EE-585 – Space Mission Design and Operations

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Ecole Polytechnique Fédérale de Lausanne

Week 12 – 06 Dec 2024

Today's outline

Deploying tethers in space

New space vs old space: definitions and applications

Fundamentals of constellation design

Major actors on orbit

Collision risk, probability and avoidance

Operations of spacecraft

Deploying tethers in space

Tethers in space – generalities

A space tether is a long cable which is used to couple two objects in space.

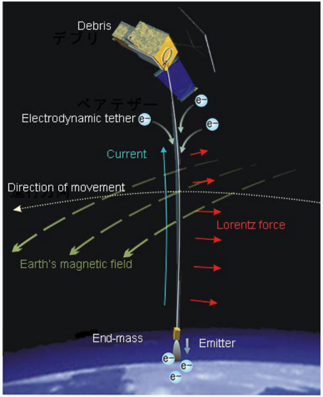
Tethers are usually made of a strong material like high-strength fibers or Kevlar, with or without an electrically conducting material in the core.

Applications of electrodynamic tethers

Electrical power generation
Orbit transfers
Ionospheric studies

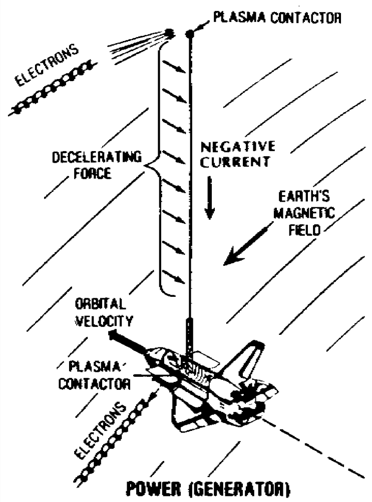
Applications of non-electrodynamic tethers

Angular momentum transfer
Space debris removal
Artificial gravity for long journeys in the Solar System
Space Elevator



Credits: JAXA

Conducting tether as an electrical generator



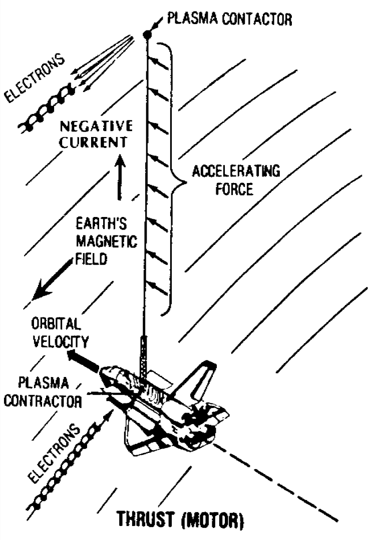
Credits: NASA, MSFC

Induced voltage caused by the motion of the tether in the Earth's magnetic field (Faraday's law of induction):

$$U_i = (\vec{V} \times \vec{B}) \cdot \vec{L}$$

where $\vec{L}$ is the tether length (m) – a vector pointing in the direction of positive current flow.

Conducting tether as an electrical motor



Credits: NASA, MSFC

Lorentz force resulting from the current flow in tether (posigrade or retrograde force).

$$\vec{F} = \int \left(I d\vec{L} \right) \times \vec{B} = I \int d\vec{L} \times \vec{B}$$

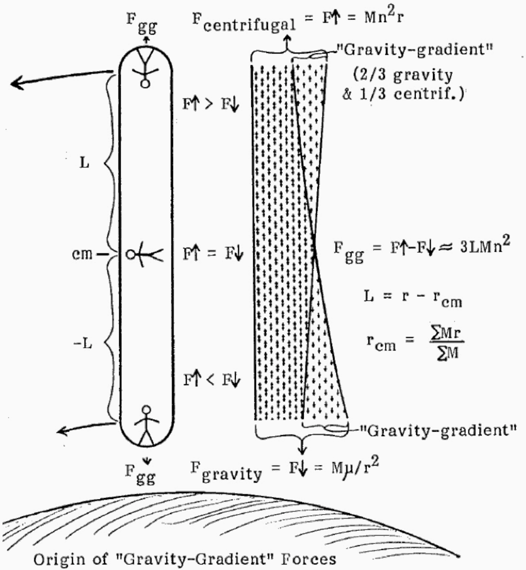
The integration is along the length of the tether.

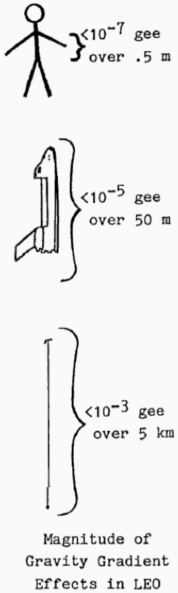
Gravity gradient effects

Forces inside a large orbiting cylinder oriented along the local vertical, without oscillations.

M is the element of mass in the cylinder
n is the mean motion in rad/s

Credits: NASA, MSFC



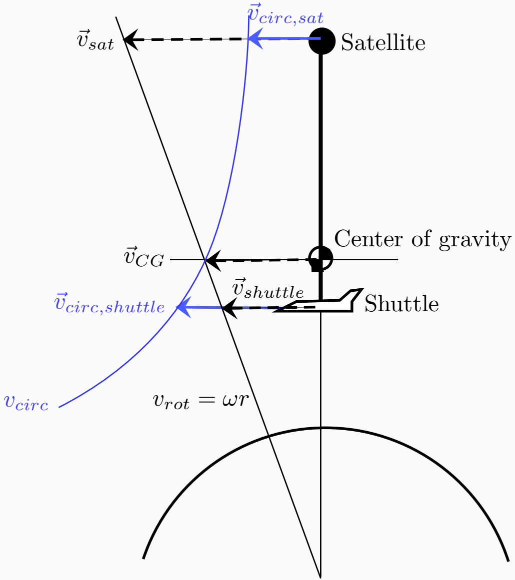


Space tether – velocity profile

As the space tether remains oriented along the local vertical, all velocities along the tether are proportional to the distance to the center of the Earth.

The tether orbits at the orbital velocity at the center of gravity, which is $v_{\text{circ}} = \sqrt{\frac{\mu}{r_{\text{CG}}}}$.

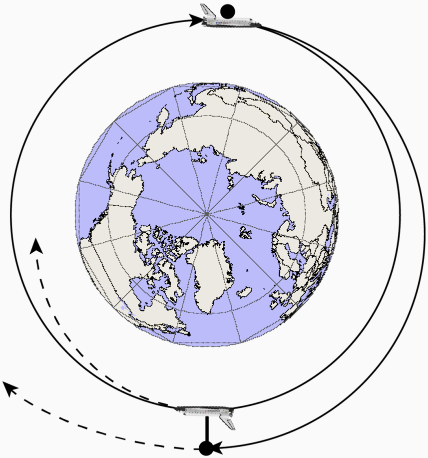
In the upper portion of the tether, any part of this tether is forced to move faster than a free satellite at the same altitude. The reverse is true for the low portions of the tether, where the tether is forced to move slower than would a free satellite at the same altitude ($\rightarrow$ *more in the exercises*).



Tether boost / deboost scenario

Here we represent a tethered satellite deployed from the Space Shuttle upwards in the LVLH frame. After full deployment of the satellite, a tether cut or break will cause the satellite to be injected into a significantly higher orbit, and the Shuttle to a slightly lower orbit.

There is exchange of angular momentum, with useful consequence for both the upper and the lower body in this case.

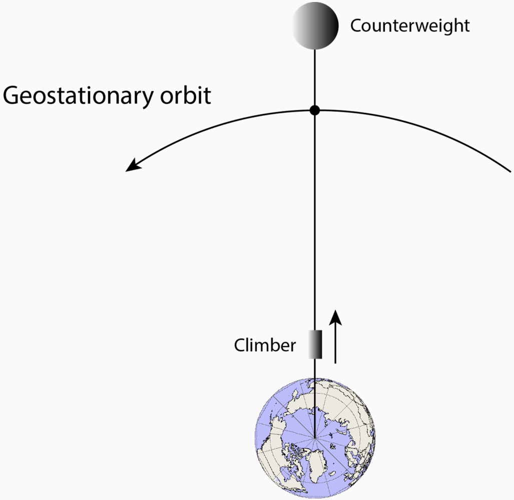


Space elevator concept

Originally proposed by Tsiolkovsky, a space elevator consists in a cable anchored at a location on the equator, and longer than the geostationary distance, with a counterweight at the end, and a climber able to move upwards and downwards along this cable.

Requirement: rotational speed of the tether is the same as the Earth (as it is attached to it!). It would allow access to nearby space without using a rocket!

→ The concept is explored in *Mars Trilogy* by Kim Stanley Robinson



New space vs old space: definitions and applications

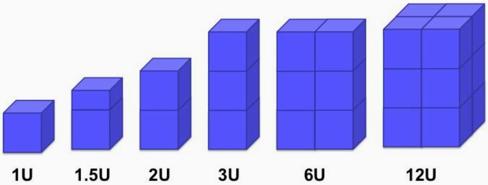
Old vs new space

Old space develops the systems government agencies ask for. It has significant achievements over the years, but it is cumbersome and risk-averse. This makes space hardware and its operation extremely expensive.
Examples: development of Ariane 6 or SLS.

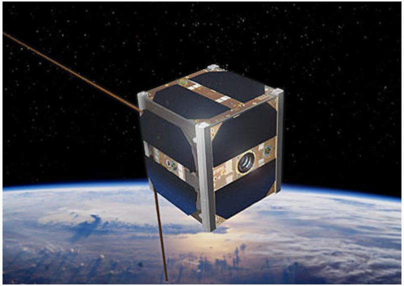
New Space should be agile, responsive, and risk-prone. Typically orders of magnitudes less expansive than old space, but results not guaranteed. Uses components off the shelf (i.e. space-only development is limited to as little as possible).
Examples: SpaceX, Aerospacelab.

Typically new space: the cubesat

CubeSats are a class of nanosatellites that use a standard size and form factor. The standard CubeSat size uses a "one unit" or "1U" measuring $10 \times 10 \times 10$ cm and is extendable to larger sizes; from 0.25, to 16U.



Credits: NASA



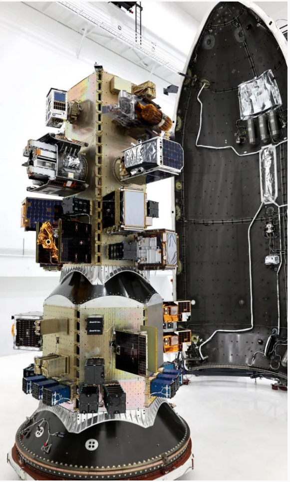
Credits: EPFL

The SwissCube project was initiated in 2005 by the EPFL. It was launched on 23 September 2009 from Indian launcher PSLV and injected at 720 km. It is now still at more than 690 km.

Trends in operations

Trends in operations that have appeared recently:

- Large so-called rideshare launches: many satellites (tens to hundred) are deployed at the same time. Challenging for tracking, identification and safety.
- Operations in dense constellations, that is as a large group, which multiplies the satellites' capabilities.
- Communications directly with other satellites to route data quickly to the ground (inter-satellite links).
- Rendezvous and proximity operations to provide in-orbit servicing.



The payload stack for the Transporter-11 mission.

Credits: SpaceX

(Optical) intersatellite links

Intersatellite links allow to transmit and relay data across one or several satellites to a spacecraft in view of ground station (e.g. ISS/Hubble may route data through GEO satellites for constant communication).

Optical intersatellite links have 4 major advantages:

1. $10 - 100\times$ RF bandwidth (because of high frequency)
2. Less power than RF
3. Less interference (narrow beam) and regulation
4. Difficult to intercept (narrow beam)

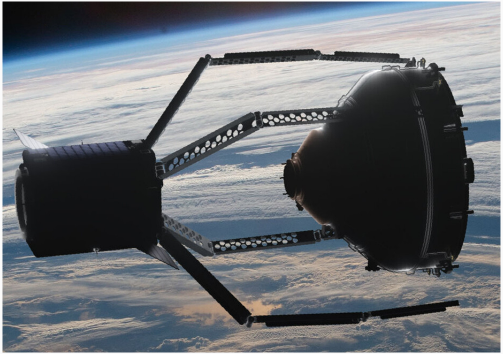
Credits: Horst et al, 2023

Several satellite constellations now use this as a standard procedure.

Emerging capability: smart satellites that share the acquisition and treatment of data according and can exchange orbital data to reach a common decision (e.g. NASA's Swarm experiment).

In-orbit servicing

- Propellant delivery (aka “petrol station in space“), delivery of subsystems (e.g. new propulsion module [MEV-1 mission])
- Close-up inspection of object (e.g. Astroscale)
- Asteroid mining
- Active Debris Removal (ADR)



ClearSpace 2020 concept. (Credits: ClearSpace)

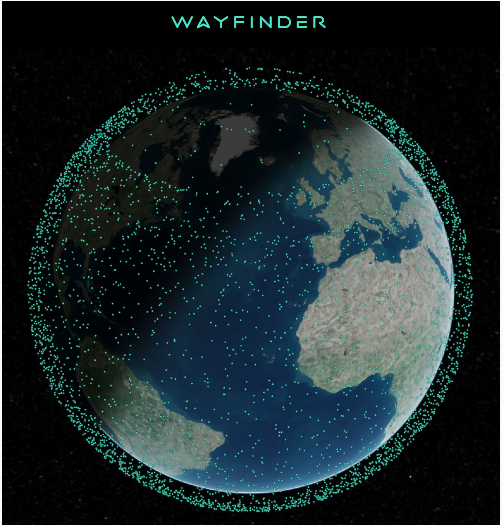
Fundamentals of constellation design

Satellite constellation

A *constellation* of satellite is a group of satellites working as one system.

Applications of constellations could be to, e.g., provide SATCOM services with continuous coverage or make Earth observations (EO) at low revisit time (e.g. take an image every hour).

There are tens of constellations, accounting for the vast majority of the operational satellite population. The largest is Starlink (SATCOM), a LEO constellation with more than 7500 satellites launched (as of Dec 2024).



Starlink constellation. (Credits: Privateer)

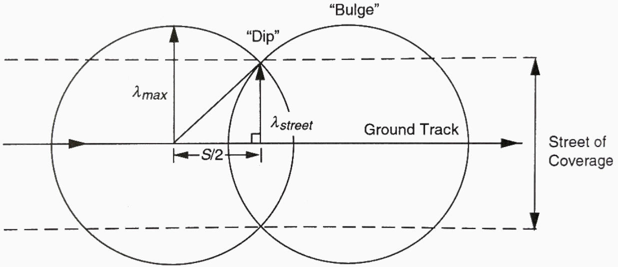
Principal design factors

Factor	Effect	Selection criteria
Number of satellites	1st cost and coverage driver	Minimise total nb of sat consistent with other criteria
Constellation pattern	Determines coverages vs latitude and other performance indicators	Select most impactful metric (e.g. best coverage, lowest revisit, . . .)
Min. elevation angle	1st driver of 1-sat coverage	Will drive the total nb of sats
Altitude	Coverage, environment, launch, positioning cost	Cost vs performance
Number of orbit planes	Determines coverage evolution	Minimise
Collision Avoidance	Prevent constellation self-destruction	Maximise intersatellite distance at plane crossing
End-of-life strategy	Disposal of nonop. satellites	Most robust & cheapest option

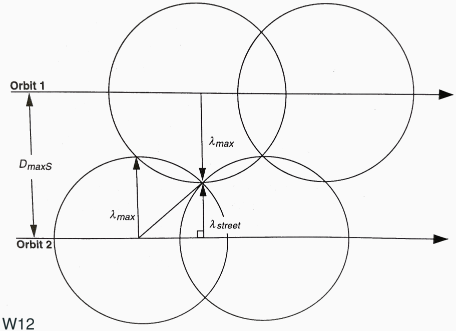
Constellation structure

The spacing between satellites in one orbit plane determines whether coverage is continuous.

The region of continuous coverage is often called a street of coverage.



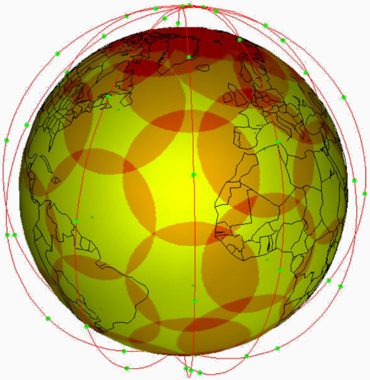
Credits: SMAD



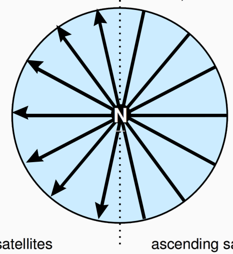
If the planes are moving in the same direction, overlapping pattern can be designed that provide maximum spacing.

Streets of coverage constellation pattern

The Iridium (SATCOM, LEO, $z = 750 - 800$ km alt, $i = 86.5°$) constellation is on a "streets of coverage" constellation design. 66 satellites needed for global coverage (more spares on orbit)



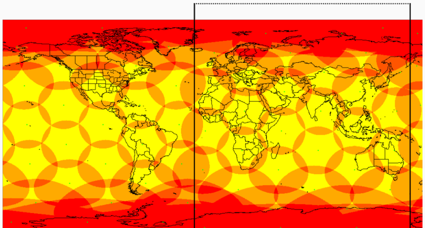
orbital seam
(coverage overlaps
even more)



descending satellites
(moving away from north pole)

ascending satellites
(moving towards north pole)

orbital seam



Credits: SaVi Constellation Designer

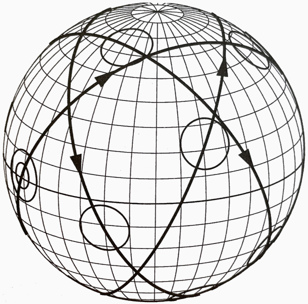
Walker$-\delta$ constellation

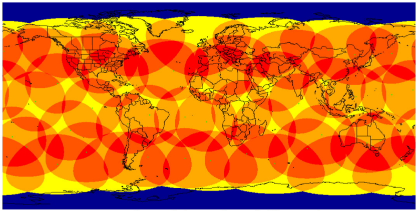
Satellites in a Walker constellation are in circular orbits of the same period, distributed uniformly in orbit planes separated equally around the reference plane.

Unlike the streets of coverage pattern, the ascending nodes are uniformly distributed around the equator.

Globalstar has 24 satellites in a Walker-δ constellation at $z \sim 1400$ km, $i = 52^\circ$.

The example (top panel opposite) has 15 satellites in 5 planes, not continuous coverage.





ascending and descending satellites overlap

The Starlink constellation design

There are not much public information on the Starlink constellation.

Made of several ”shells“ (14 as of Dec 2024) that behave like independent constellations at different altitudes and inclinations (43, 53, 70, 97.5°). There is a clear trend to lower the shell's altitude (initially 550-570 km, now 340-480 km).

Collision avoidance manoeuvres are automated (several tens of thousands per year!).

Several software updates per week. Very automated approach. Current satellite model (”v2-mini“ is 730 kg).

Direct-to-cell (DTC) shell has just reached 24 planes of 13 satellites each (as of Dec 2024).

Starlink constellation. (Credits: Privateer)

Major actors on orbit

1967 Outer Space Treaty (1/2)

Treaty on principles governing the activities of States in the exploration and use of outer space, including the Moon and other celestial bodies.

The Treaty bars States from placing weapons of mass destruction in orbit around Earth, installing them on the Moon or any other celestial body, or otherwise stationing them in outer space.

It exclusively limits the use of the Moon and other celestial bodies to peaceful purposes and expressly prohibits their use for testing weapons of any kind, conducting military maneuvers, or establishing military bases, installations, and fortifications.

However, the Treaty does not prohibit the placement of conventional weapons in orbit and thus some highly destructive attack strategies are still potentially allowed.

1967 Outer Space Treaty (2/2)

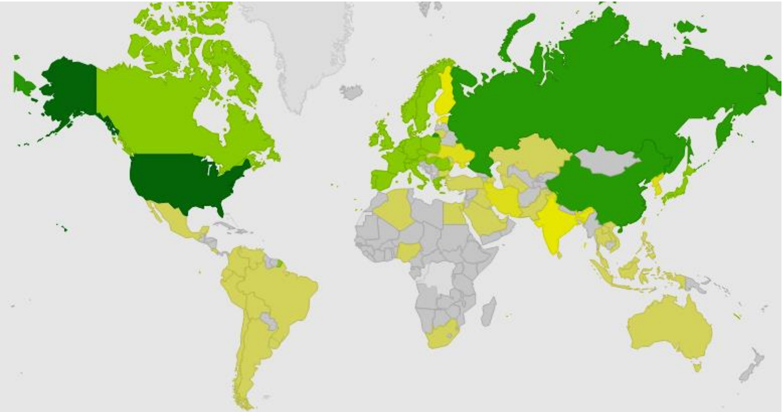
The Treaty also states that the exploration of outer space shall be done to benefit all countries, and that space shall be free for exploration and use by all the States.

The Treaty forbids any government from claiming a celestial resource such as the Moon or a planet. Article II of the Treaty states that ”Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means”.

The State that launches a space object retains jurisdiction and control over that object. The State is also liable for damages caused by their space object.

→ What about lunar/asteroid mining?
→ The Artemis Accord are US-led efforts to clarify some of the issues
→ Responsabilities in case of satellite collisions should be clear

Space activities in the world



Manned extraterrestrial exploration + operates space station + manned space flight + operates extraterrestrial probes + launch capability + operates satellites	Launch capability + operates satellites
Manned space flight + operates space station + operates extraterrestrial probes + launch capability + operates satellites	Operates satellites
Operates space station + operates extraterrestrial probes + launch capability + operates satellites	None of the above
Operates extraterrestrial probes + launch capability + operates satellites	No information

Some governmental space agencies (non-exhaustive list)

Private operators (even less non-exhaustive list)

As of Nov 2024, there were $\sim 10'200$ operational satellites in orbit, 82% were commercial satellites. 75% are Starlinks ! Clear trend towards more private assets (with governmental support but private).
In Nov 2020, there were 3390 operational satellites, with 60% commercial.

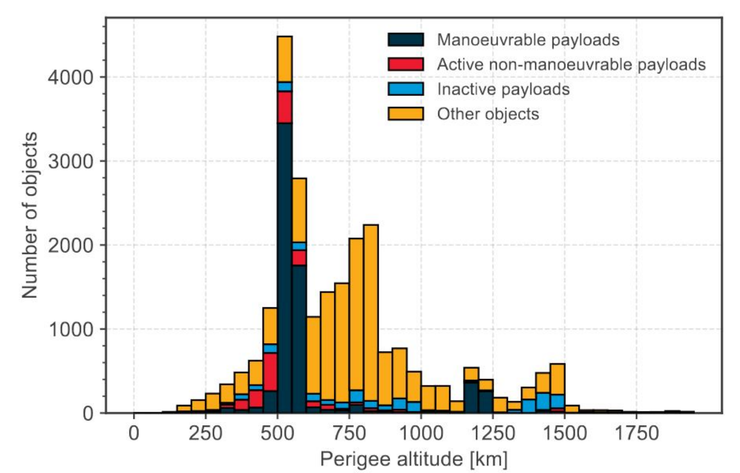
Collision risk, probability and avoidance

Reminder: Altitude distribution of payloads and debris

Objects are not distributed uniformly with altitude or inclination.

First generation of Starlinks at $\sim 520 - 570$ km

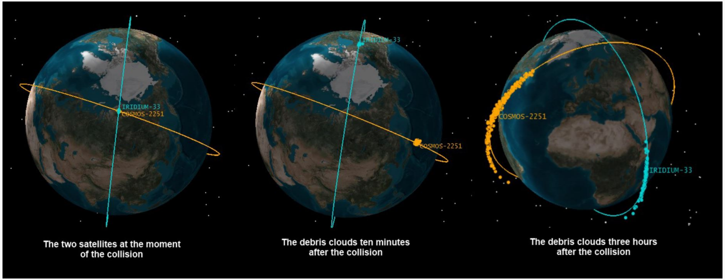
Higher peak at ~ 800 km from the Irdium 33/K2251 collision.



Credits: ESA Space environment report 2024

Reminder: 2009 Iridium 33 / Cosmos 2251 collision

On 10 Feb 2009 an operational Iridium satellite collided with a non-operational Cosmos 2251 at about 800 km and 11.7 km/s. $\sim$ 2000 pieces of debris generated.



The debris cloud will remain on orbit for decades.

Although the orbital data was available, there was no daily screenings for possible collisions and no procedure to quickly manoeuvre.

Legally, the launching state is responsible, but K2251 was launched by the Soviet Union, so unclear situation.

Kessler Syndrom

- A large population on many different orbits $\implies$ some objects will come punctually close to each other (*conjunctions*).
- If the *miss-distance* at the *time of closest approach (TCA)* is smaller than the object's size $\rightarrow$ collision.
- Fragments from the collisions can lead to further collisions $\rightarrow$ *collision cascade*
- Kessler Syndrom (from 1978 paper) is the creation of a debris belt through a runaway effect of collisions chain reaction.

$\implies$ Some/all orbits would become unusable maybe could not even crossable.

- Fairly well known outside the orbital mechanics/space sector $\rightarrow$ movie Gravity (2013).

Risk of collisions

- Risk = probability $\times$ severity

- *Negligible non-catastrophic.* Does not significantly impact the short-term or long-term environment. Example: clean cut of a boom or antenna. If the 2 objects involved are debris, difficult to observe and characterise.

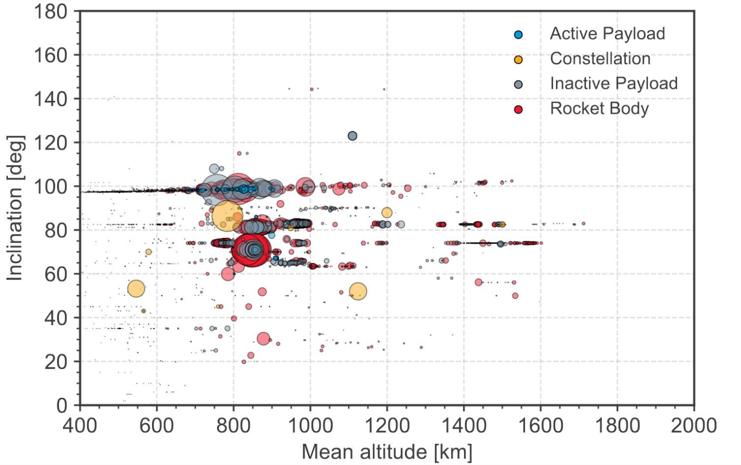
- *Non-catastrophic.* Generates a limited number of debris that re-enter quickly in the atmosphere (short-term impact). Most of the debris cannot be catalogued. (Lethal & non-lethal non-trackable objects)

- *Catastrophic.* Generates a large population of non-trackable and trackable debris that will contribute to a collision cascade. A collision between 2 intact objects will be catastrophic.
  $\gtrsim$ 40 J/gr is a fuzzy threshold for catastrophic collisions for the Energy-to-Mass Ratio (EMR, in Joules of impactor energy divided by mass of the target in grams)

Altitude / inclination of risky objects

Areas with high risk concentration can be observed around 850 km of mean altitude and 70-80 degrees in inclination.

The size of the marker indicates the debris index value and an aggregated score is shown for constellations.



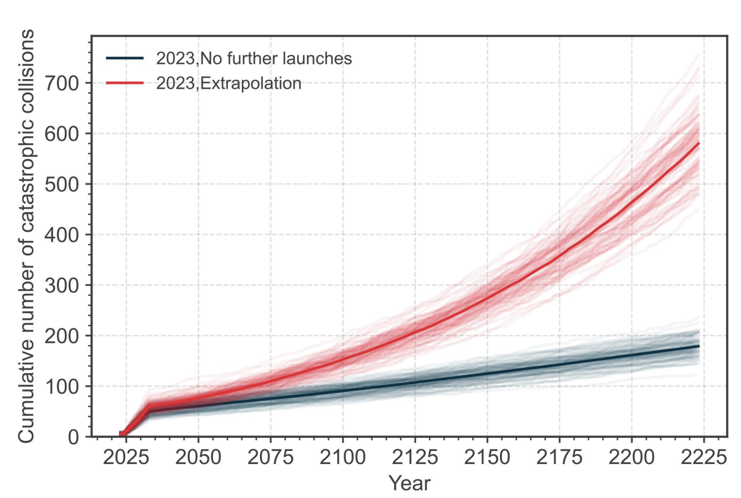
Credits: ESA Space environment report 2024

Estimation of the number of catastrophic collisions

Number of cumulative collisions in LEO

Catastrophic collisions will happen – and more and more frequently – even if we stop launching now

$\rightarrow$ We need collision avoidance techniques.



Credits: ESA Space environment report 2024

Probability of collision

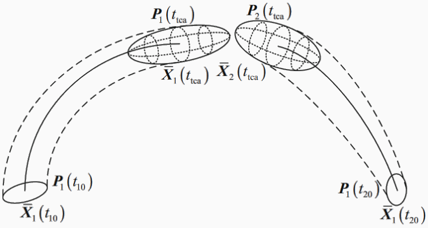
An object is initially at $\vec{X}$ with an uncertainty ("covariance") $\vec{P}$.

At the time of closest approach (TCA), a the probability of collision P_C can be derived.

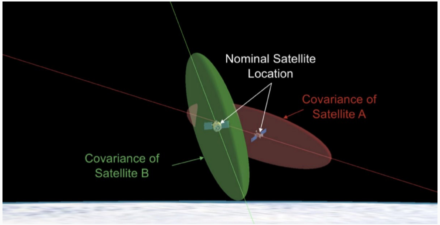
Short-term encounter $\rightarrow$ relative motion is linear, uncertainties are constant Gaussian distributions.

P_C is the probability that the miss distance between two objects is less than the sum of their safety-radii (i.e. object size + margin).

Different methods available to compute P_C. e.g. Foster 1992, Patera 2001 or Alfano 2005.



Credits: Chen, L. et al, 2017



Credits: The Aerospace Corporation

Collision Screenings

The population of space resident objects (RSO) is screened multiple times a day by the Space-Track. These whole population ("$N \times N$") screenings require a lot of computational power.

It publishes warnings if:

- LEO: miss distance < 1 km, $P_C > 10^{-7}$, alert by email if $P_C > 10^{-4}$.
- GEO: miss distance < 5 km, by email if TCA too close.

Collision warnings are distributed freely to the spacecraft operators. These Collision Data Messages (CDMs) contain a technical description of the event (P_c, TCA, covariances, ...).

CDMs are distributed between $\sim 12 - 72$ hours before TCA $\rightarrow$ time for analysis is short!

Feeding data back to Space-Track (manoeuvrability, manoeuvre plans and even ephemerides) is possible $\rightarrow$ satellite operators can help.

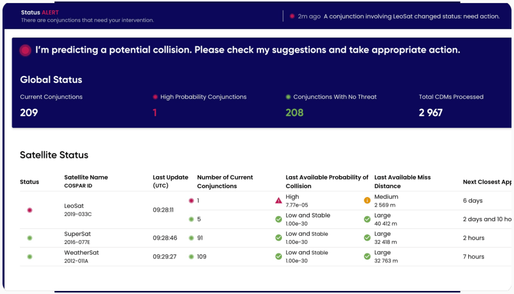
CDM analysis

It is left entirely to the operator to decide what to do and whether or not to coordinate with the other operator.

10 – 100s of CDMs can be expected every week for operators of a few satellites.

There are many false positives and too uncertain alerts.

Refinements of orbital data can be tasked to observatories → smaller covariances.



Credits: Neuraspace

The evolution of P_c as epoch is closer to TCA is an important indicator of false positive.

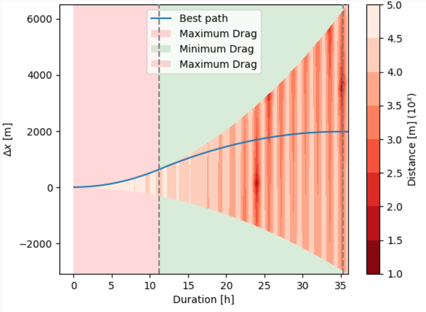
Most of the time, no action is taken.

There are dedicated Collision Avoidance Assessment services (e.g. Neuraspace, Okapi Orbits, ESOC, . . .).

Collision avoidance manoeuvres

Manoeuvres can be computed for collision avoidance (COLA), but they should:

- minimise propellant use, i.e., $\min \Delta v$
- maximise the miss distance
- occur at the latest possible time
- minimise the subsequent risk of collision with the same or other objects



Credits: APCO T/Jegou, S, 2023, Optimal drag manoeuvres

In LEO: for impulsive manoeuvres, t_{man} TCA $- 3 - 12$ hours, $\Delta v \sim 0.1$ m/s. Mostly in the direction of $\vec{v}$. Non-impulsive like electrical propulsion or drag differential manoeuvres are tricky for COLA.

COLA must also be performed for launches to avoid a collision between the launch vehicle and a space resident object.

Operations of spacecraft

Major mission tasks (1/2)

Mission tasks	Examples
Mission Management	• Managing resources (cost, schedule, performances, facilities, people, . . .).
Mission Planning and Analysis	• Planning mission timelines and sequencing events • Analysing trade-offs between competing technical options • Defining flight rules during nominal and off-nominal flight conditions
Systems Engineering	• Defining and validating system and subsystem-level requirements • Applying analysis and design tools to define system architectures • Designing subsystems and constituent components
System Assembly, Integration, and Testing (AIT)	• Screening components for form, fit, and function • Assembling components into subsystems, integrating subsystems into systems • Testing subsystems and systems to ensure they perform under flight conditions

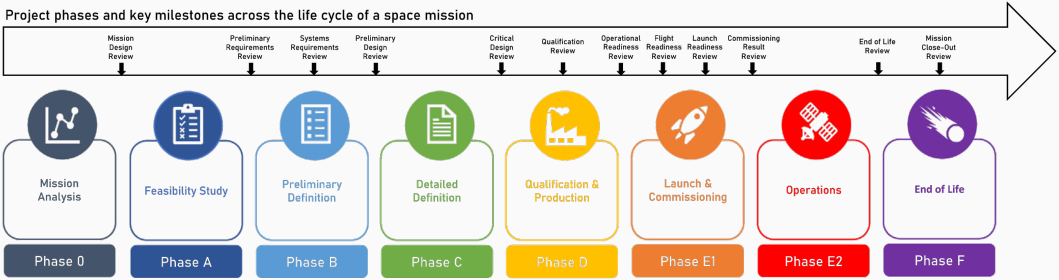
Adapted from Sellers J., *Understanding Space*, 3rd Ed.

Major mission tasks (2/2)

Mission tasks	Examples
Simulations and Training	• Simulating major mission events • Practicing operational procedures using simulations
Flight Control	• Monitor and interpret telemetry to determine a spacecraft's health and status • Tracking a spacecraft's or launch vehicle's position and velocity • Sending commands to change operating conditions or fix problems
System Maintenance and Support	• Performing routine maintenance to clean rooms, thermal/vacuum chambers, and other operations systems • Updating ground software to enhance performance or fix problems
Data Processing and Handling	• Mission data processing • Distributing mission data to users • Archiving spacecraft mission and engineering data

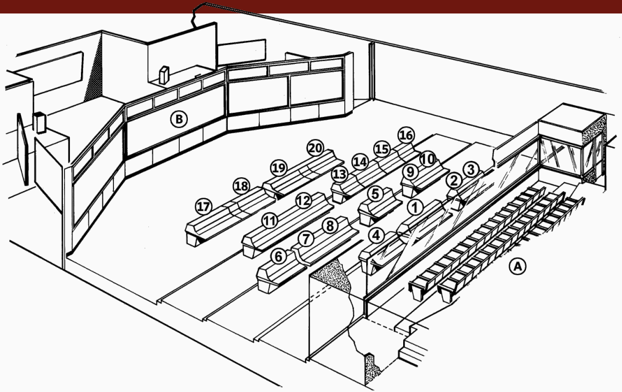
Adapted from Sellers J., *Understanding Space*, 3rd Ed.

ESA’s mission lifetime cycle



Credits: Wilson A.R. & Vasile, 2023.

Apollo Mission Operations Control Room



B: Display and projection area

Fourth row, "The Trench"
17: BOOSTER – Booster Systems Engineer
18: RETRO – Retrofire Officer
19: FDO – Flight Dynamics Officer
20: GUIDO – Guidance Officer

Third row:
11: SURGEON – Life Systems Officer/Flight Surgeon
12: CAPCOM – Capsule Communicator
13: EECOM – Electrical, Environmental, and Communications
14: GNC – Guidance, Navigation, and Control
15: TELMU – Telemetry, Electrical, and EVA Mobility Unit (LM EECOM)
16: CONTROL – LM Guidance & Navigation

Second row:
6: INCO – Instrumentation and Communications Officer
7: O&P – Operations and Procedures
8: AFLIGHT – Assistant Flight Director
5: FLIGHT – Flight Director
9: FAO – Flight Activities Officer
10: NETWORK – Network Controller

First row:
4: PAO – Public Affairs Office
1: DFO – Director of Flight Operations
2: HQ – NASA headquarters (Mission Operations Directorate)
3: DOD – Department of Defense

A: Glass fronted viewing room seating 74 authorized visitors

Credits: NASA/Aurich Lawson

The crewed Apollo missions were managed from Johnson Space Center in Houston, Texas.

A flight director made the decisions, supported by expert flight controllers who could contact additional ”backroom“ technical experts. The flight direction contacted the crew via the CAPCOM, astronauts dedicated to supporting the mission.

→ Gene Kranz, *Failure Is Not an Option: Mission Control From Mercury to Apollo 13 and Beyond*

Mission operation structure: mission director, flight director, flight controller, subsystem engineer, simulation officers, . . .

Apollo era: very large teams on shifts. Today's crewed missions: large teams on shifts.

European Space Operations Centre
Credits: ESA

Satellite operations: similar structure, but much smaller. Trend: from several persons per satellites to several satellites per controller thanks to automation.

Iridium manages $\sim$ 80 satellites in LEO.
Credits: Iridium

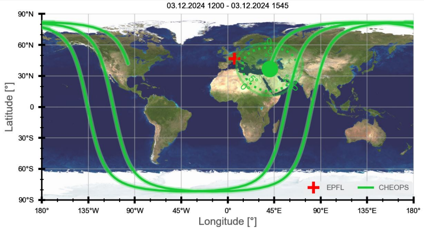
Communicating with satellites: exploiting passes over ground stations

For non-GEO objects, satellites are not in continuous view of ground stations (i.e. antennas that can communicate with satellites).

The number of passes per day depends on the orbit and the latitude of the ground station(s) (GS). A link can be established between a satellite on SSO and high-latitude GS (e.g. Kiruna in Northern Sweden) each orbit. For low latitude GS, there might be only 1 pass per day. Depending on mission and budget constraints, there might be only a few (1-5) contacts per week.

The time between Acquisition of Signal (AoS) and Loss of Signal (LoS) varies, but is typically of order of 5-10 minutes ($\rightarrow$ *week 04*).

Credits: ESA



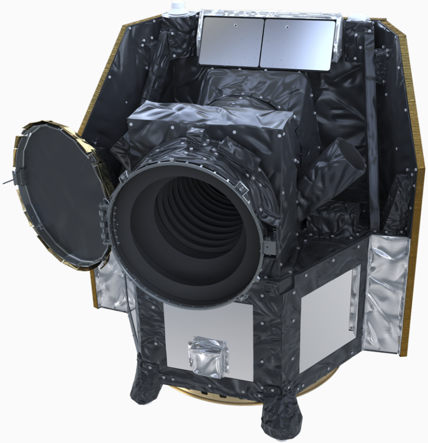
Case study: CHEOPS (CHaracterising ExOPlanets Satellite)

First S-class (small) mission in ESA's science programme. Partnership between ESA and Switzerland. Consortium of 11 European countries led by the University of Bern. Delivered on time and on budget!

High-precision photometry in the visible.
Effective aperture = 30 cm.

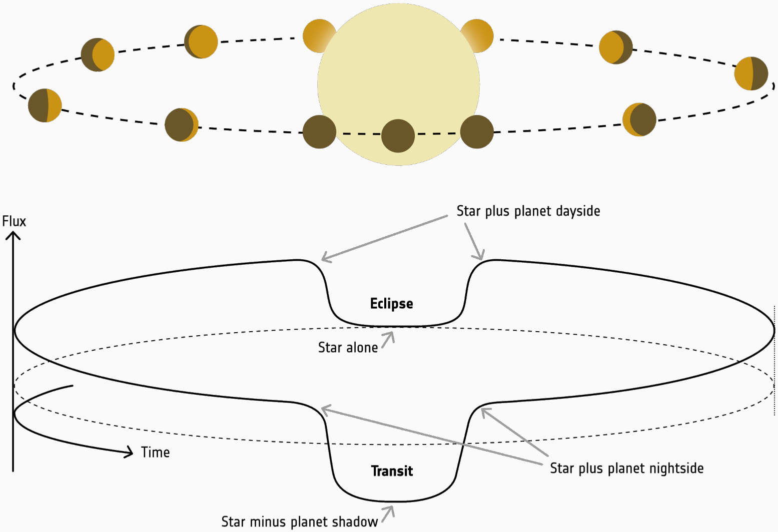
Sun-synchronous orbit, 700 km altitude, $\sim$ 98° inclination, Local Time of Ascending Node 6 a.m.

Slides adapted from N. Billot, CHEOPS Operations Manager, June 2024.



Credits: Cheops consortium

The science: measuring the transits of exoplanets



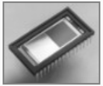
CHEOPS mission timeline

CHEOPS consortium

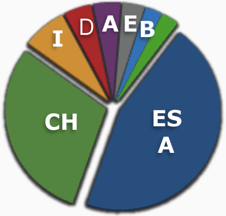
Shared lead

esa

- Mission architect
- Launch services & launching state
- Platform procurement
- CCD procurement
- Space Debris Service
- Guest Observer (**GO**) programme **(20->30%)**



Budget



Total cost: ~105 M€

ESA : 50 M€

Only 5 years between adoption and launch!

Consortium

CHEOPS

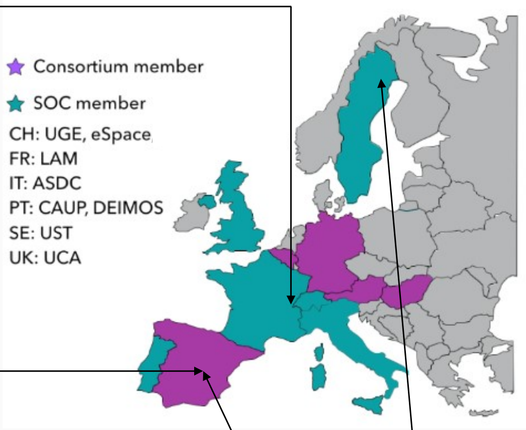
- Mission concept
- Instrument design, manufacture, calibration
- **Spacecraft operations**
- **Science operations**
- Guaranteed Time Observations (**GTO**) programme **(80->70%)**

CHEOPS ground segment

Science Operation Center

SOC

Geneva Observatory



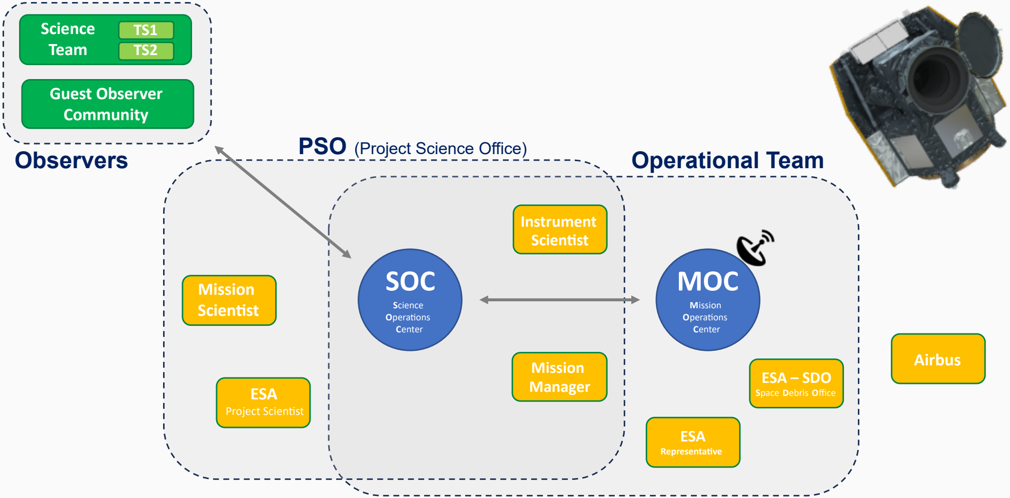
Mission Operation Center

MOC

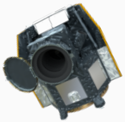
INTA Torrejón

Ground Stations : VIL1, VIL2, (TOR, KIR)

CHEOPS ground segment



CHEOPS concept of operations (1/2)



MOC @ INTA

3

SOC sends sequence of telecommands to MOC, for uplink

(once a week, sequence covering one week)

1

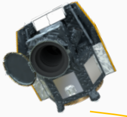
SOC receives observation requests from GO/GTO community and instrument team

SOC updates orbit information

2

Optimization of CHEOPS observing schedule

CHEOPS concept of operations (2/2)



4

MOC downlinks data when CHEOPS is in visibility (4-5 times a day)

5

MOC automatically pushes data to SOC

6

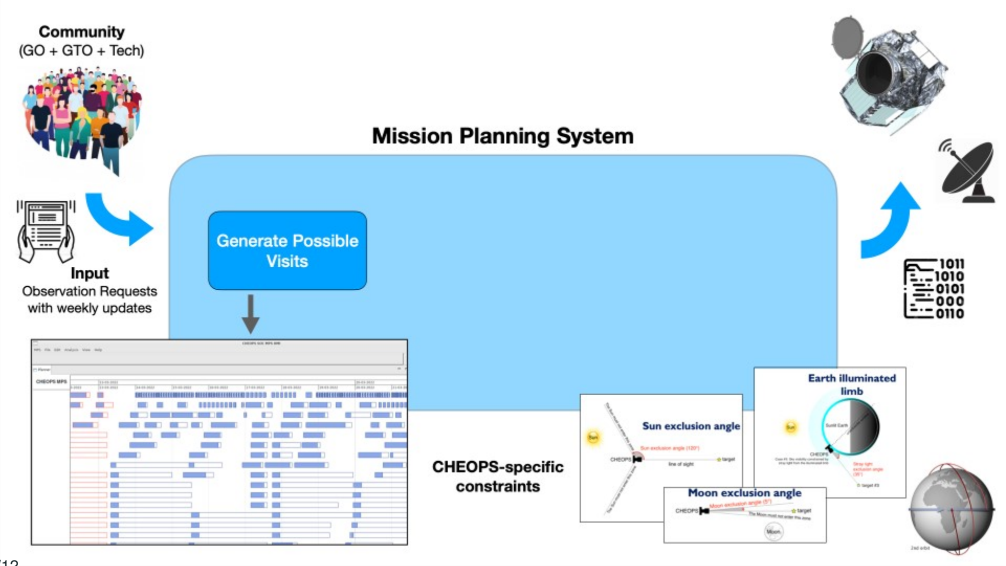
SOC monitors all incoming packets from spacecraft.

SOC automatically processes data and pushes them to the archive + mirror archive

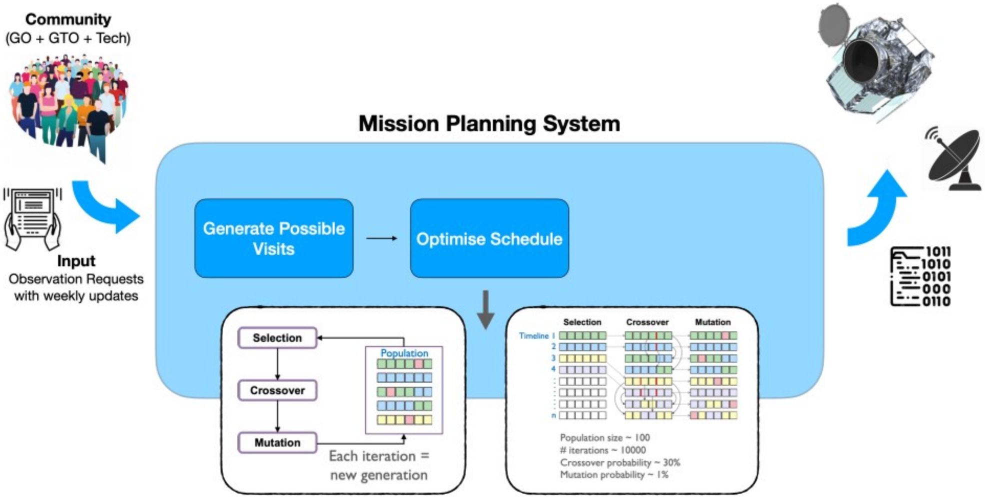
7

Principal Investigators (PIs) retrieve their data from SOC

CHEOPS Mission Planning (1/4)

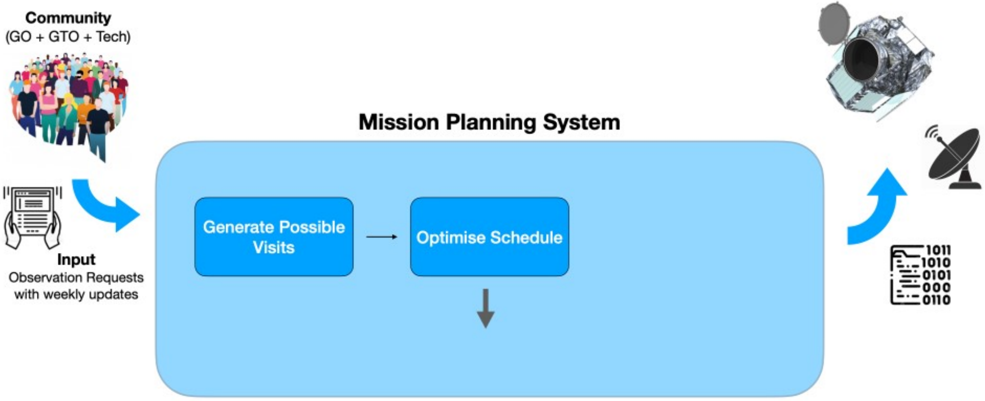


CHEOPS Mission Planning (2/4)



Optimise sequence of observations with genetic algorithm :
Generate millions of timelines and pick the best one

CHEOPS Mission Planning (3/4)

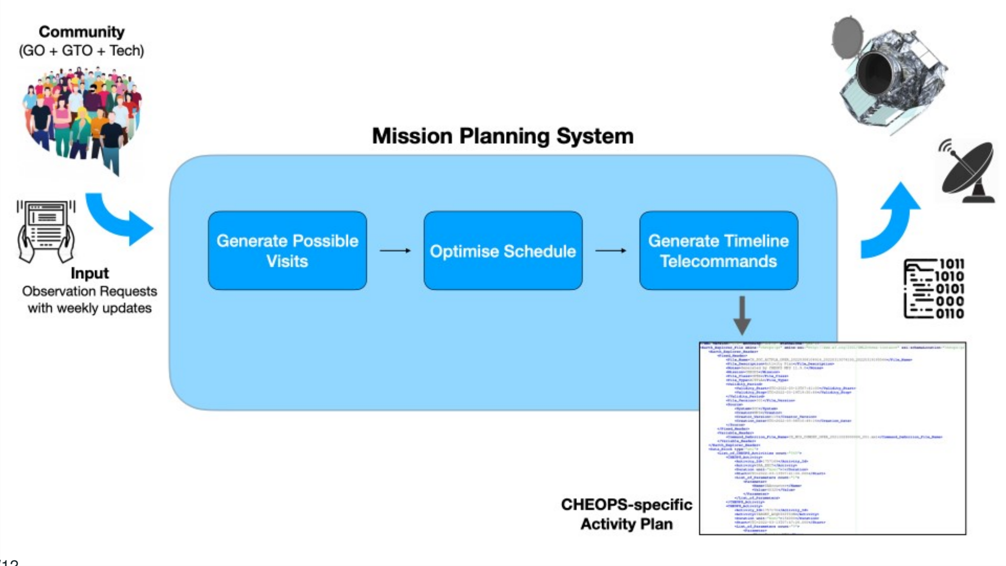


$$Score_{timeline} = \sum_{i=0}^{n} EffectiveDuration_i \times \frac{CompletionRate_i}{Priority_i^2} \times GuaranteedOpenBalance$$

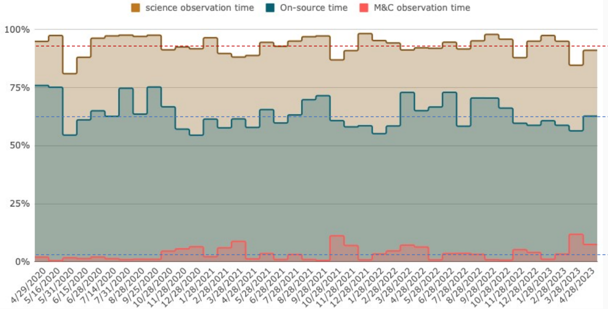
Optimise sequence of observations with genetic algorithm :

Maximise a **merit function** to promote certain solutions

CHEOPS Mission Planning (4/4)



Planning performance



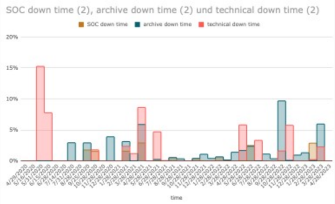
CHEOPS telescope usage

93.5% Science Time

67% On-Source Time

Remaining 1.3% down time, 1% idle, 0.6% slew

3.7% Monitoring & Characterisation



SOC occasional down times

Usually well below 1 day, except when issue occurs over the weekend.

A few interesting numbers

- Out of 27 kg of propellant available, only 150 g used during nominal mission (2 kg to date)
- 5 collision avoidance manoeuvres out of 15 warnings
- 130 GB of data received from MOC so far (all raw data would fit on a USB stick!)
- Two major anomalies at SOC
  - Double disk failure (retrieving archive data from tape)
  - 5-day internet cut (rodent ate sole optical fiber connecting SOC to outside world)
- Two full archive re-processing (resource intensive, requires higher level of automation)
- $>$ 1000 meetings! (different teams, different rythms - from daily to quarterly)
- Minimum staffing, bare redundancy

Lessons learned & future challenges

Recipe for success in CHEOPS SOC

- Excellent leadership and mentorship
- Good team spirit (generally comes with the above)
- Dedication, expertise/experience and quality of individuals
- Agile development scheme (adequate balance between pragmatic and formal approach)
- Automation built in the design allows for small operational team
- including automatic generation of documentation (source code related)

Major challenges

- Do not edit manually the action plan !
- Detector ageing may trigger changes in the MPS to adjust instrument operations
- Maintaining the IT infrastructure (including software!)
- Retention of key staff

Interactive quiz

→ 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