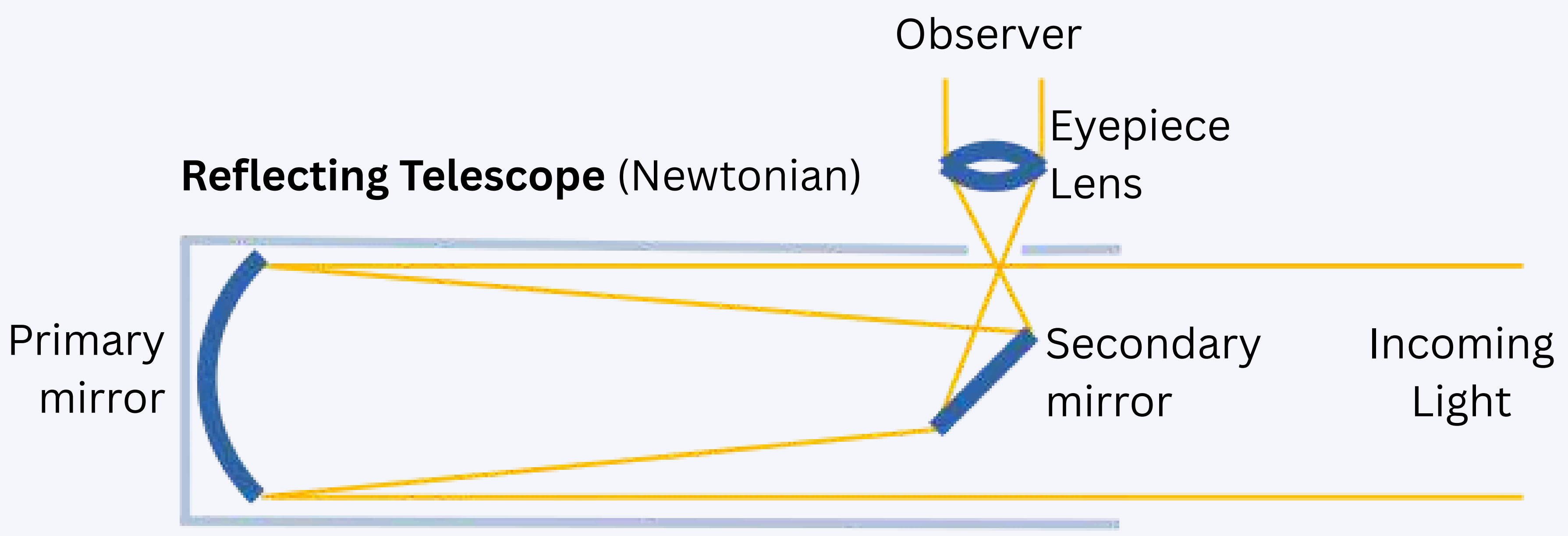
ESA's OGS. Part of Teide Observatory, located at 2400 m above sea level. Note the green laser (it looks curved because this picture was taken with a fisheye lens), more details about it later.
https://www.esa.int/ESA_Multimedia/Images/2019/05/ESA_s_Optical_Ground_Station

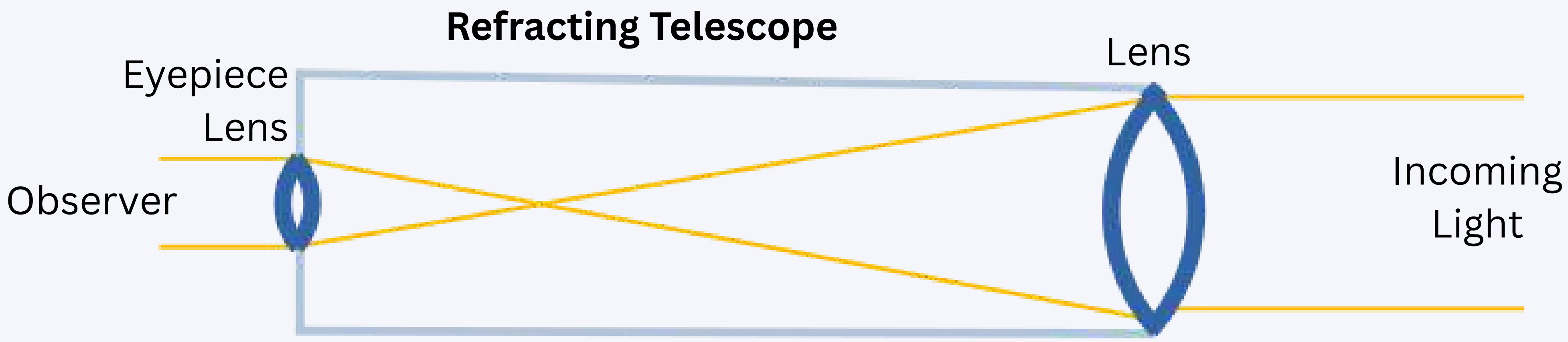
ESA's OGS, inside the dome. Note the size of the equipment (there is a person there), the 1m diameter reflective telescope, the equatorial mount, the aperture in the rotating dome.
https://www.esa.int/ESA_Multimedia/Images/2012/06/Telescope_at_ESA_s_Optical_Ground_Station_Tenerife

Types of Telescopes

Telescopes could be built with lenses (refracting telescope) or mirrors (reflecting telescope).
Large telescopes (>25 cm in diameter) are usually built with mirrors because:

- Large mirrors are easier and cheaper to build than large lenses → Because have 1 optical surface instead of 2
- Large lenses are heavy and can be deformed by their own weight, distorting the image quality. On the contrary, mirrors are lighter and are supported from behind in their entire surface.
- Mirrors do not suffer color aberration (glasses have slightly different refraction indices for different colors). → The laser is monochromatic to avoid this
- When a high power light (e.g. a laser) passes through a lens, its glass could become hot, generating deformations that could degrade the quality of the image. → Only applicable for uplink classical optical communications





Diameter of Telescopes

Telescopes collect photons proportionally to their aperture area. In other words, to the square of their primary mirror/lens diameter.

For example: A telescope with a 1-meter mirror collects x25 times more light than a telescope with a 20 cm mirror.

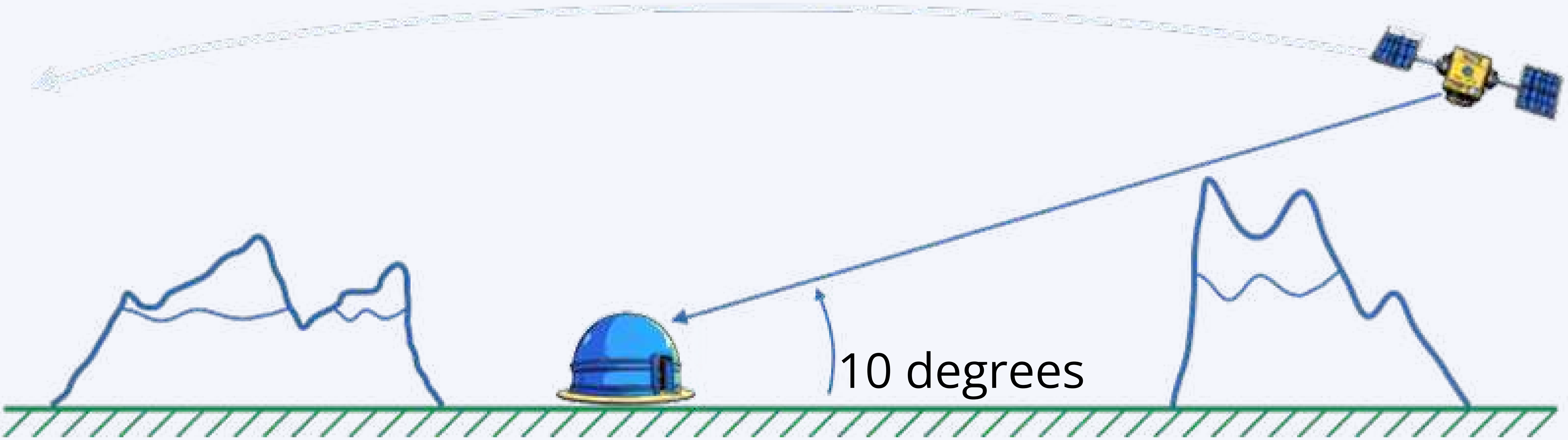
This is an easy way to improve the signal-to-noise of the system.

The time to transfer data is limited

LEO satellites fly over ground stations very quicky. The time available for transmitting information is limited.

Elevation of the Horizon

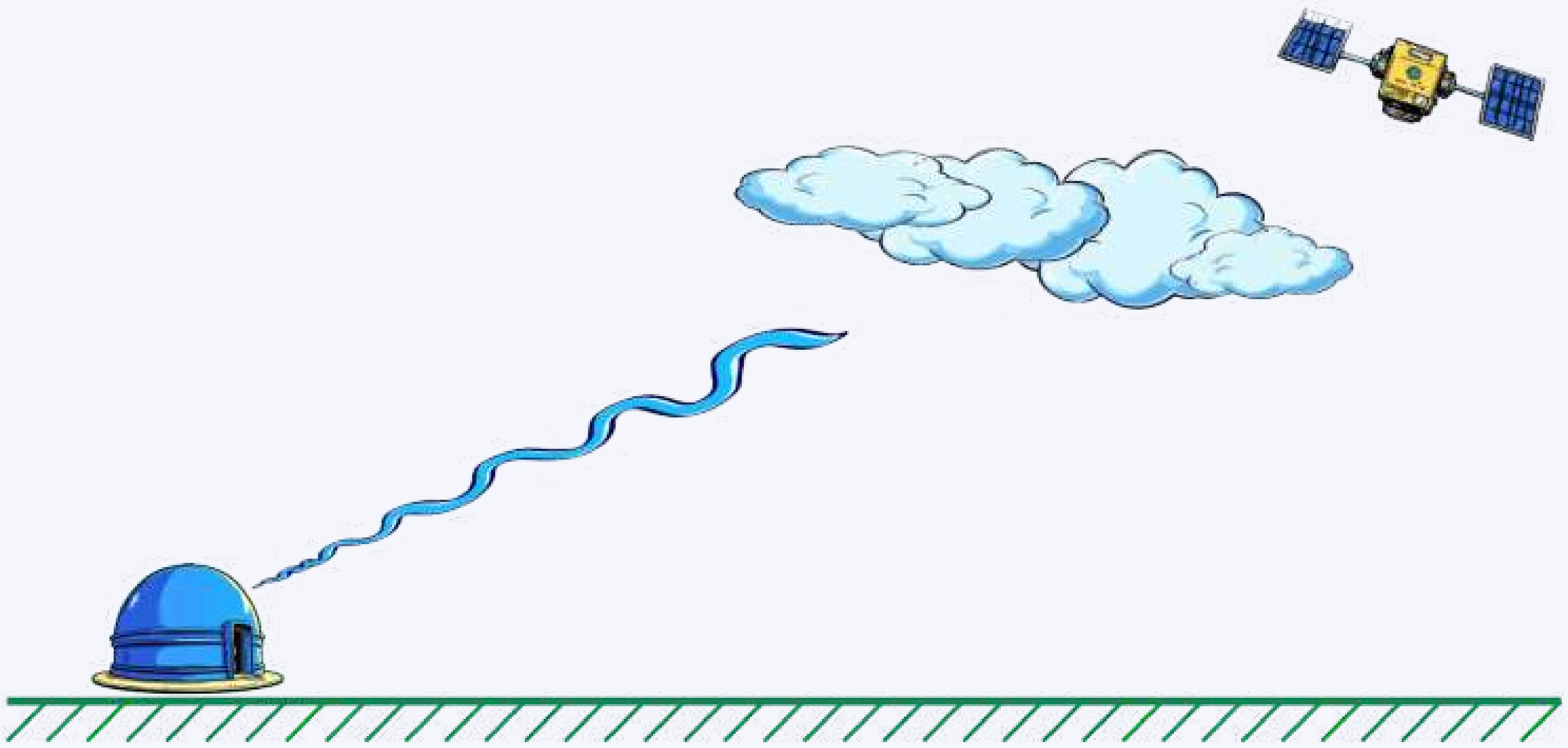
Since satellites fly above the OGS (and ground stations in general) in just a few minutes, from one part of the horizon to another part of the horizon, it is important to maximize its visibility time. Therefore, OGS are located in places where the horizon is not obstructed (for example by mountains). Typically there are requirements like “the elevation of the horizon as seen from the OGS shall be lower than 10 degrees”.



Local climate

Optical light (and infrared wavelengths) are obstructed by clouds. Therefore, it is normal practice to build the OGS in areas with limited number of cloudy days per year.

Even building them in high mountains, at an altitude above the “sea of clouds” (above the typical height of the clouds in that region).

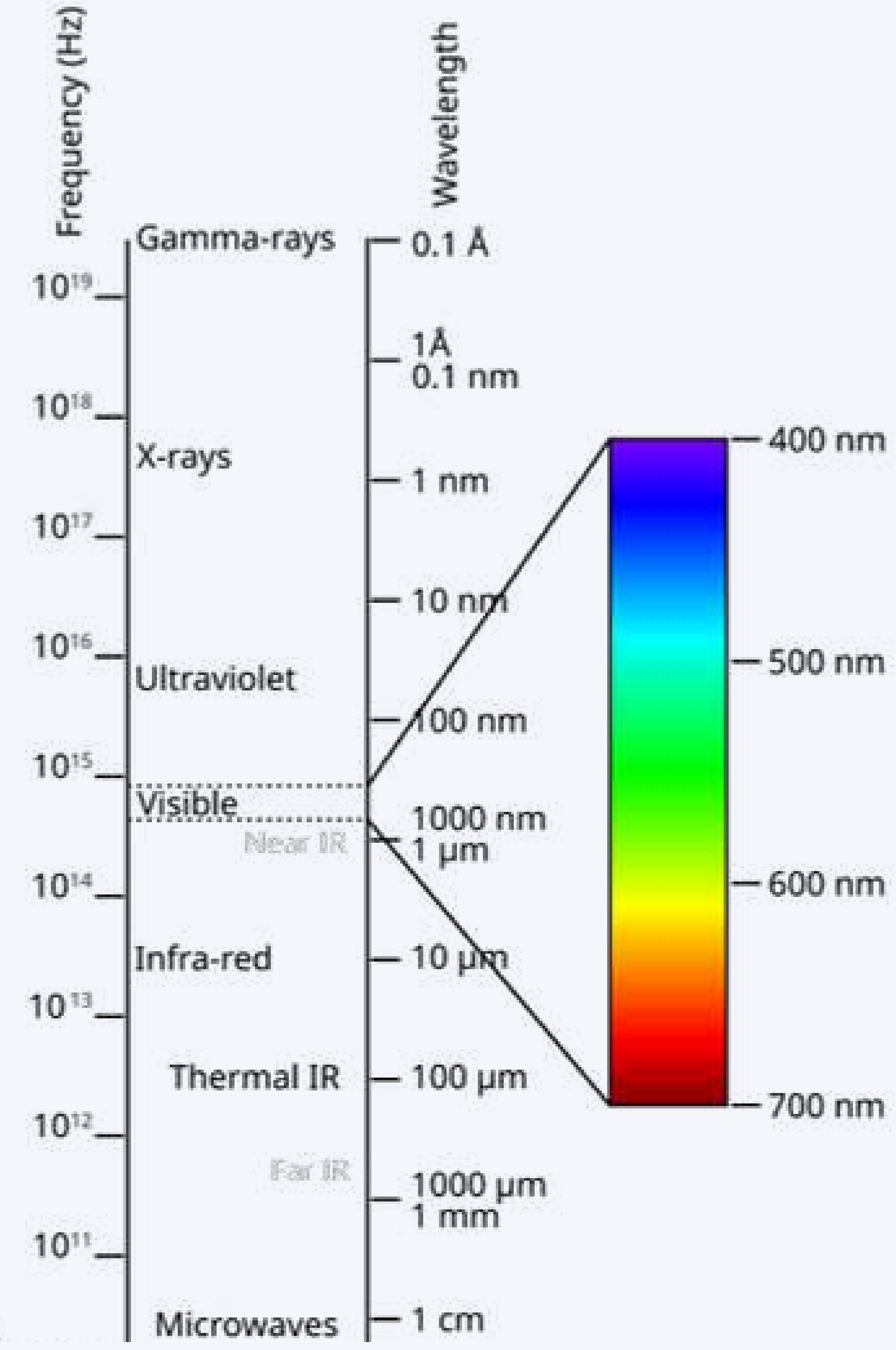


By Daniel Simpson - Flickr, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=1706329

Narrowband Laser

Free Space Optical (FSO) communications use narrowband wavelengths (typically in the near-infrared spectrum (e.g., 1550 nm or 850 nm) for several reasons:

- Minimizing Atmospheric Absorption. The Earth's atmosphere absorbs and scatters light at most wavelengths, but there are atmospheric "windows" where absorption is minimal.
- Reducing Chromatic Dispersion. Different wavelengths travel at slightly different speeds in the atmosphere, causing chromatic dispersion that degrades signal quality.
- Compatibility with Optical Fibers. Many FSO systems interface with fiber-optic networks. Narrowband wavelengths (e.g., 1550 nm) match the low-loss windows of optical fibers, simplifying integration and reducing losses at the fiber-FSO interface.
- Mitigating Background Noise. Solar radiation and artificial light sources (e.g., streetlights) can introduce noise, overwhelming the FSO signal. Narrowband optical filters can isolate the FSO signal from background light, improving the signal-to-noise ratio (SNR).
- Facilitating Adaptive Optics (AO) Correction. AO systems correct atmospheric distortions by measuring and compensating for wavefront errors at a specific wavelength.

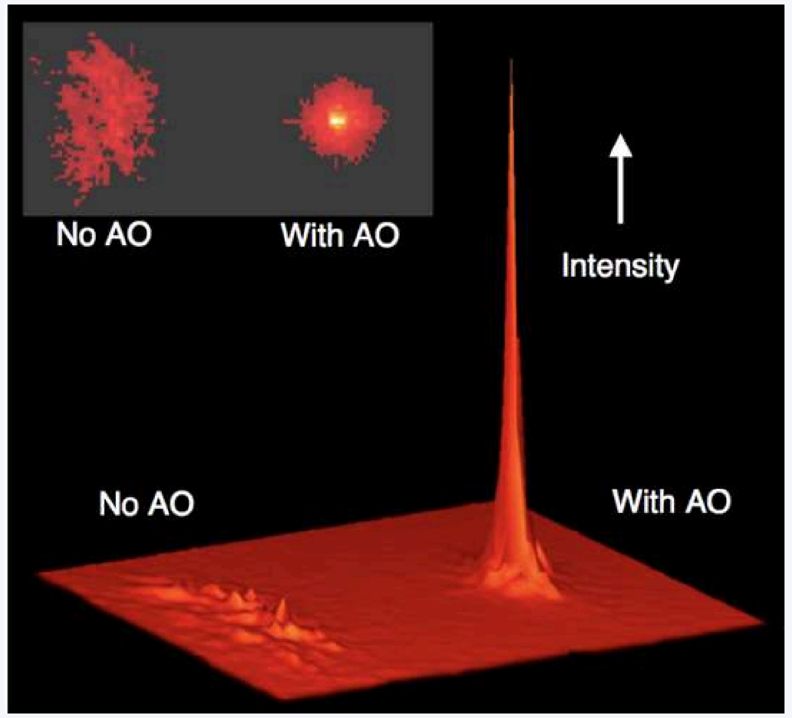


Adaptive Optics (AO)

Issue: The Earth's atmosphere distorts optical signals due to variations in temperature, pressure, and humidity, causing beam wandering, spreading, and scintillation (intensity fluctuations). These distortions degrade signal quality and increase bit error rates.

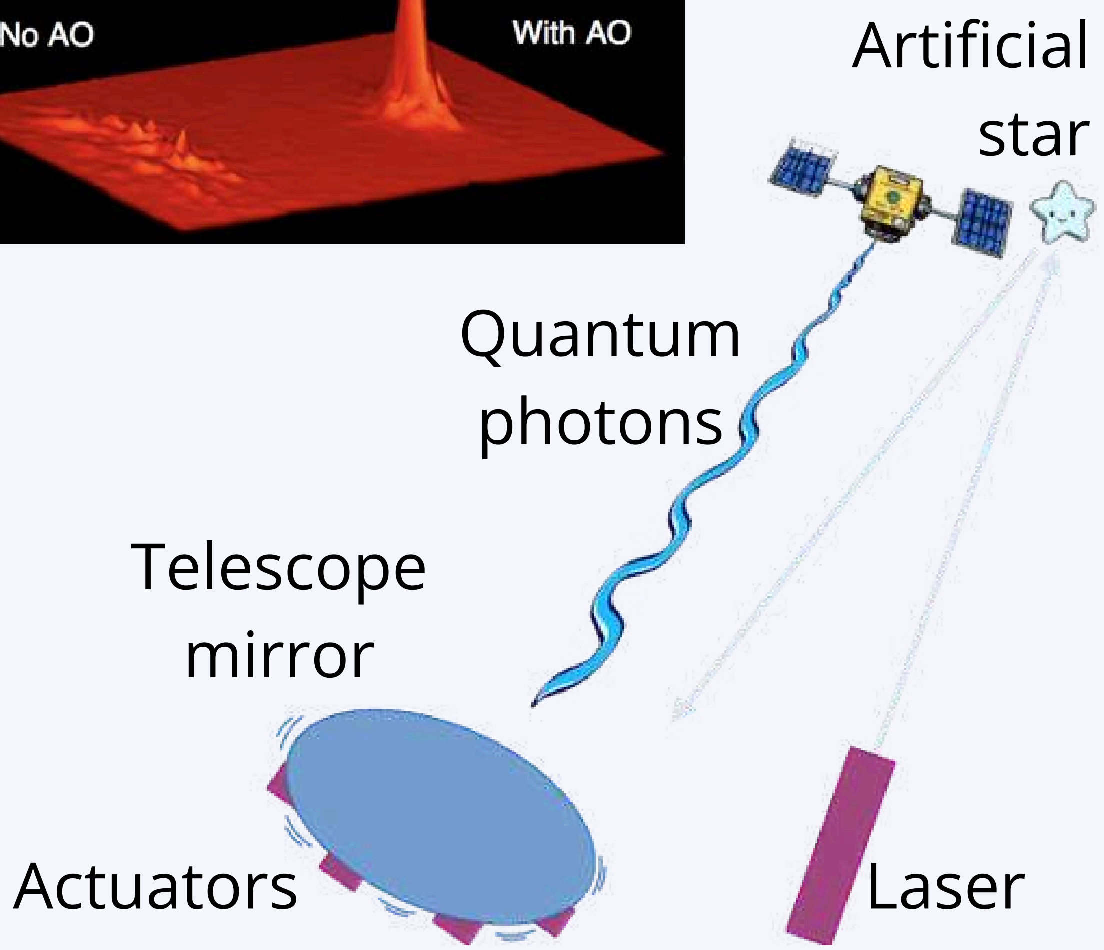
Solution: <u>Correct the wavefront</u> of the incoming photons in real time.

https://astrobites.org/2022/11/20/guide-to-adaptive-optics/



How does the Adaptive Optics system work?

- There is a <u>laser</u> that points in the same direction than the telescope.
- The laser emits light that excites ions in the high atmosphere and generates there an <u>artificial star</u>.
- The telescope takes an image with both the intended light from the target (the satellite) and the light from this artificial star.
- We assume that this artificial star has point-like shape. If the detected artificial star is not point-like, <u>actuators</u> modify the curvature of the <u>deformable mirror</u>.
- Iterate until the image of the artificial star is point-like (in real-time, many times per sec).

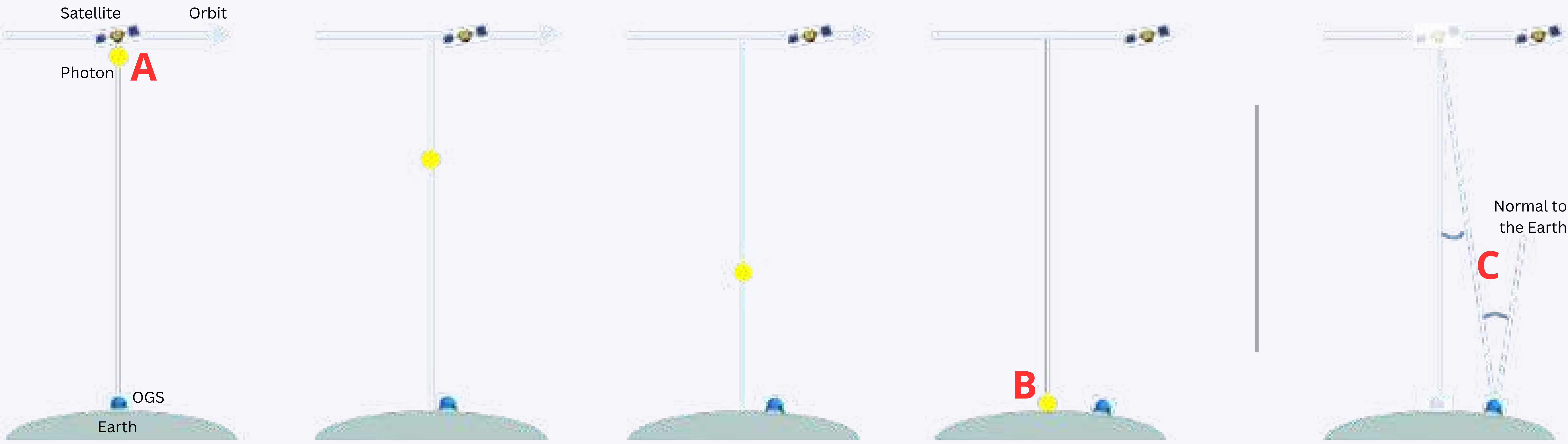


The Point Ahead Angle

Both the satellite and the OGS are moving:

- The satellite in its orbit
- The OGS due to the rotation of the Earth

When a photon is sent (in this case from the satellite to the OGS), it starts to travel at the speed of light (A), and after some time it arrives at its intended destination (B). But the OGS is not there anymore. Therefore, both the satellite and the OGS have to point their telescopes a few arcseconds away from the current target position (C). This angle is a consequence of the finite speed of light.



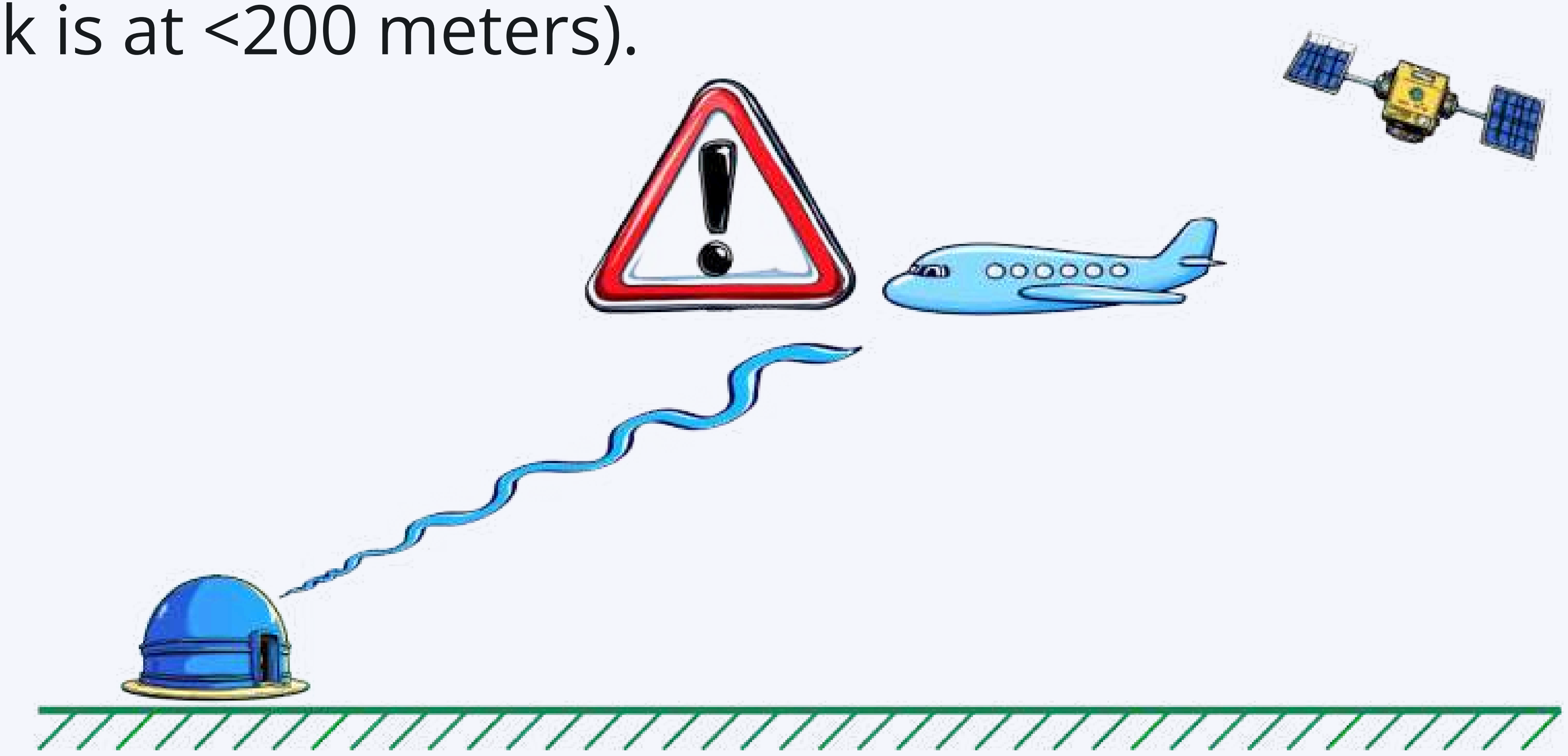
Laser: A hazard for people's eyesight

Lasers, either from the satellite or from the OGS (although note that this is only applicable when the OGS sends an optical signal to the satellite, that only happens in classical optical communications, not in QKD) are dangerous.

Reasons: These lasers are powerful and typically invisible to human beings (infrared wavelength).

Solutions:

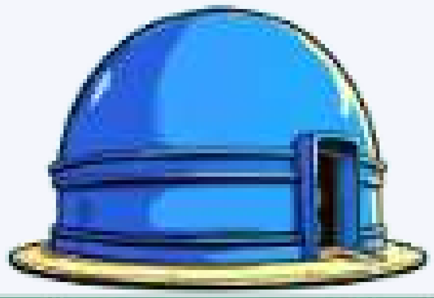
- Implement an airplane detector and switch off the laser in case of detection.
- Keep distance to the emitter (typically the larger risk is at <200 meters).
- keep a no-fly area around the OGS.



Delivery of Keys to Users

- The OGS will collect the keys sent by the satellite, and will keep them in a database: The Key Management System.
- This database will contain the keys along with metadata for using those keys.
- The users will connect to the OGS via quantum channels on ground, to collect their keys.

OGS



Key Management System

ID	Time	Recipient	Key
1	01/01/2027 22:00	Embassy A	10110001...
2	02/01/2027 22:00	Police Dep.	01001100...
3	03/01/2027 22:00	Ministery Health	01110010...
...	...	...	...

User

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Conclusions

- QKD (Quantum Key Distribution) implemented with FSO (Free Space Optical) communications allow the transfer of keys over long distances.
- Users could be located anywhere on the Earth.
- This course presents the application of space engineering to the case of QKD and FSO.