An introduction to SmallSats and their applications: from academic demonstrators to operational service providers

Prof. A. Camps, CommSensLab-UPC, Dept. of Signal Theory and Communications, Universitat Politècnica de Catalunya
E-mail: camps@tsc.upc.edu

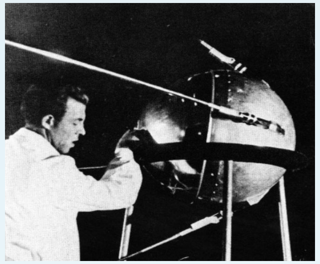
Special thanks to all the ^{3}Cat-4 team and the rest of the UPC NanoSat Lab for their enthousiastic hard work!

1. NanoSats and SmallSats:

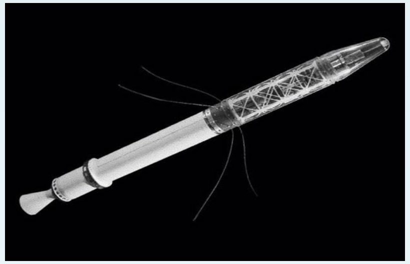
Current trends in Scientific and Communications Missions

1. Introduction to Small Satellites (i)

- At the beginning of the space age all satellites were "small."



Sputnik-1



Explorer-1

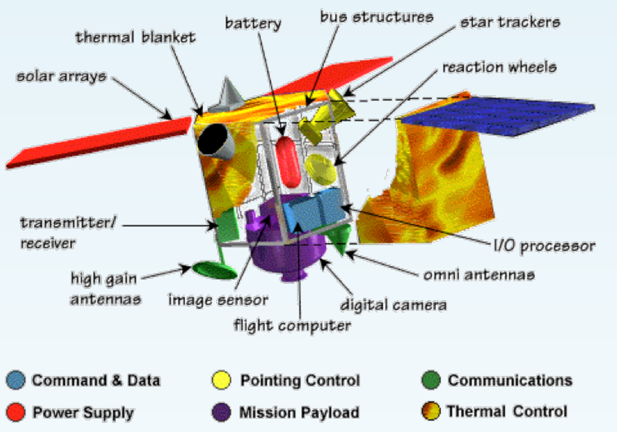
Vanguard-1

- 1st two decades of the space age: each satellite had its own design.
- Standard spacecraft buses practically unknown until end of '70s.
- Early '80s micro-satellites emerged and adopted a radically different design approach to reduce costs, focusing on available and existing technologies, and using COTS components.
- "Small satellite mission philosophy": design-to-cost approach, with strict cost and schedule constraints, mostly combined with a single mission objective, to reduce complexity.

[From "2019 Nano/Microsatellite Market Forecast, 9th Edition", SpaceWorks]

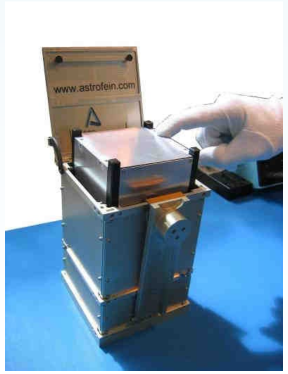
1. Introduction to Small Satellites (ii)

- "CubeSat standard" (1999) profs. J. Puig-Suari of CalPoly and Bob Twiggs of Stanford Univ.
- Goal: to allow graduate students to conceive, design, implement, test and operate in space a complete spacecraft, often using COTS components.
- Include **ALL subsystems** as in large satellites
- Because of the simplicity of the CubeSat "standard", it became a "de facto" standard.
- 1st CubeSats launched on a Russian Eurockot in June 2003.



- Current CubeSat Design Specification defines the envelopes for 1U, 1.5U, 2U, 3U, and 3U+, and 6U form factors, and work in progress for 12U and PocketQubes

1 U = 10 cm x 10 cm x 10 cm
Weight: < 1.3 kg
Average power : ~1 W, peak power: ~2-3 W

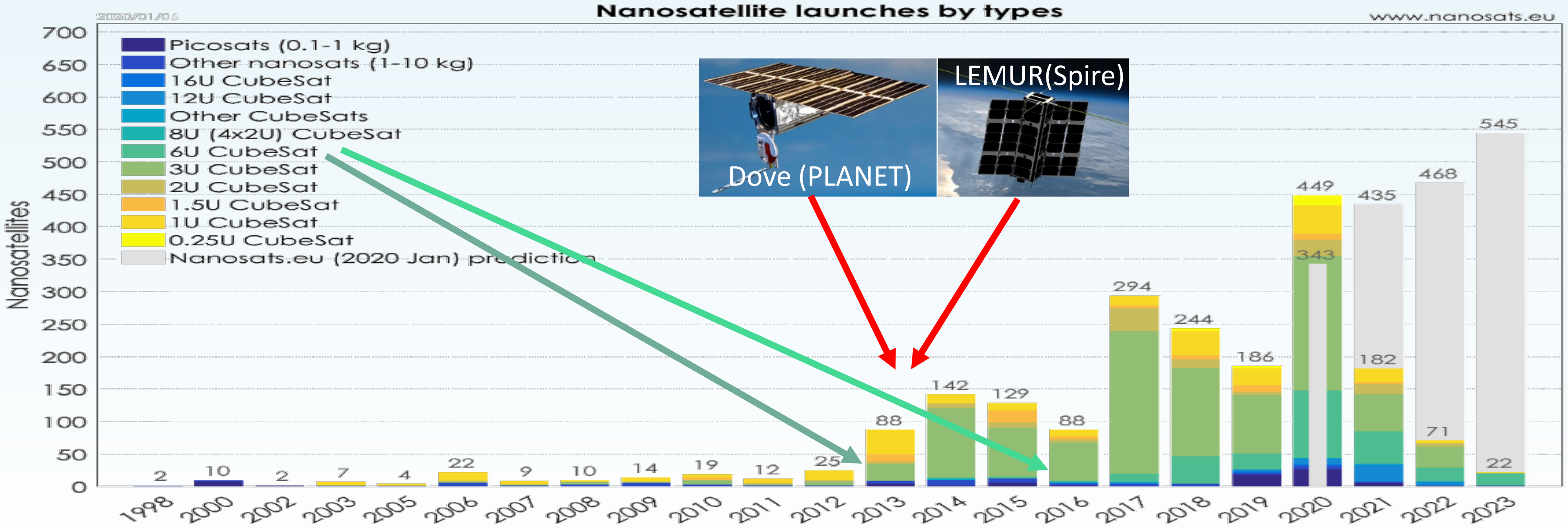


P-POD

- Today 3U CubeSats are dominating the scene, and they will over the next decade.
- Next wave of growth will be based on 6U and 12U CubeSats:
  right balance between very capable payloads, and limited manufacturing and launch costs.

Number of CubeSats launched per year as of January 6, 2020

Lemur (SPIRE)

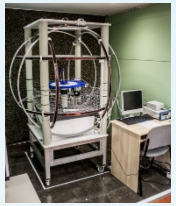


[https://www.nanosats.eu/], last visited January 2020

UPC NanoSat Lab

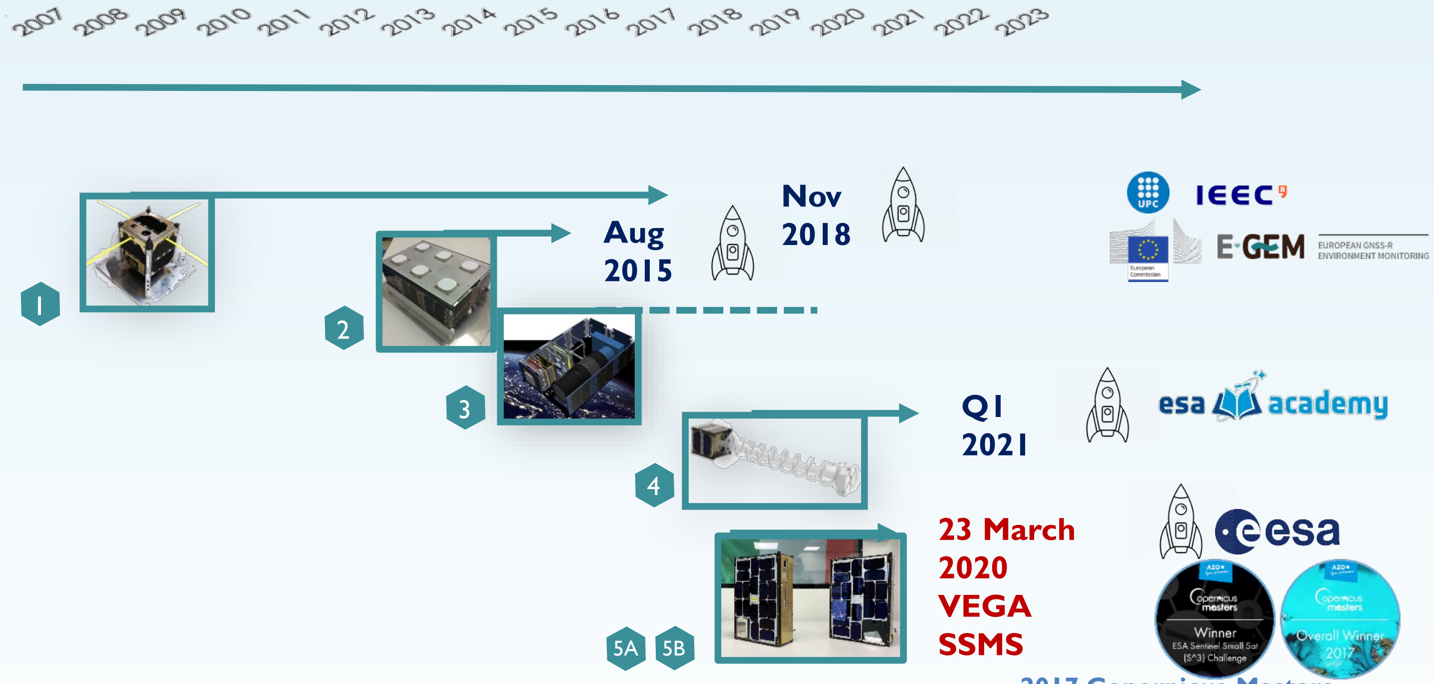
[https://nanosatlab.upc.edu/en]

Class 8 Clean room: TVAC & shaker



Helmholtz coils

Montsec Observatory: VHF, UHF & S-band ground station



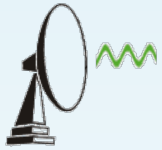
2017 Copernicus Masters winner

2. Applications of CubeSats to Earth Observation (i)

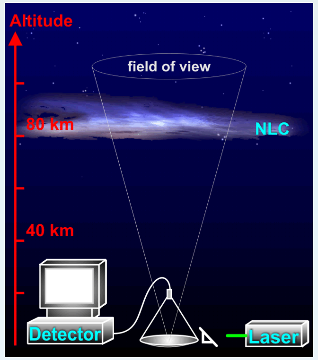
- Most CubeSats perform Optical and Passive Microwave EO mission due to power (and bandwidth) limitations

Frequency

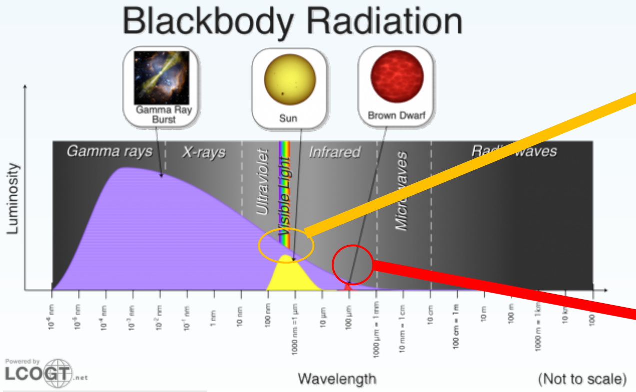
	Microwaves	Optical
Active:	RADAR	LIDAR
Passive:	Microwave Radiometers	Optical Radiometers

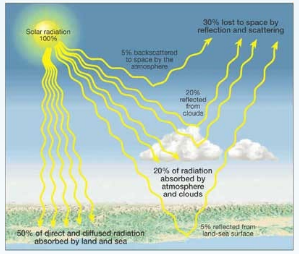


[http://www.srh.noaa.gov/srh/sod/radar/radinfo/radinfo.html]

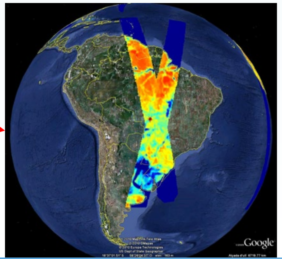


[http://web.physik.uni-rostock.de/cluster/students/fp3/lidar_en.html[]

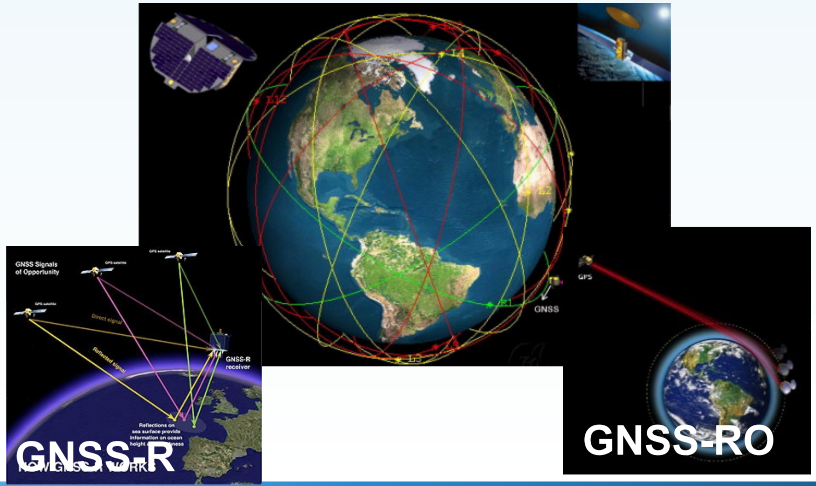




[http://dusty.physics.uiowa.edu/~goree/teaching/thermal.html]



Using Signals of Opportunity



2. Applications of CubeSats to Earth Observation (ii)

- Optical EO followed by GNSS-RO. **Telecom is coming fast!** (also to support EO constellations)
- > 10% of all nano/microsatellites launched in 2018 were for communications

Organization	Launched / Planned size	First launch	Form factor	Field
ExactEarth	67 / 67	2008	Nanosat, Hosted	AIS
Planet	355 / 150	2013	3U	Earth observation
Spire	103 / 150	2013	3U	Weather, AIS, ADS-B
Astro Digital	6 / 25	2014	6U, 16U	Earth observation
Sky and Space Global	3 / 200	2017	8U	IoT / M2M
GeoOptics	7 / ?	2017	6U	Weather

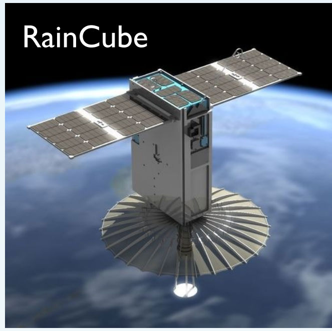
Only ones that have launched satelittes in 2016

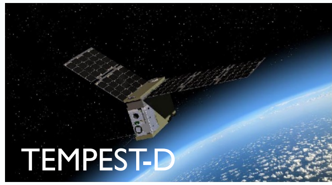
2. Applications of CubeSats to Earth Observation (iii)

- **Science mission feasibility** based on nanosatellites: **huge change in just 5 years!**
  Huge investements in P/L developments, deployable solar panels and improved downlinks

Technology	Selva and Krejci, 2012	Freeman et al. 2017	Justification
Atmospheric chemistry instruments	Problematic	Feasible	**PICASSO,** IR sounders
Atmospheric temperature and humidity sounders	Feasible	Feasible	-
Cloud profile and rain radars	Infeasible	Feasible	JPL **RainCube** demo
Earth radiation budget radiometers	Feasible	Feasible	SERB, **RAVAN**
Gravity instruments	Feasible	Feasible	No demo mission
Hi-res optical imagers	Infeasible	Feasible	Planet
Imaging microwave radars	Infeasible	Feasible	Ka-Band 12U design
Imaging multi-spectral radiometers (Vis/IR)	Problematic	Feasible	AstroDigital
Imaging multi-spectral radiometers (μW)	Problematic	Feasible	**TEMPEST**
Lidars	Infeasible	Feasible	DIAL laser occultation
Lightning imagers	Feasible	Feasible	-
Magnetic field	Feasible	Feasible	InSPIRE
Multiple direction / polarization radiometers	Problematic	Feasible	HARP Polarimeter
Ocean color instruments	Feasible	Feasible	SeaHawk
Precision orbit	Feasible	Feasible	CanX-4 and -5
Radar altimeters	Infeasible	Feasible	Bistatic LEO-GEO
Scatterometers	Infeasible	Feasible	CYGNSS (GNSS-R)

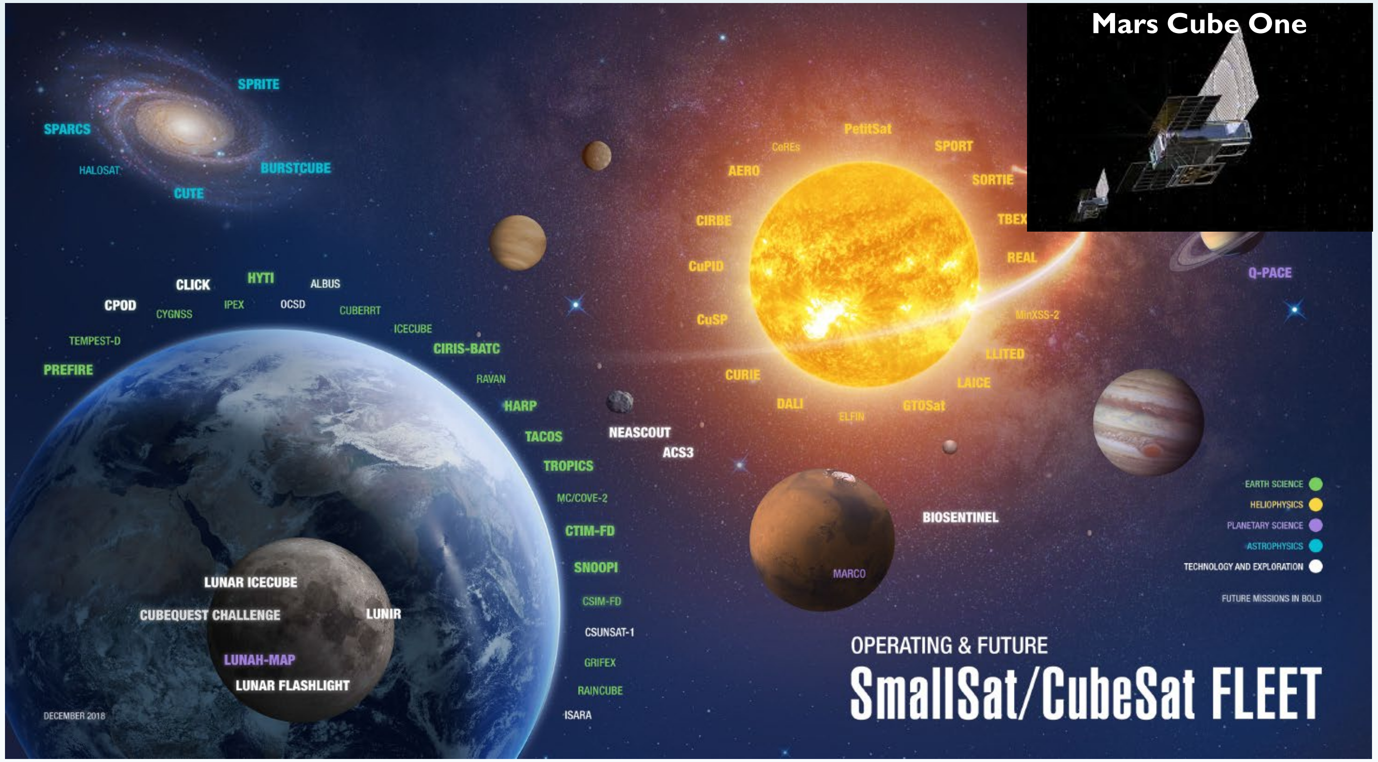
[adapted from "Deep Space cubesats and nanosats at JPL," T. Freeman, May 2017]





3. Applications of CubeSats to Astrophysics

- **NASA Science Mission Directorate sponsored SmallSat/CubeSat missions** in operation or under development



- **ASTERIA – exoplanets**
- **PicSat - giant planet β Pictoris b**

NASA astronomy missions

- **HaloSat - soft X-ray emission from Milky Way hot halo**
- **CUTE - exoplanet transit spectroscopy in near-UV**
- **SPARCS - far- and near-UV low-mass stars**
- **BurstCube gamma ray transients**

[E. Shkolnik, "On the verge of an astronomy CubeSat revolution", Nature Astronomy, May 2018]

- From 2003-2018, only 14 nano/microsatellites intended for destinations outside of LEO: MARCO 1st interplanetary cubesat mission (launch May 2018)
- Four nano/microsatellites made their way beyond Earth Orbit in 2018, more than in the past 5 years combined. Over the next 5 years, as many as 35 are expected to be launched.

4. Applications of CubeSats and SmallSats for Communications (i)

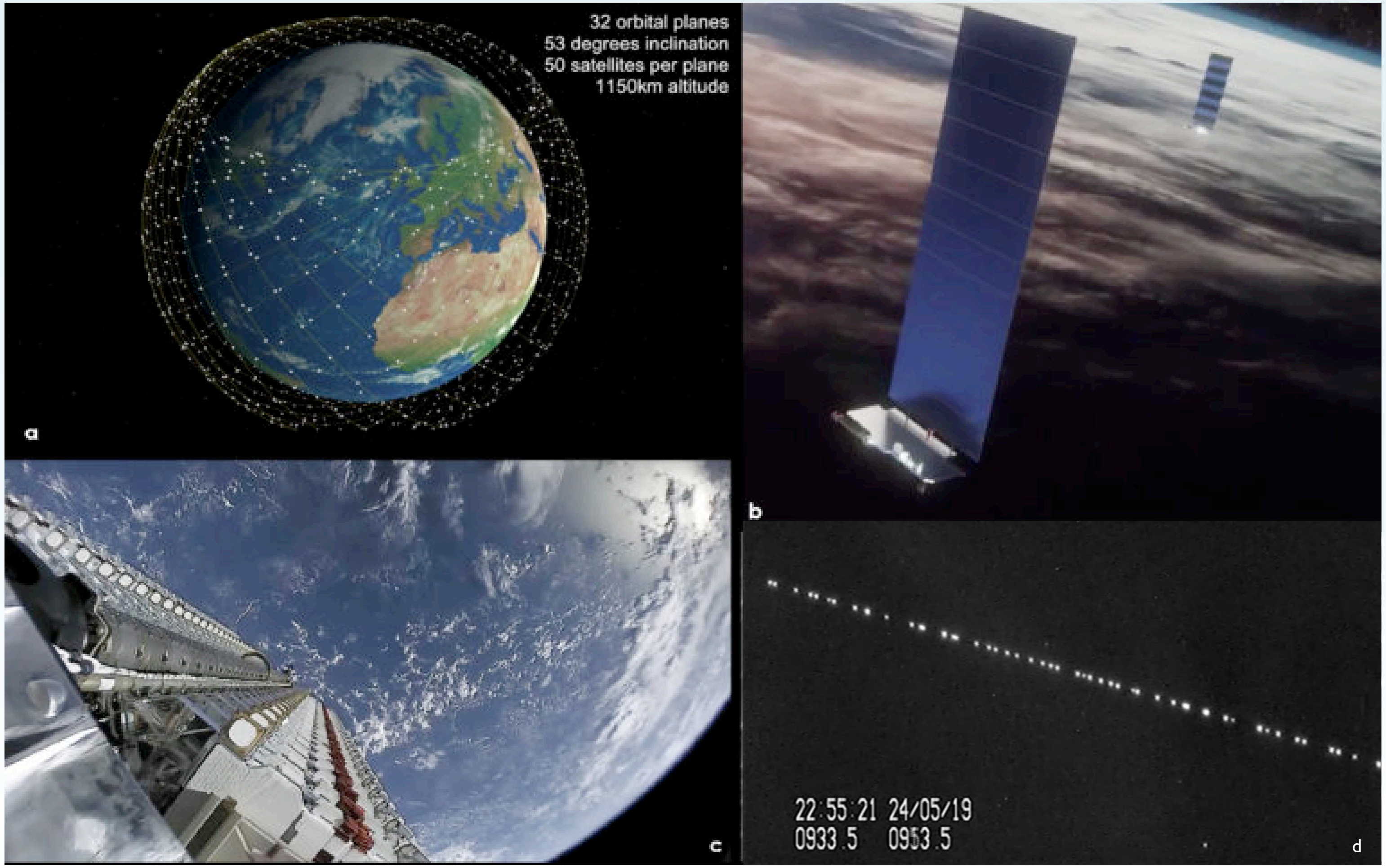
Most are for IoT & M2M ⇒ CubeSats

Two are for Internet ⇒ SmallSats (first launches in 2018 and 2019)

1	SpaceX	Starlink	2018	Internet	Smallsat
2	Orbcomm	OG2	1991	IoT / M2M AIS	Microsat Smallsat
3	Swarm Technologies		2018	IoT / M2M	0.25U 1U
4	Commsat	Ladybug / Ladybird	2018	IoT / M2M AIS	Microsat 6U 3U
5	Guodian Gaoke (Guodian Gaokeji, ...	Apocalypse	2018	IoT / M2M	6U
6	OneWeb		2019	Internet	Smallsat

4. Applications of CubeSats and SmallSats for Communications (ii)

Star Link Constellation: 4425 satellites planned !!



(a) Starlink constellation **coverage**. (b) Starlink **satellites**. (c) **Starlink satellites prior to being released** by the second stage of Falcon 9. (d) **First Starlink satellites in orbit captured in May 2019 by Netherlands-based satellite tracker Marco Langbroek.** Credits: (a) Mark Handley, (b, c) Space X (d) Marco Langbroek.

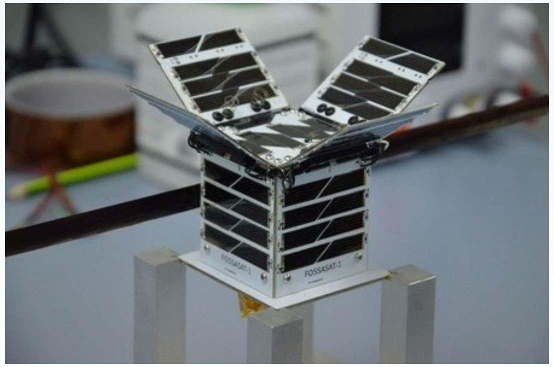
IoT in Space: LoRa on board Satellites

→ **State of the art:**

- Balloon Flight experiment: range = 600 km
- **Lacuna Space** (1st satellite launch April 1, 2019)
  - LoRaWAN Payload
  - **6U CubeSat (30x20x10 cm³) from Nanoavionics**
  - Semtech SX126x transceiver
  - Quadrifilar helix antenna
- **Fossa Systems:** (1st satellite launch December 6, 2019)
  - LoRa transceiver used for telemetry
  - **1Q PocketQube (5x5x5 cm³)**
  - Commercial LoRa transceiver
  - Monopole antenna

Lacuna space

Source: Lacuna Space



FOSSA

Source: Fossa Systems
https://github.com/FOSSASystems

4. Applications of CubeSats and SmallSats for Communications (iv)

Towards a New Paradigm: Federated Satellite System (FSS)

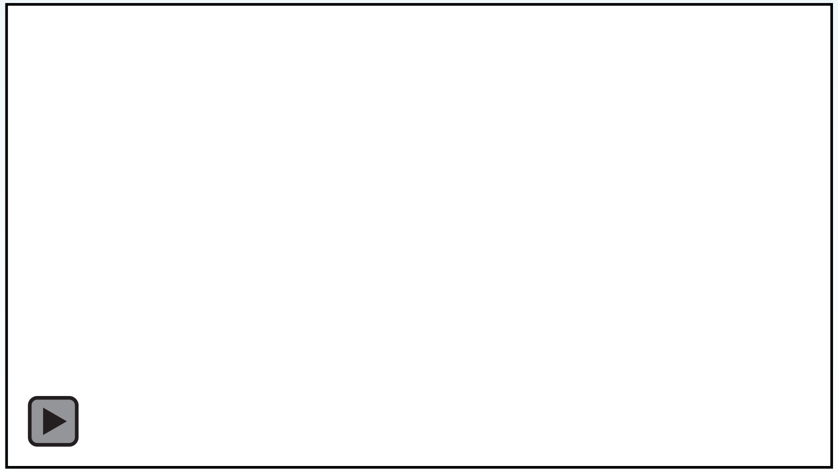
- Interaction of **heterogeneous satellites**
- **Win-win collaboration** between satellites
- **Share unused resources → "Uber of Space"**
- **Sporadic** and **Opportunistic** nature

→ FSS Inter-Satellite Links required:

- Different Physical Technologies
- Different Missions
- Different Medium Access
- Temporal behaviour: **Link lifetime, sporadic connections, architectural analysis, disruption of FSS service**

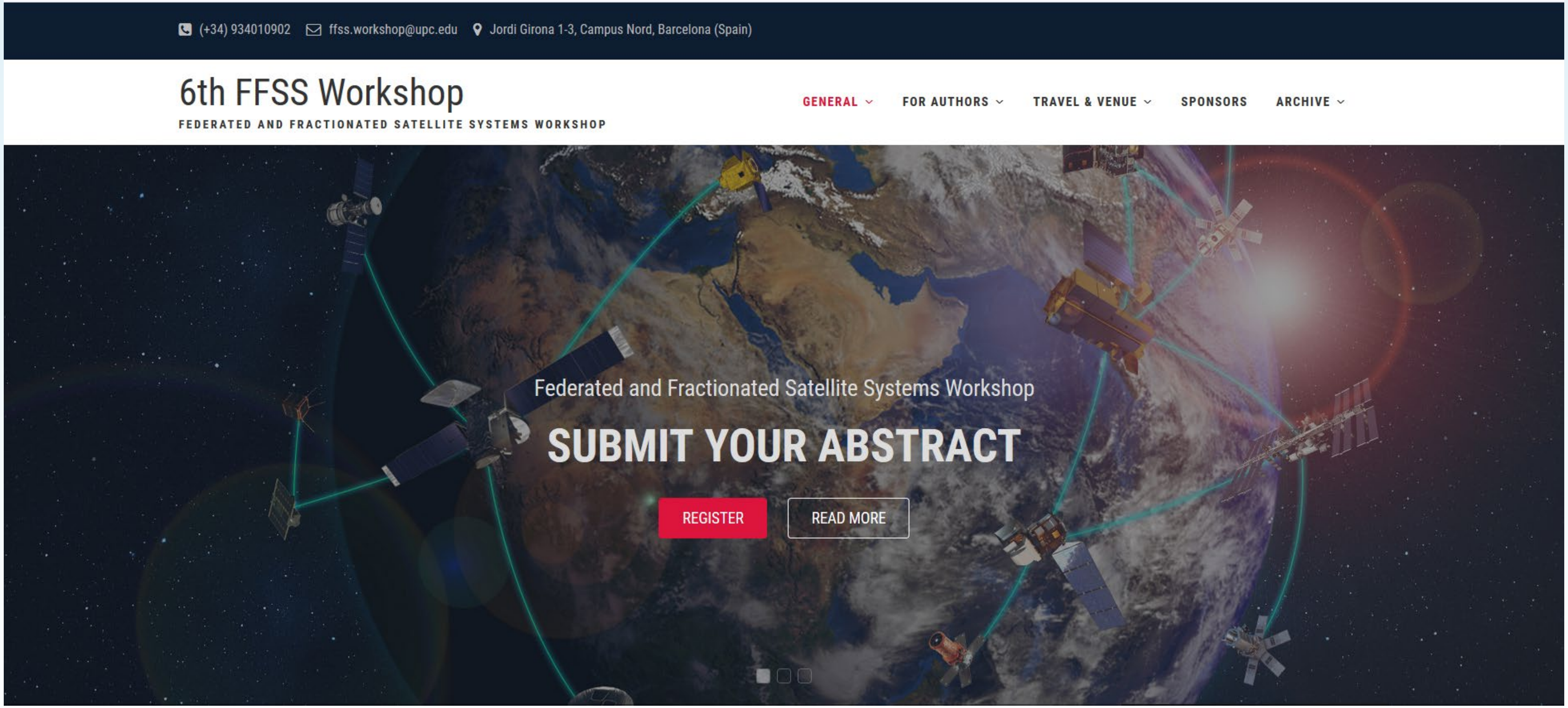
→ISL Range Impacts on: disruption and low coverage

Golkar and I. L. I Cruz, ''The federated satellite systems paradigm: Concept and business case evaluation,'' Acta Astronautica, vol. 111, pp. 230–248, 2015.



FSS concept needs to be extended to multi-hop communications

Federated and Fractionated Satellite Systems Workshop Barcelona (Spain), June 17-19, 2020



https://golkar.scripts.mit.edu/fss/

5. Conclusions

- CubeSats have produced a “disruptive innovation,” displacing established competitors.
- Early CubeSats had short lifetimes (a few months). Increased ground testing and added redundancies have increased lifetimes significantly (up to 4-5 y. in some cases).
- CubeSats cannot displace all large space scientific (laws of Physics cannot be changed), and cannot replace medium/large communication satellites as directive antennas and high transmitted powers are needed
- … but cubesats are finding their own niche in many EO, Astrophysics, and Communications (IoT and M2M) applications where NRT or even continuous monitoring are required.
- Still many new technologies to be developed!
- **Massive constellations of EO + communications will be the newest space revolution**

[https://www.intechopen.com/online-first/nanosatellites-and-applications-to-commercial-and-scientific-missions]

2. The ^{3}Cat-4 Mission:

2.1. Mission Overview.

2.2. Orbit Analysis and Reentry Calculations.

2.3. Thermal Control System and Radiation Analysis.

2.4. Electrical Power Supply (EPS) System.

2.5. Communications System (COMMS).

2.6. On Board Data Handling (OBDH) System.

2.7. Attitude Determination and Control System (ADCS).

2.8. Assembly, Integration, Verification and Testing .

2.1. Mission overview

To demonstrate the capabilities of nano-satellites for challenging Earth Observation using GNSS-R and L-band microwave radiometry, as well as for Automatic Identification System (AIS)

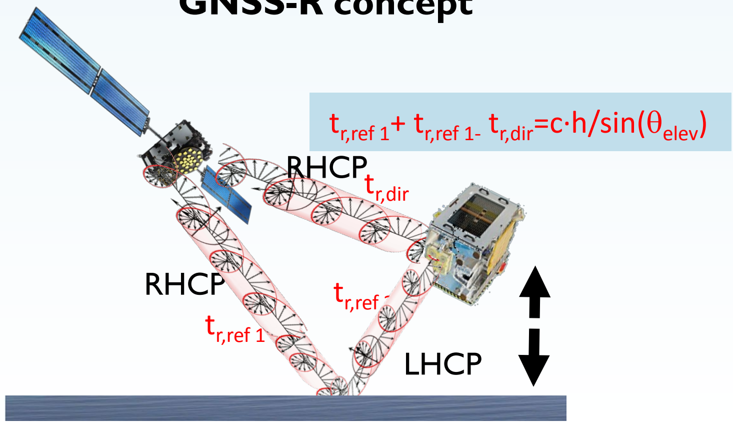
→ Research Objectives

- Miniature GNSS-R receiver
- Testing RFI detection/mitigation techniques
- Testing AIS receiver for ship tracking

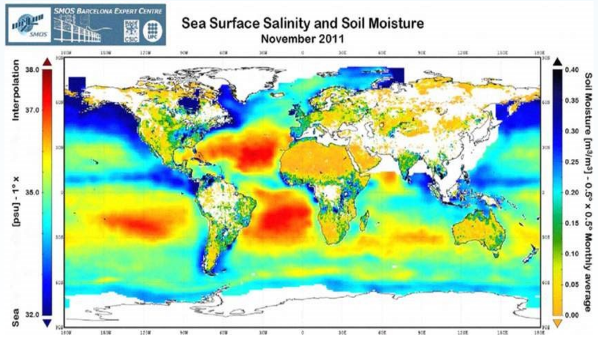
→ Motivation

- Foster development of GNSS-R techniques
  - Low altimetry resolution can still detect ocean features
  - Polar regions: unbeatable resolution for marine traffic
- ESA SMOS detected RFI from Earth communications
- Technologies can be adopted as future hosted P/Ls

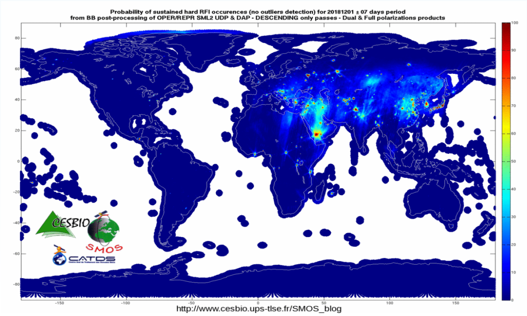
GNSS-R concept



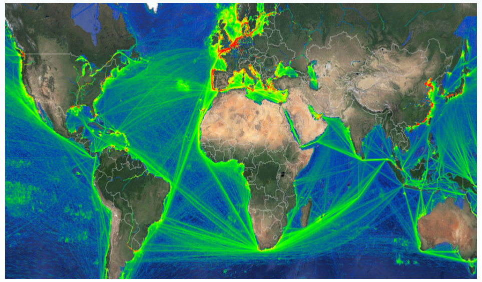
SMOS Soil Moisture and Ocean Salinity maps (L-band MWR)



SMOS RFI map

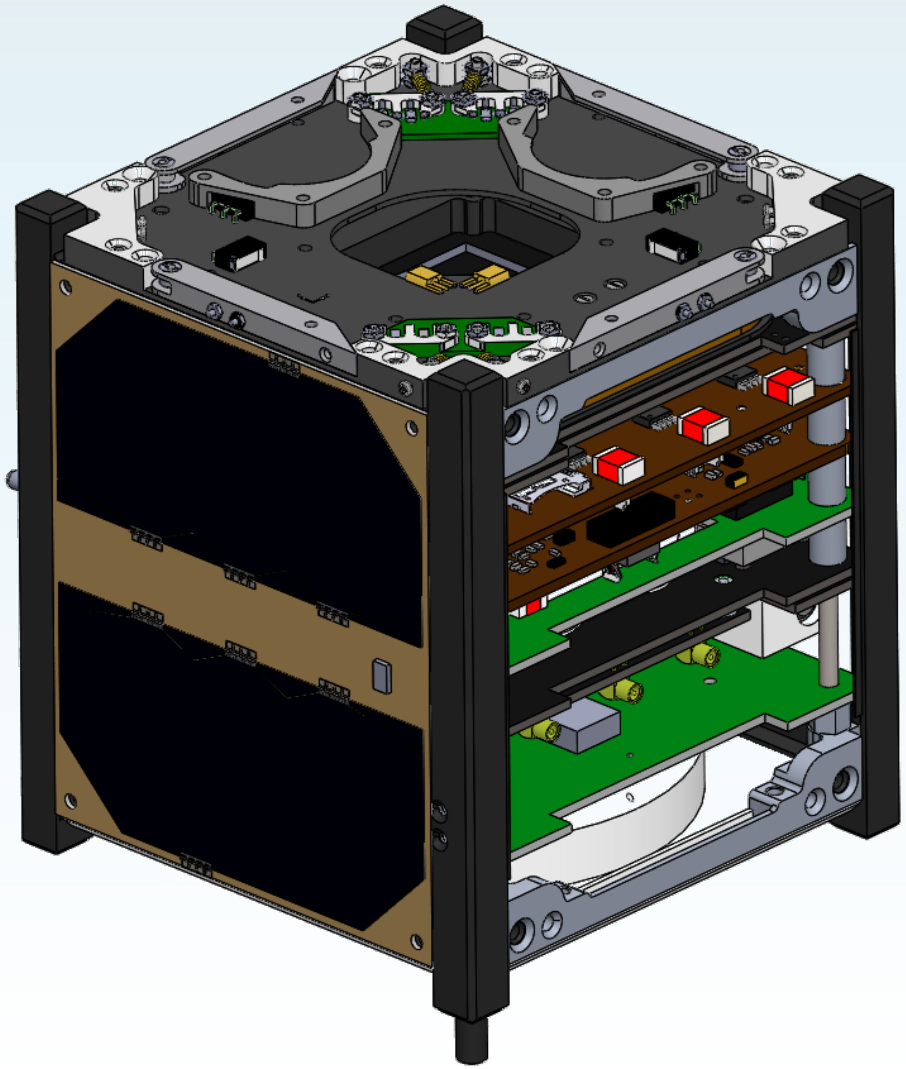


Global ship route density

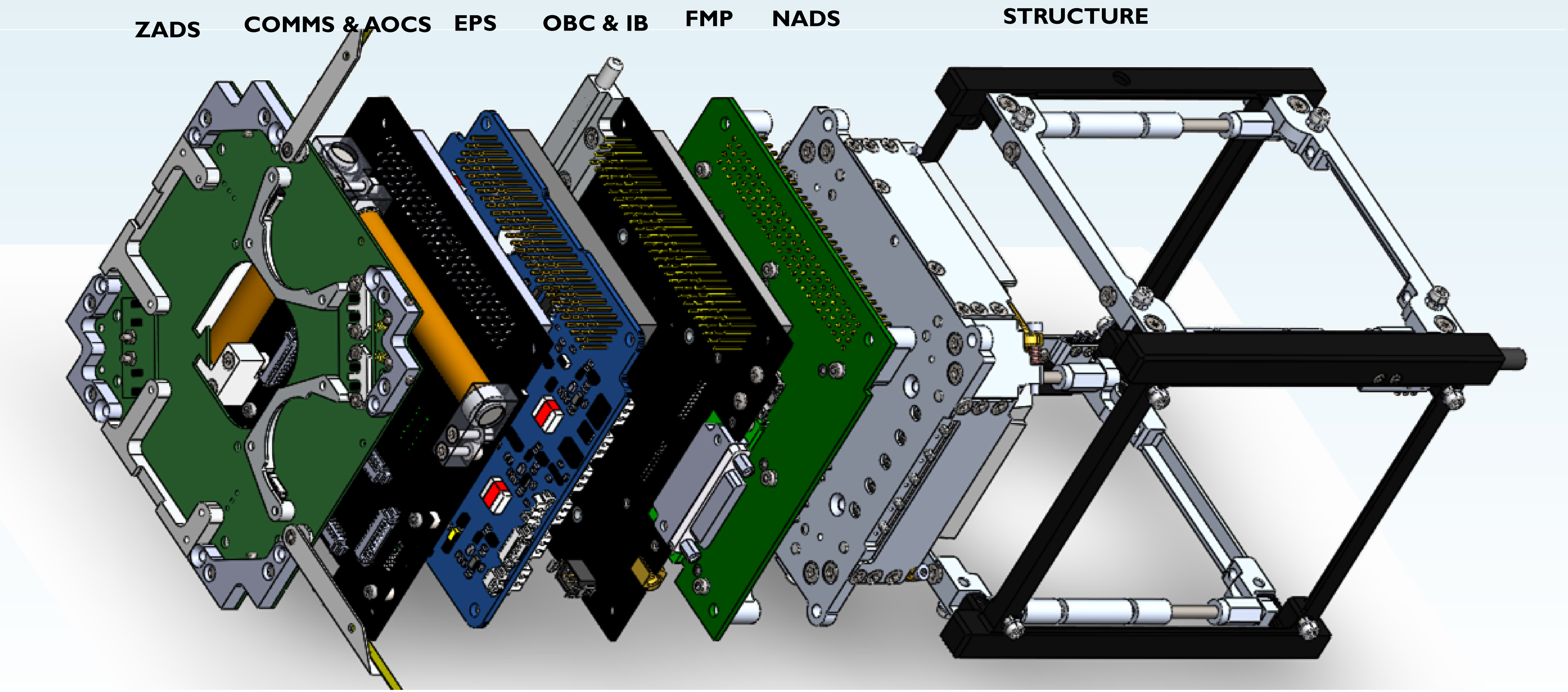


2.1. The ^{3}Cat-4 Mission: Spacecraft Overview (i)

- 1-Unit CubeSat → ISISpace 1U Structure
  - Dimensions: 100 x 100 x 113,5 mm
  - Mass: 950 g – 1050 g
- Subsystems
  - On-Board Computer
    - GomSpace NanoMind A3200
  - Electrical Power System
    - GomSpace NanoPower P31u
    - GaAs based Solar Panels
  - UHF Half Duplex Communications (435-438 MHz)
    - NanoSat Lab UHF Transceiver
    - ISISpace Deployable UHF Antenna
  - Attitude Determination & Control System
    - Active control with magnetorquers
    - Passive control with gravity boom
    - Determination: magnetometer, gyro, sun sensors
- Payload
  - GNSS Reflectometer
  - L-Band Radiometer
  - AIS Receiver

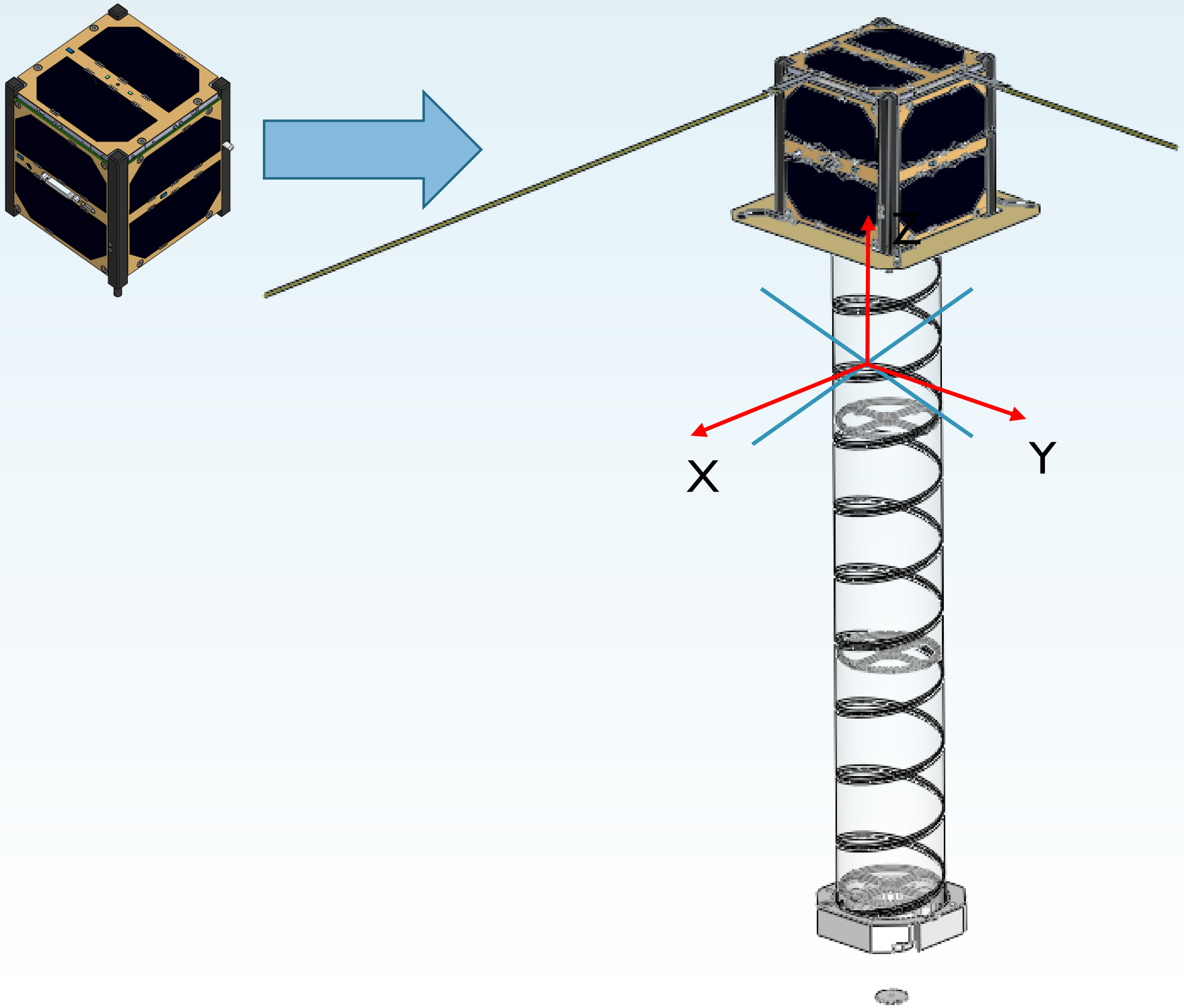


2.1. The ^{3}Cat-4 Mission: Spacecraft Overview (ii)



2.1. The ^{3}Cat-4 Mission: Spacecraft Overview (iii)

- 1U Cubesat in **stowed configuration**
  1. ISIS 1U structure
  2. 121.50 mm x 100 mm x 100 mm dimensions
  3. Launch Campaign
  4. Launch and Early Orbit Phase (LEOP)



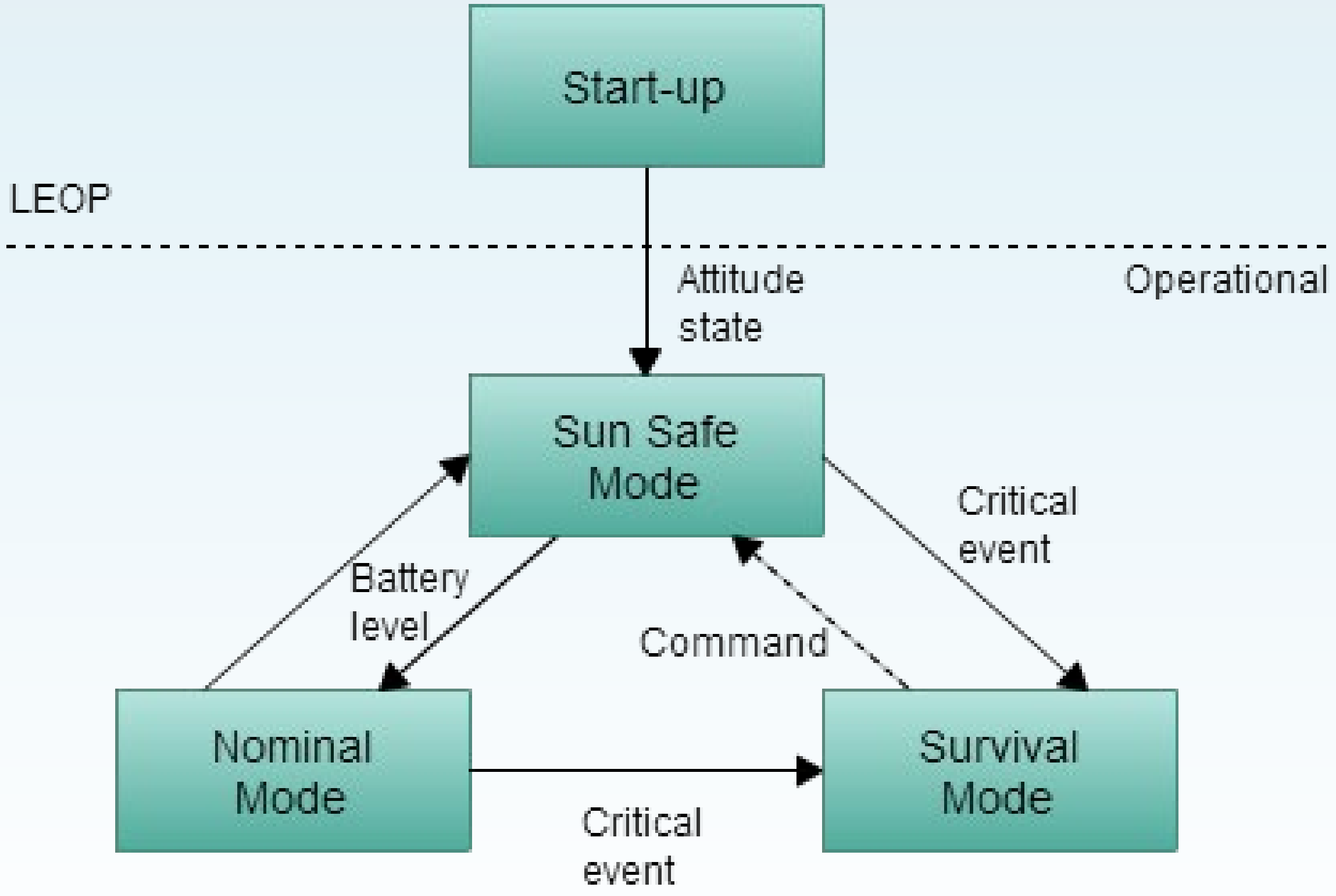
- **Deployed configuration**
  1. 595.75 mm x 150 mm x 150 mm dimensions
  2. Deployment by stages
  3. All antennas deployed
  4. Operational phase

2.1. The ³Cat-4 Mission: Mission Phases (i)

→ Launch & Early Orbit Phase (LEOP)
- Init Sequence
  - Initial stand-by
  - Comms antenna deployment
  - Detumbling phase
- Comissioning
  - Spacecraft health check
  - Payload antennas deployment
  - Nadir pointing

→ Operational Phase
- Nominal Mode → Payload Operations
- Sun Safe Mode → Energy constrained
- Survival Mode → Contingency state

→ Decommissioning Phase
- Reentry between 1 to 2.5 years
- Minimum mission objectives achievable in 3 months



2.1. The ^{3}Cat-4 Mission: Mission Phases (ii)

Active subsystem during
Survival mode

Subsystem	Active	Duty Cycle
OBC	Yes	100%
EPS	Yes	100%
ADCS	Yes	100%
TT&C (periodic downlink)	Yes	5%
TT&C (on-request downlink)	No	-
TT&C (uplink)	Yes	-
ZADS Deployment	Yes	10%
NADS Deployment	Yes	10%
Payload	No	-

Active subsystem during
Sun Safe mode

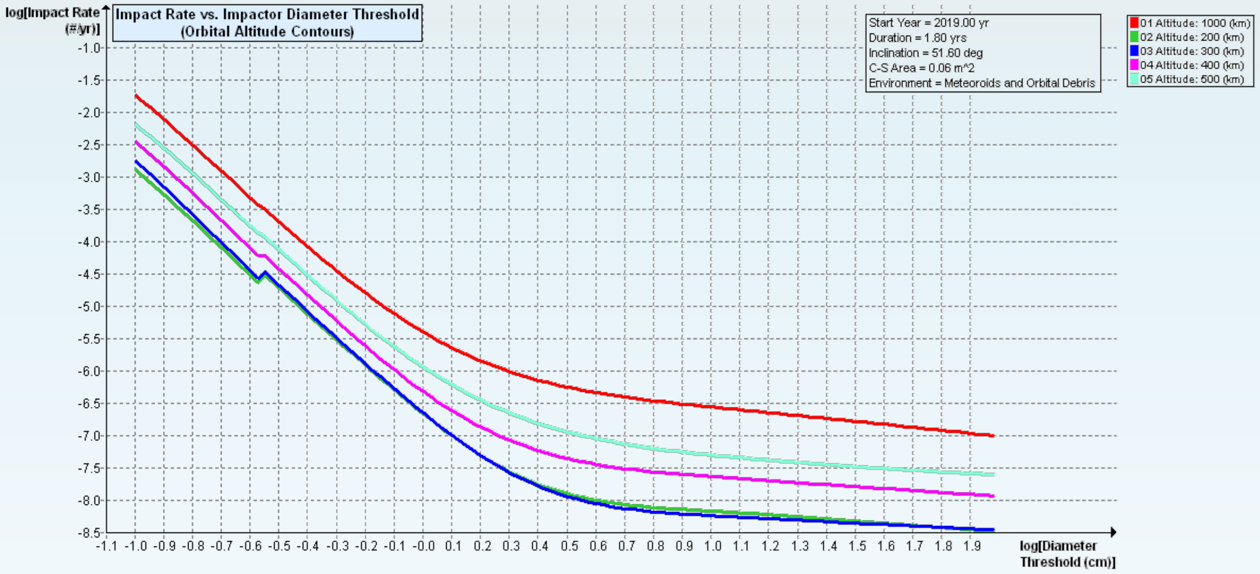
Subsystem	Active	Duty Cycle
OBC	Yes	100%
EPS	Yes	100%
ADCS	Yes	100%
TT&C (periodic downlink)	Yes	10%
TT&C (on-request downlink)	Yes	-
TT&C (uplink)	Yes	-
ZADS Deployment	Yes	10%
NADS Deployment	Yes	10%
Payload	No	-

Active subsystem during
Nominal mode-stand by
(P/L activity = 0%), and
Nominal mode-data acquisition
(P/L activity = 10% of orbit)

Subsystem	Active	Duty Cycle
OBC	Yes	100%
EPS	Yes	100%
ADCS	Yes	100%
TT&C (periodic downlink)	Yes	10%
TT&C (on-request downlink)	Yes	-
TT&C (uplink)	Yes	-
ZADS Deployment	Yes	10%
NADS Deployment	Yes	10%
Payload	Yes	0 or 10%

… related to – determines the power budget

2.1. The ^{3}Cat-4 Mission: Mission Phases – EOL (iii)



→ Impact rate vs. impact diameter (top left)

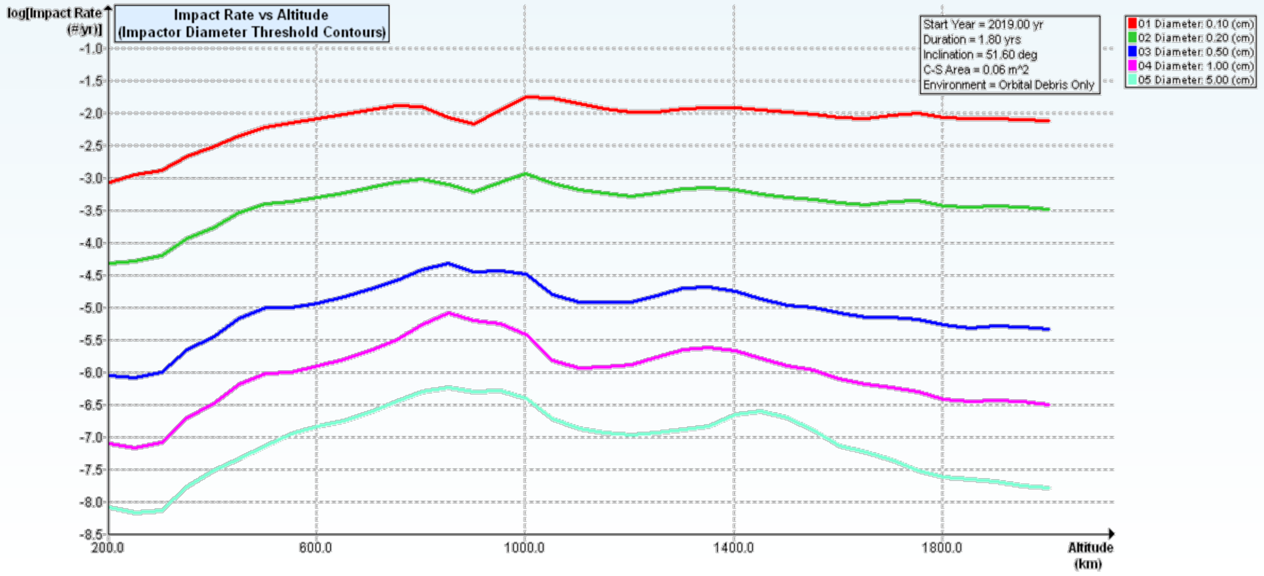
→ Cross-section of the satellite with the antenna deployed = 0,06 m^2.

→ A fragment of 1 cm^2 has am impact probability ~5x10^{-7}.

→ Impact rate vs. altitude (bottom right)

→ Cross-section of the satellite with the antenna deployed = 0,06 m^2.

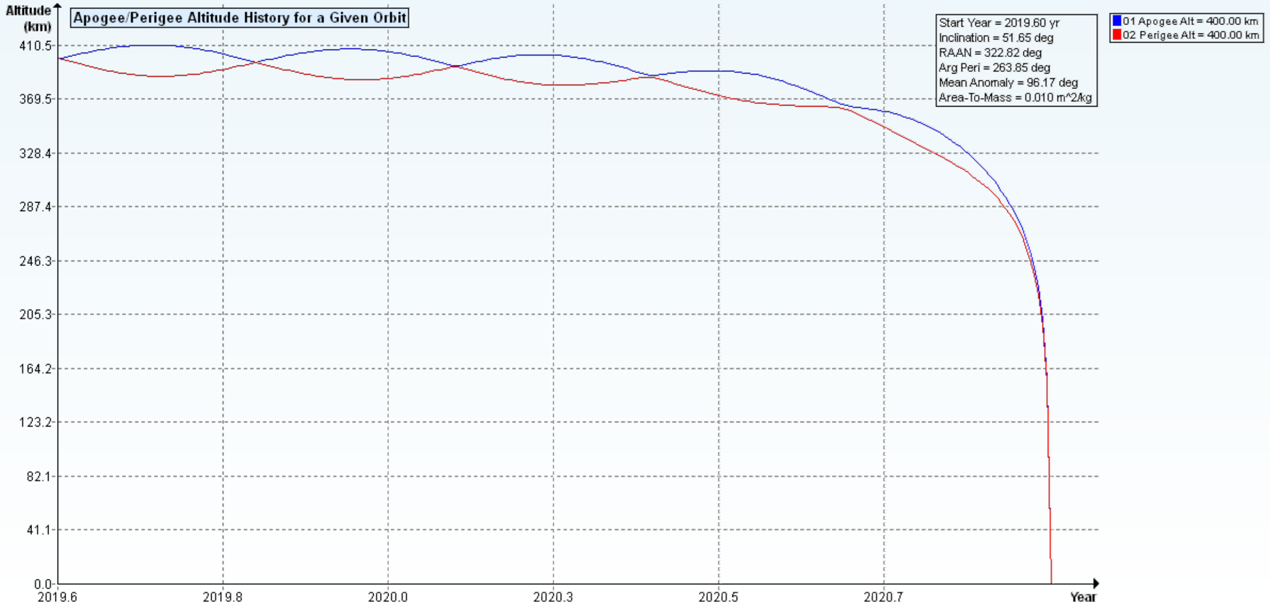
→ Larger fragment impacts are less probable at all orbital heights.

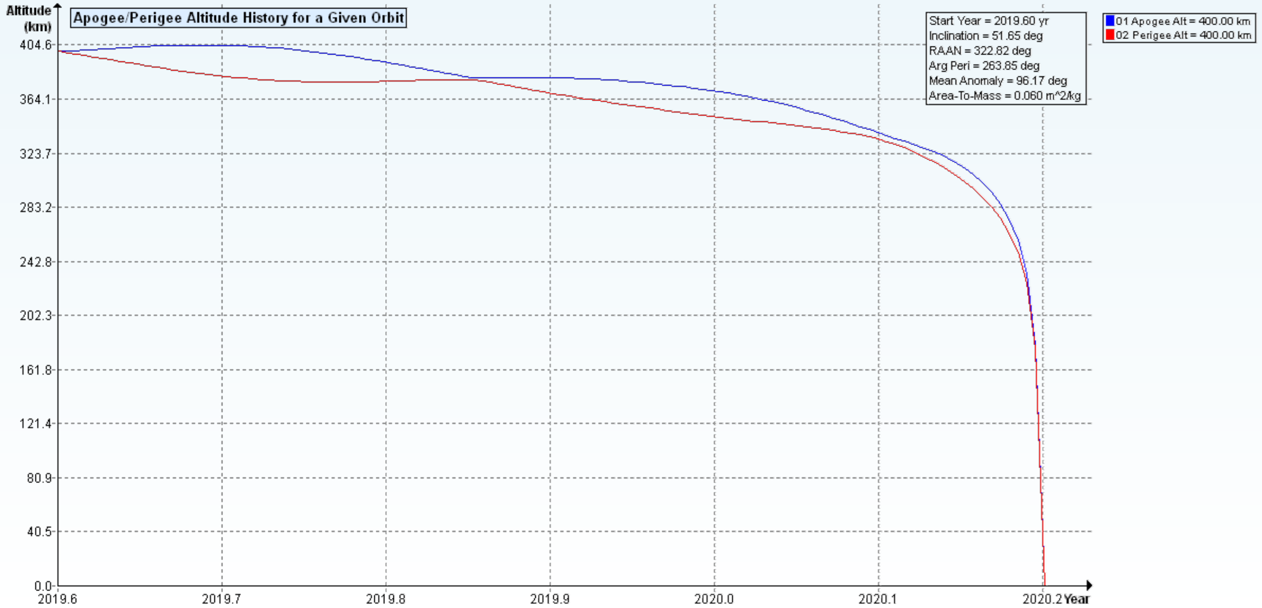


2.1. The ³Cat-4 Mission: Mission Phases – EOL (iv)

- → Altitude: 400 km
- → Launch date: 00:00:00 01/08/2019
- → Inclination: 51.65 °
- → RAAN: 322.82 °
- → Argument of the perigee: 263.85 °
- → Mean Anomaly: 96.17 °

- → Orbital lifetime for 0,06 m^2 cross-section = 8 months (right).
- → Orbital lifetime for 0,01 m^2 cross-section = 14 months (left).

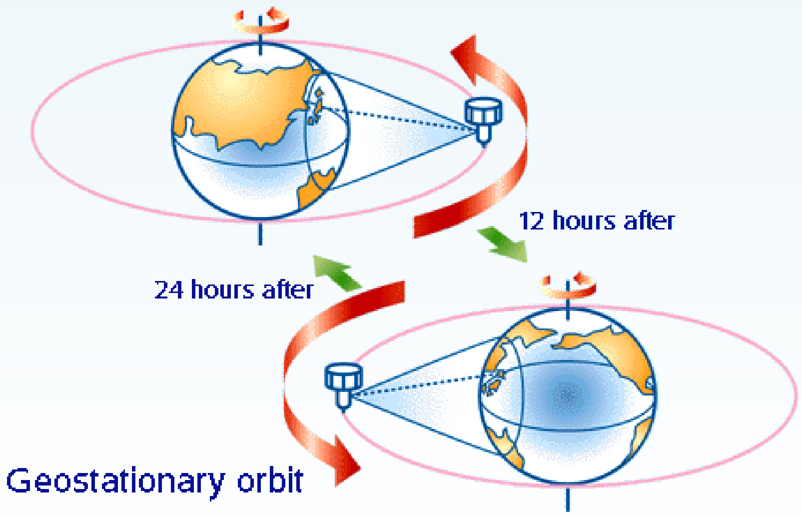




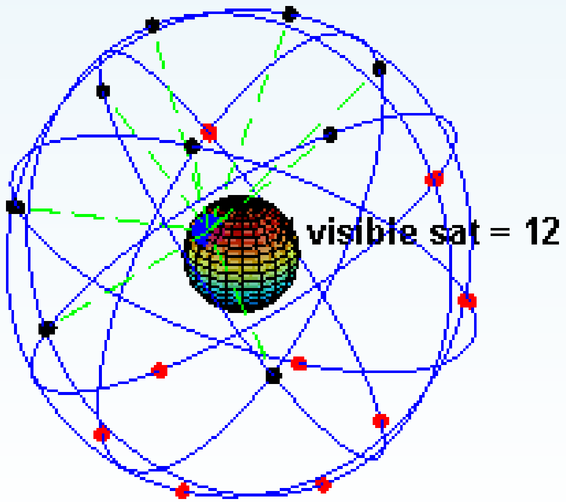
2.2. Orbit Analysis and Reentry Calculation.

Orbit selection depends on application and payload
Examples:

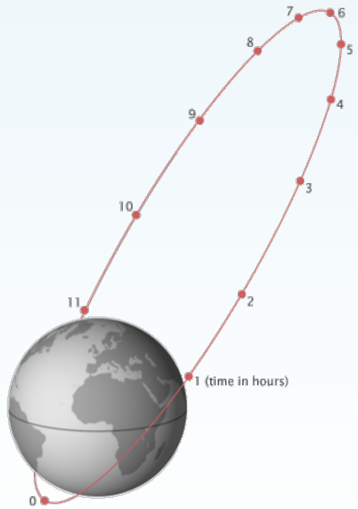
Meteosat (Geostationary)
- Always looking at same point
- 3 satellites for global coverage



GPS (Medium Earth Orbit)
- At least 4 satellites in view required



OKO URSS Spy Satellite (Molniya orb)
- Large fraction of the orbital period over the region of interest
- Telecom at high latitudes and spy

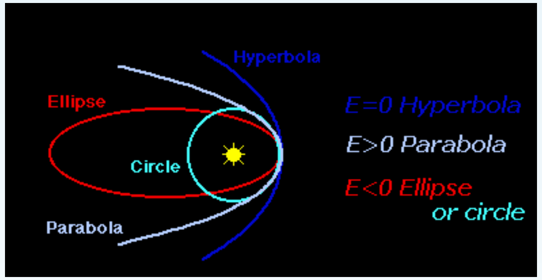


2.2. Orbit and reentry calculation (ii)

Kepler' s laws:

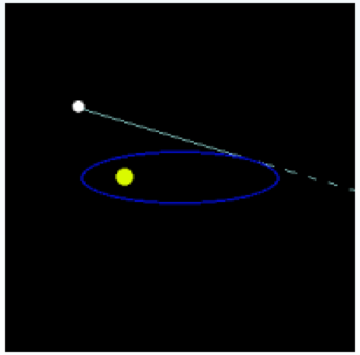
1. The secondary body describes an elliptical orbit around the primary body.

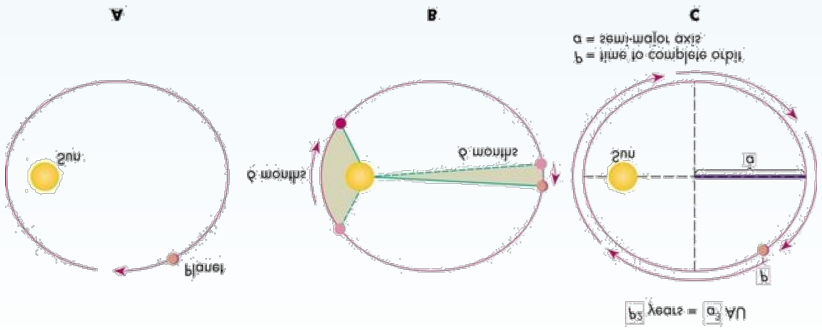
Eccentricity e	Type of Orbit
0	Circular
0 < e < 1	Eliptical
1	Parabollic
1 < e	Hyperbolic



2. The area swept by the radio-vector going from the primary body to the secondary body is the same in equal time intervals.

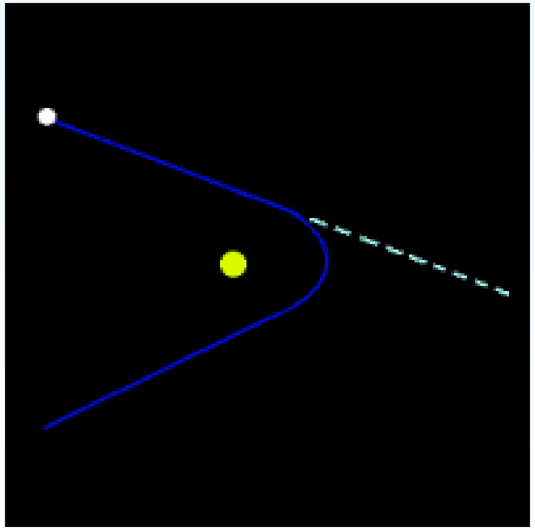
3. The orbital period is determined by the average distance that separates them and by the mass of the primary

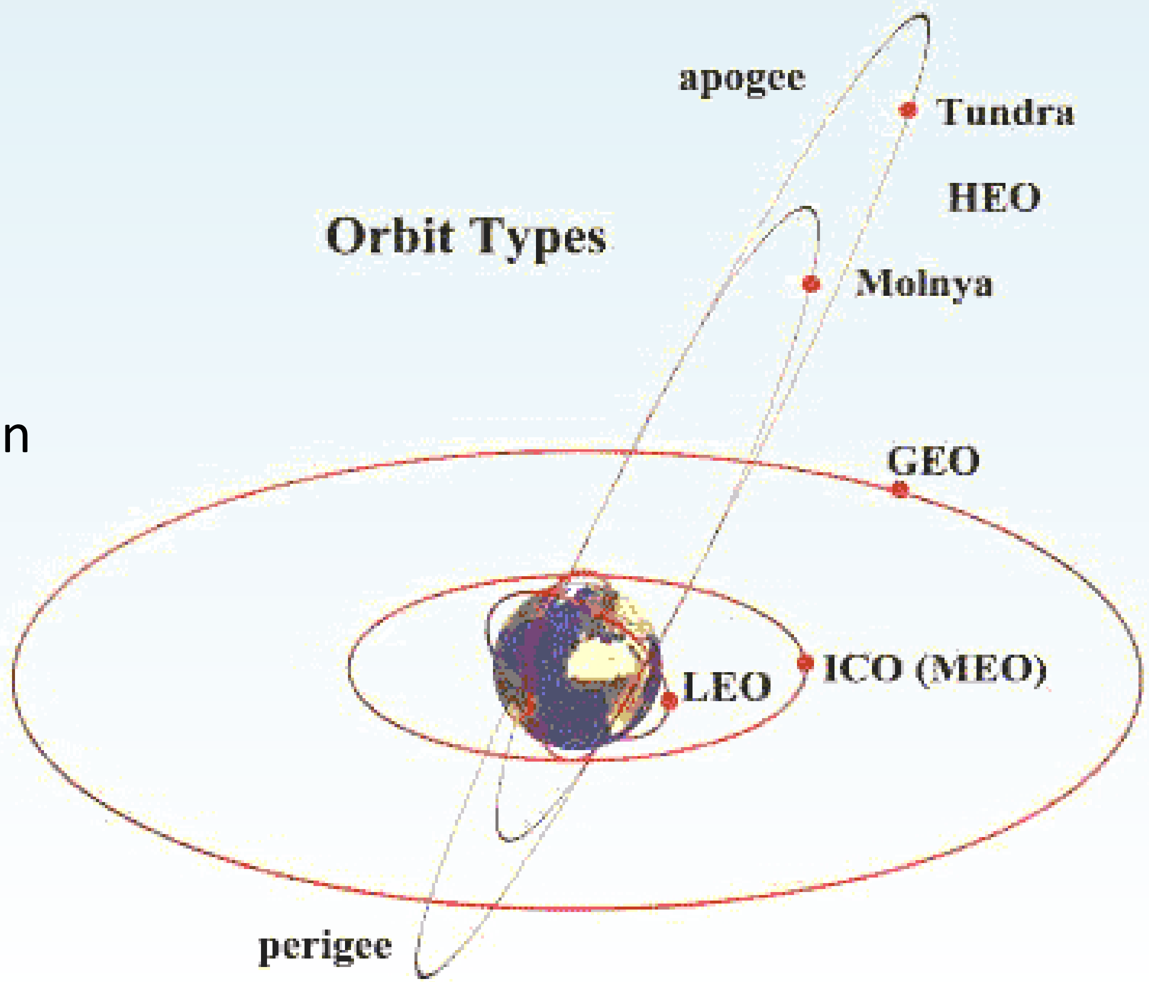




Types of orbits:

- By height:
  - LEO: Low Earth Orbit
  - MEO: Medium Earth Orbit
  - GEO: Geosynchronous Earth Orbit
  - HEO: Highly Elliptical Orbit
    (e.g. Tundra, Molniya)
  - Non-geocentric orbits: interplanetary navigation





Keplerian elements: 6 Orbital Parameters (derived from the 2-body Newton equation):

$$\frac{d^2\vec{r}}{dt^2} + \frac{\mu}{r^2}\vec{r} = 0$$

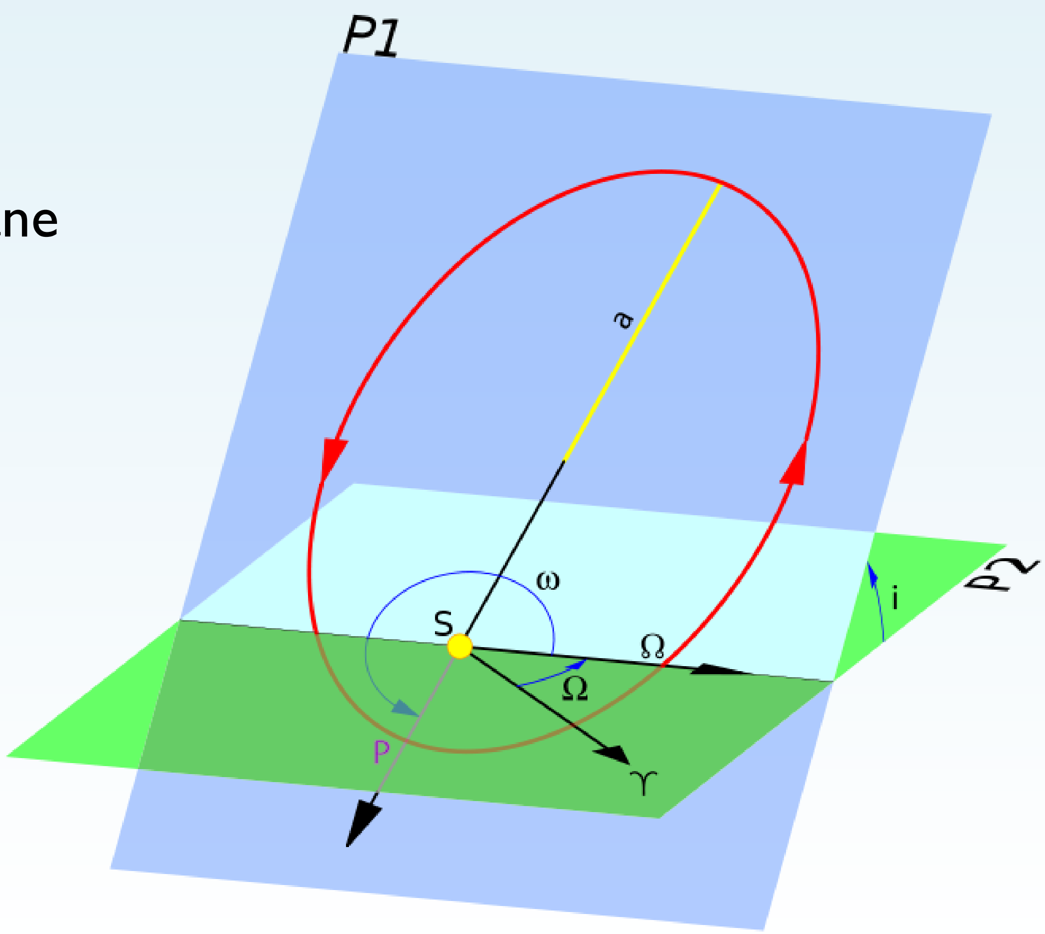
$$\frac{1}{2}mV^2 - \mu\frac{m}{r} = \varepsilon \qquad (\mu = GM)$$

$$r = \frac{h^2/\mu}{1 + e\cos\theta}$$

- Ω: longitude of the ascending node on the equatorial plane
- i: inclination of the orbital plane with respect to the equatorial plane
- γ: argument of the perigee at the ascending node
- a: semi-major axis of the ellipse
- e: orbit eccentricity

$$e = \sqrt{1 - \left(\frac{b}{a}\right)^2}$$

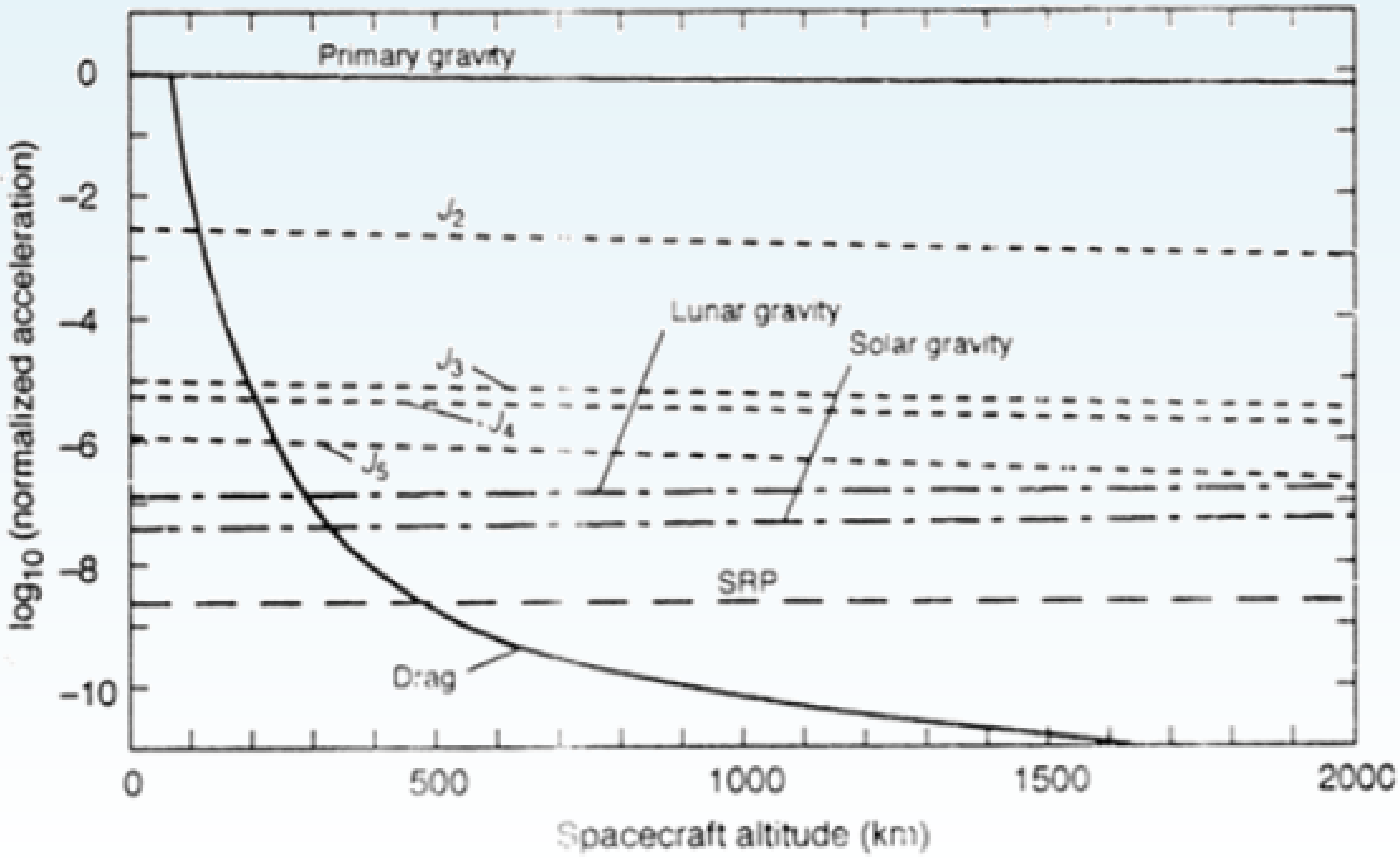
- t_p: time of passage at the perigee (reference initial time)



2.2. Orbit and reentry calculation (v)

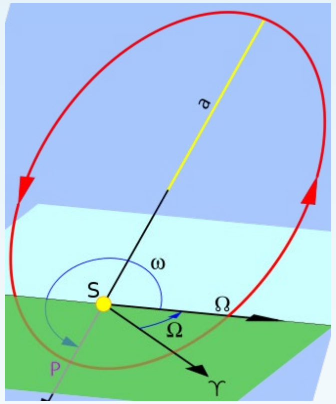
Orbital perturbations:

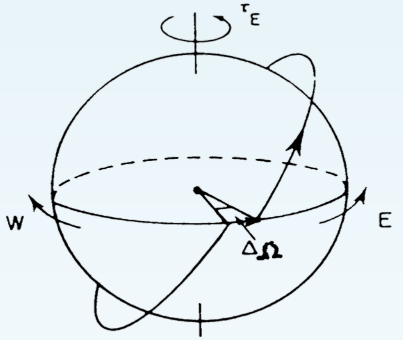
- Accelerations caused by the main perturbation sources
- Comparisons of the disturbing accelerations for the main sources of perturbation Forteskue et al.



LEO orbit:

- **Polar LEO orbit:** Global coverage (passes by the poles), typical altitude between 600 and 800 km
- **Earth-synchronous orbit:** the ground track repeats its trace over the Earth at regular intervals





Longitude shift $\Delta\Omega = \Delta\Omega_1 + \Delta\Omega_2$ in one orbit for the Ecuator due to:

- The Earth's rotation (dominant term)

$$\Delta\Omega_1 = -2\pi \frac{T}{T_e} \quad \text{[rad/orbit]}$$

- Regression of the ascending node

$$\Delta\Omega_2 = -3\pi \left(\frac{R}{a}\right)^2 \cdot \frac{1}{(1-e^2)^2} \cdot J_2 \cdot cos\psi \qquad \text{[rad/orbit]}$$

An **Earth-synchronous orbit** satisfies:

$n\,|\Delta\Omega| = m \cdot 2\pi$, where n is the number of orbits

m is the number of Earth revolutions (days)

An **Earth-Sun synchronous orbit**:

Combination of the two previous requirements

$n\,|\Delta\Omega| = m \cdot 2\pi$

$$\mathrm{n} \cdot \left| -2\pi \frac{T}{T_e} + 2\pi \frac{T}{T_{es}} \right| = m \cdot 2\pi \rightarrow n \cdot T \left(\frac{1}{T_e} - \frac{1}{T_{es}} \right) = m$$

The orbit is indicated with indices **n:m**

$$\Delta\Omega_2 = 2\pi \frac{T}{T_{es}} \text{ [rad/orbit]} \qquad \Delta\Omega = -2\pi T \left(\frac{1}{T_e} - \frac{1}{T_{es}} \right) \text{ (towards the West)}$$

2.2. Orbit and reentry calculation (vii)

- Orbit calculation (+ power + communications budgets)
[to be used during the hand-on session at the end of this tutorial, time permitting]
xhttps://www.open-cosmos.com/open-app/#free-trial

- Calculation of the reentry time using the following tool:

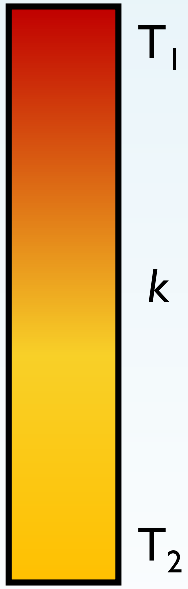
http://www.lizard-tail.com/isana/lab/orbital_decay/

2.3. Thermal Control System (TCS) and Radiation Analysis

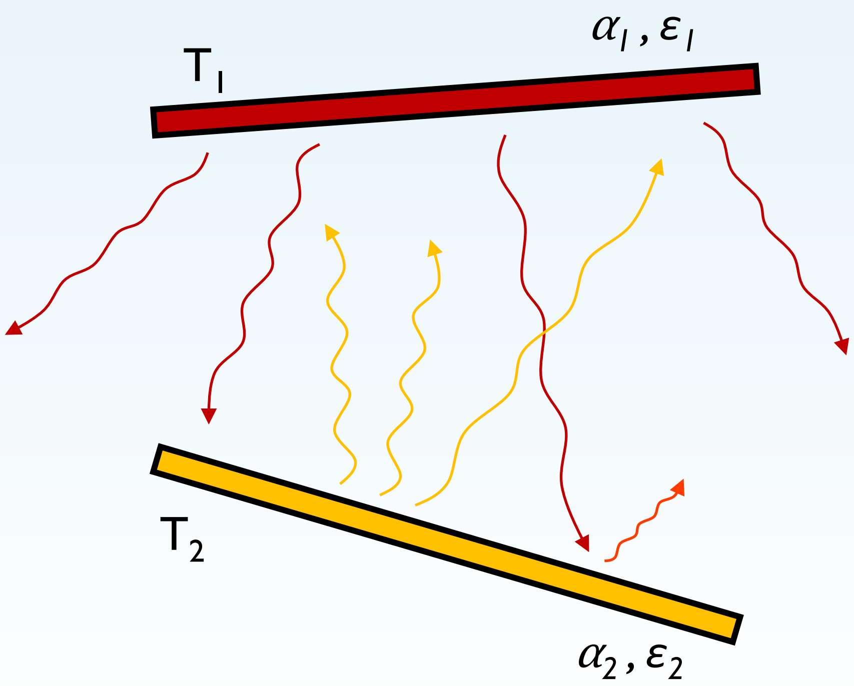
2.3. TCS: Description of the Problem (i)

→ Heat transfer modes in space

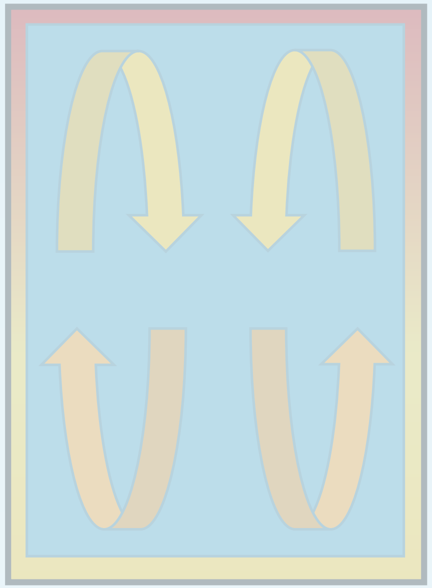
Conduction



Radiation



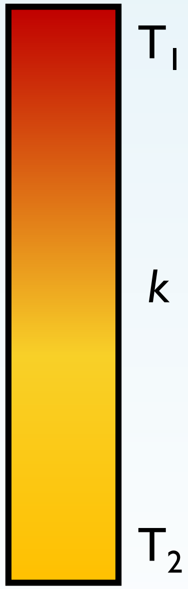
Convection



2.3. TCS: Description of the Problem (ii)

→ Heat transfer modes in space

Conduction



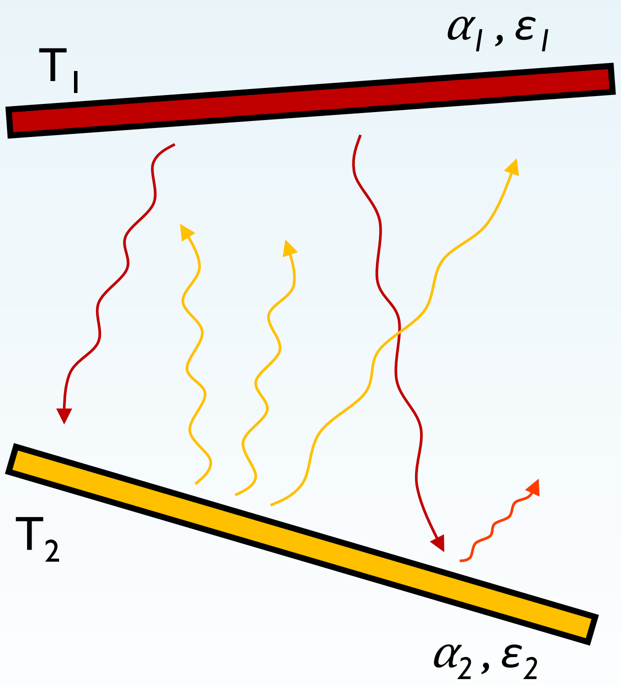
Process described by **Fourier's law**:

$$q_n = -k\frac{\partial T}{\partial n}$$

q_n : Conduction heat rate per unit area in the n direction.

k : Thermal conductivity.

Radiation



Process described by **Stefan-Boltzmann law**:

$$Q_{nb}^{e} = \varepsilon A\,\sigma T^4$$

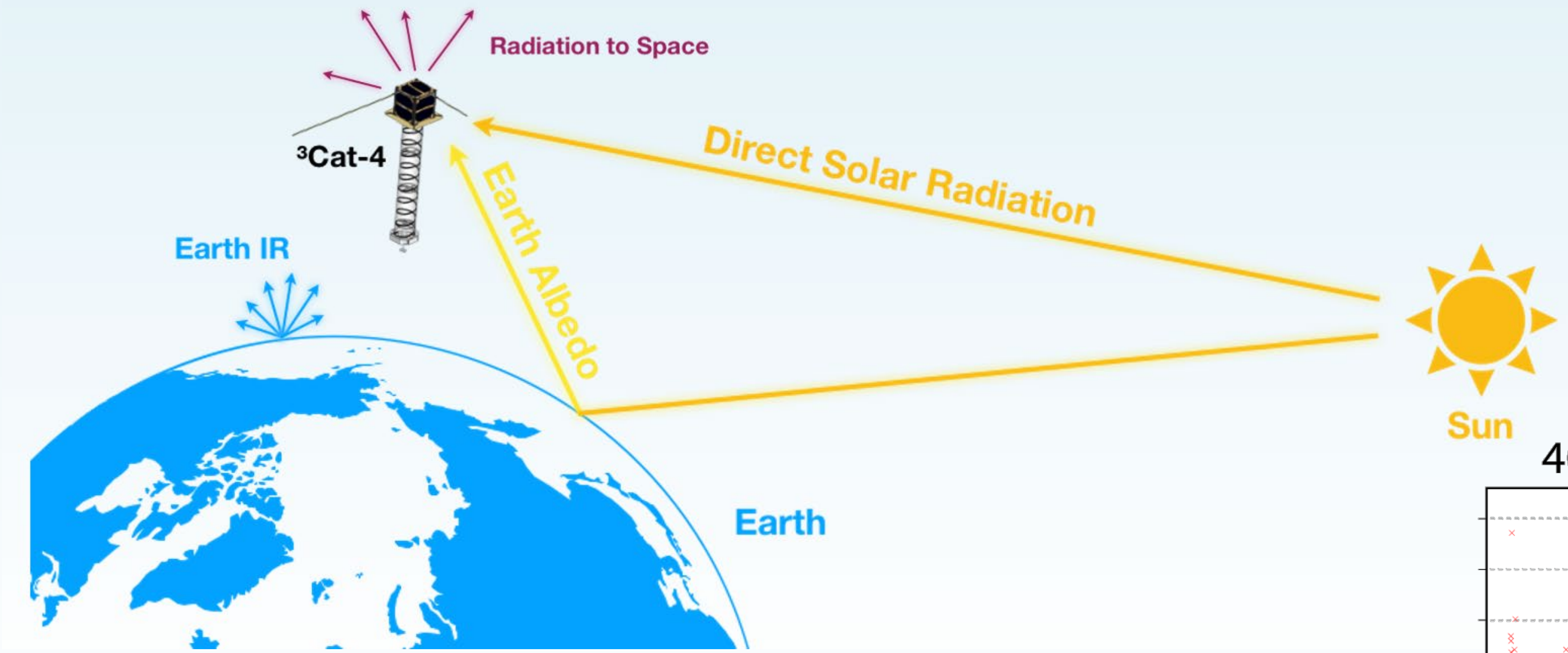
Q_{nb}^{e} : Radiative heat emitted by a non-black surface of area A.

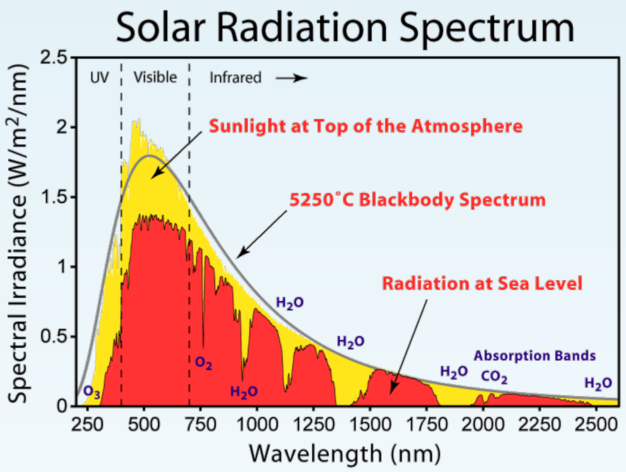
ε : Emissivity of the surface.

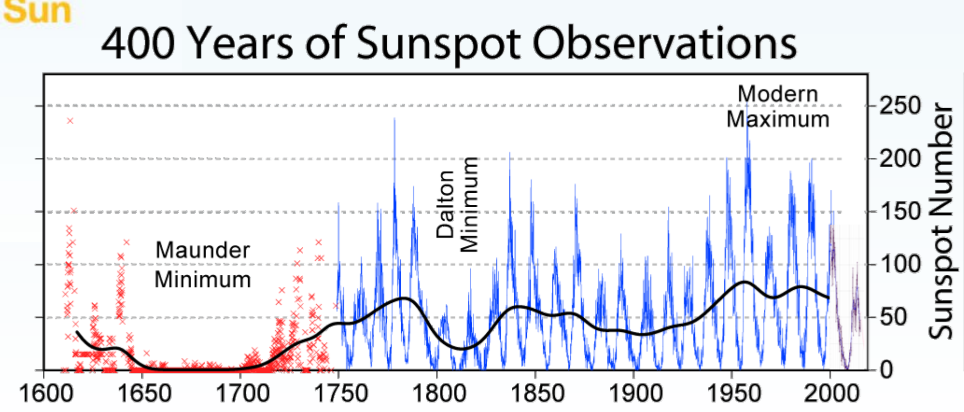
σ : Stefan-Boltzmann constant ($\sigma = 5.6705 \times 10^{-8}$ W/m^2/K^4).

2.3. TCS: Description of the Problem (iii)

→ Space thermal environment







2.3. TCS: Description of the Problem (iv)

→ Transient problem

- Allows to consider the ***heat storage*** in the spacecraft components.

Thermal energy balance equation (from 1st law of thermodynamics):

$$\rho\, c_p \frac{\partial T}{\partial t}\, dV = Q_{in} - Q_{out} + P_{int}$$

$Q_{in} - Q_{out}$: In- and outgoing heat flows.

P_{int} : Internal heat sources (e.g. heaters, electronics, etc.).

$\rho\, c_p \frac{\partial T}{\partial t}\, dV$: models the *time domain*.

The ***density*** ρ (kg/m^3) and ***specific heat capacity*** c_p (J/kg/K) influence how much **heat** is ***stored or delivered*** **by a certain material**.

→ Heat balance

- Absorbed

  P_{direct} = Direct solar $\cdot S_{illuminated} \cdot \alpha_s$ [W/m^2]

  P_{albedo}= Albedo $\cdot S_{illuminated} \cdot \alpha_s$ [W/m^2]

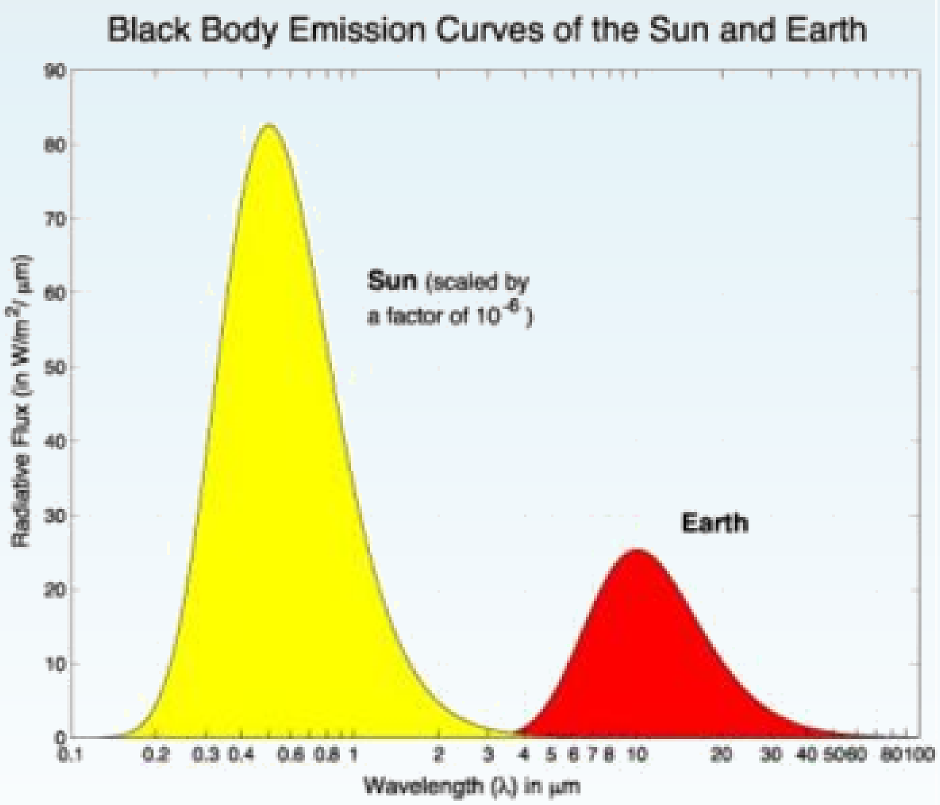
  $P_{earthshine}$=Earthshine $\cdot S_{illuminated} \cdot \varepsilon$ [W/m^2]

  $P_{dissipated}$=Power [W]

- Emitted

  $P_{emitted} = S_{total} \cdot \varepsilon \cdot T^4 \cdot \sigma$

- Absorptivity and emissivity examples
  - White paint: α=0.15, ε=0.9
  - Black paint: α=0.9, ε=0.85
  - Aluminum: α=0.15, ε=0.05
  - Gold: α=0.25, ε=0.04
  - Solar cells (Si): α=0.75, ε=0.82
  - Solar cells (AsGa): α=0.88, ε=0.80



2.3. TCS – Requirements (i)

[3]Cat-4 requirements affecting the thermal-design:

- **TCS-FUNC-001**:
  The TCS shall ensure that each hardware component works in its operational temperature range during all mission phases (until the end of the operating lifetime).

- **TCS-FUNC-003**:
  The TCS shall control the spacecraft temperature using passive and active mechanisms.

. . .

- **TCS-VER-006**
  The satellite acceptance margin shall be 5 °C.

- **TCS-VER-012**
  The satellite qualification margin shall be 5 °C.

- **TCS-VER-013**
  An uncertainty margin of 10 °C shall be applied to predicted temperatures.

2.3. TCS – Requirements (ii)

Thermal Margins and Design Temperatures as defined in [ECSS-E-ST-31C]:

→ **Thermal Uncertainty Margin:** ±10°C

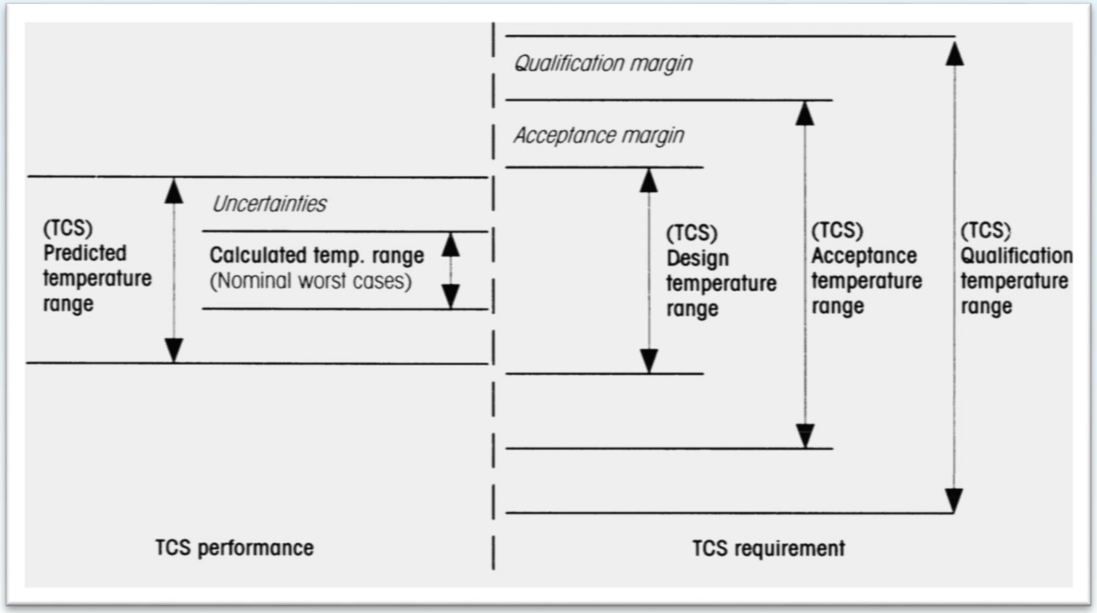
- **Margin of safety** applied to all calculated temperatures in order to account for inaccurate physical, environmental and modeling parameters.

→ **Acceptance Thermal Margin:** ±5°C

- **Contingency** to account for unpredictable TCS-related events.

→ **Qualification Thermal Margin:** ±5°C

- **Contingency** to account for unexpected events.



Temperature definitions for the TCS (Figure 3-1 in [ECSS-E-ST-31C]).

2.3. TCS – Requirements (iii)

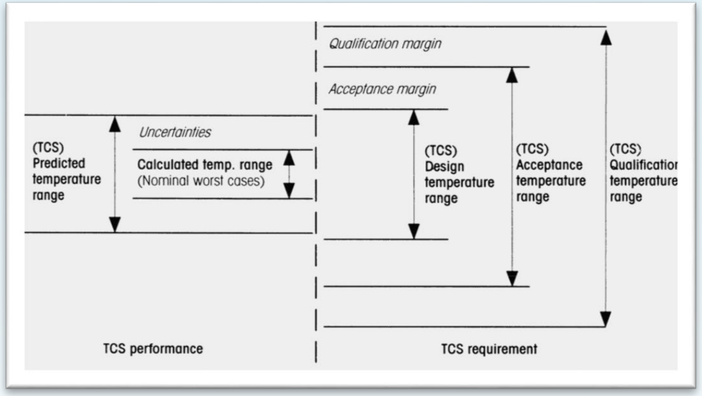
Thermal Margins and Design Temperatures as defined in [ECSS-E-ST-31C]:

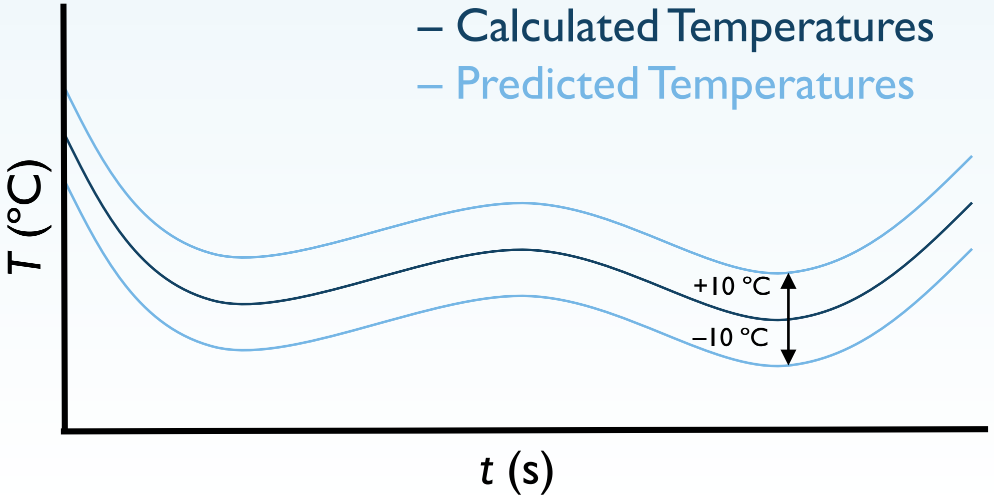
Table 1: Qualification temperature range of all satellite subsystems, in operating mode.

Subsystem	Qualification temperature range (ºC)	
	Min	Max
ZADS	**-20**	**60**
ZADS (ISIS)	-20	60
COMMS/AOCS	**-25**	**75**
COMMS	-40	85
AOCS	-25	75
OBC	**-40**	**85**
OBC (GomSpace)	-40	85
EPS	**-5**	**45**
EPS board (GomSpace)	-40	85
EPS battery cells (GomSpace)	-5	45
INTERFACE	**-40**	**85**
Interface board	-40	85
Payload (FMP)	**-20**	**75**
Mainboard	-20	75
Daughterboard	-20	85
NADS	**-40**	**85**
NADS Mainboard	-40	85
Gravity boom	-73	121
*L-Band Helix Antenna**	*n/a*	*121*
Fabric sheath (Precision Coating)	*-73*	*288*
*Counterweight***	*-200*	*260*
Upper Solar Panel (SP +Z)	**-40**	**85**
Up-looking GPS antenna	-40	85
Solar Cell	n/a	150
Photodiode	-40	125
Temperature sensor	-55	125
Lateral Solar Panels (SPs ±X and ±Y)	**-40**	**125**
Solar Cell	n/a	150
Photodiode	-40	125
Temperature sensor	-55	125
Operating mode		

Table 2: Acceptance and Design temperature ranges of all satellite subsystems, in operating mode.

Subsystem	Acceptance temperature range (ºC)		**Design temperature range (ºC)**	
	Min	Max	Min	Max
ZADS	**-15**	**55**	**-10**	**50**
ZADS (ISIS)	-15	55	-10	50
COMMS/AOCS	**-20**	**70**	**-15**	**65**
COMMS	-35	80	-30	75
AOCS	-20	70	-15	65
OBC	**-35**	**80**	**-30**	**75**
OBC (GomSpace)	-35	80	-30	75
EPS	**0**	**40**	**5**	**35**
EPS board (GomSpace)	-35	80	-30	75
EPS battery cells (GomSpace)	0	40	5	35
INTERFACE	**-35**	**80**	**-30**	**75**
Interface board	-35	80	-30	75
Payload (FMP)	**-15**	**70**	**-10**	**65**
Mainboard	-15	70	-10	65
Daughterboard	-15	80	-10	75
NADS	**-35**	**80**	**-30**	**75**
NADS Mainboard	-35	80	-30	75
Gravity boom	-68	116	-63	111
*L-Band Helix Antenna**	*n/a*	*116*	*n/a*	*111*
Fabric sheath (Precision Coating)	*-68*	*283*	*-63*	*278*
*Counterweight***	*-195*	*255*	*-190*	*250*
Upper Solar Panel (SP +Z)	**-35**	**80**	**-30**	**75**
Up-looking GPS antenna	-35	80	-30	75
Solar Cell	n/a	145	n/a	140
Photodiode	-35	120	-30	115
Temperature sensor	-50	120	-45	115
Lateral Solar Panels (SPs ±X and ±Y)	**-35**	**120**	**-30**	**115**
Solar Cell	n/a	145	n/a	140
Photodiode	-35	120	-30	115
Temperature sensor	-50	120	-45	115
Operating mode				





2.3. TCS – Thermal Control Methods

→ Thermal Control Methods:

- Thermal Insulation and Coating
  - Multi-layer Insulation (MIL)
  - **Surface coating**
- Passive Thermal Straps
- …

- Heaters
  - Electrical resistance (Joule effect)
  - **EPS module integrated heater**
- Thermal Switches
- …

2.3. TCS – Design Approach

Dimensioning using a **worst case approach**.

Mainly based in **passive thermal control**.

The **heater** available in the EPS will only be used after exploring all possible (and reasonable) passive mechanisms.

→ Design **Process**:

Isothermal Analyses → Radiation (only) Analyses → Thermal Model Analysis

Isothermal Analyses
- First identification of an adequate outer coating/painting.

Radiation (only) Analyses
- Gain knowledge on the satellite internal thermal behaviour.
- Create and validate a "base" to develop more accurate models.

Thermal Model Analysis
- Model all heat transfer modes.
- Validate the TCS requirements.
- Propose (if needed) thermal design and thermal model improvements.

Used software:

MATLAB, PrincetonSATELLITE SYSTEMS | MATLAB, C&R TECHNOLOGIES® Thermal Desktop and SINDA/FLUINT | C&R TECHNOLOGIES® Thermal Desktop and SINDA/FLUINT

2.3. TCS: Worst Hot and Cold Case Definition

IEEC UPC

→ External Heating Environment

- Satellite launched from the ISS

Heating Environment	Solar Flux (W/m²)	Earth Albedo factor	Earth IR (W/m²)	Orbit β angle (º)
Hot Case	1428	0.4	254	75.08
Cold Case	1316	0.2	209	0

→ Satellite Internal Heat Dissipation and Attitude

Satellite Operating Mode	Mean Power Consumption (mW)	Attitude state in which can occur	NADS configuration (stowed / deployed)
Commissioning phase			
Standby (Sb)	0	RR	Stowed
Released (R)	454	RR	Stowed
Pre-detumbling (PD)	682	RR	Stowed
Detumbling (D)	842	RR	Stowed
Detumbled (Dd)	912	RR, NP, ZP	Stowed
Operational phase			
Sun Safe (SS)	912	NP, ZP	Deployed
Survival (S)	1030	NP, ZP	Deployed
Nominal (N)	1110	NP, ZP	Deployed
Satellite Off (OFF)	0	NP, ZP	Deployed

NP: Nadir Pointing
RR: Random Rotation
ZP: Zenith Pointing

Overall hot and cold worst cases

From a thermal point of view,
RR assumed to be less critical than NP and ZP.

2.3. TCS: Isothermal Analyses

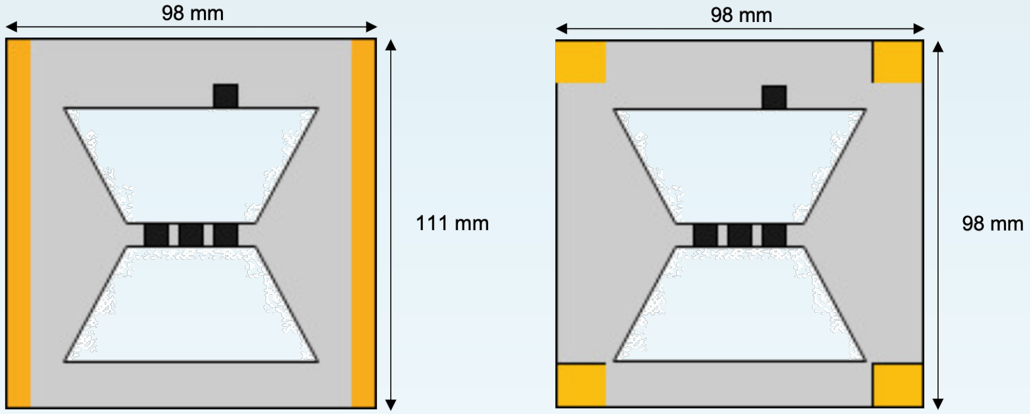
→ Isothermal Cube Model Analysis

Candidate coatings/paintings for the outer faces of the spacecraft.

Material	Absorptivity (α)	Emissivity (ε)	α/ε
Black Paint	0.96	0.87	1.10
Gold (ENIG)	0.25	0.04	6.25
Tin (HASL)	0.15	0.05	3.00
FR-4	0.12	0.94	0.13

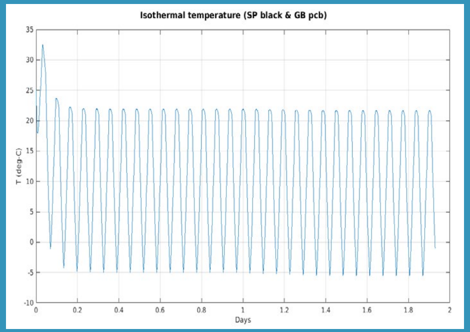
Properties of structure and board materials.

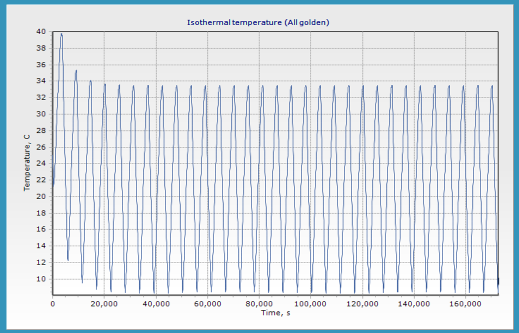
Component	Specific heat (J/kg/K)	Mass (%)
Structure (Aluminum)	900	10.41
Boards (FR-4)	1200	89.59



Lateral (left) and top (right) face layouts.

Simulations: MATLAB/Princeton + Thermal Desktop verification





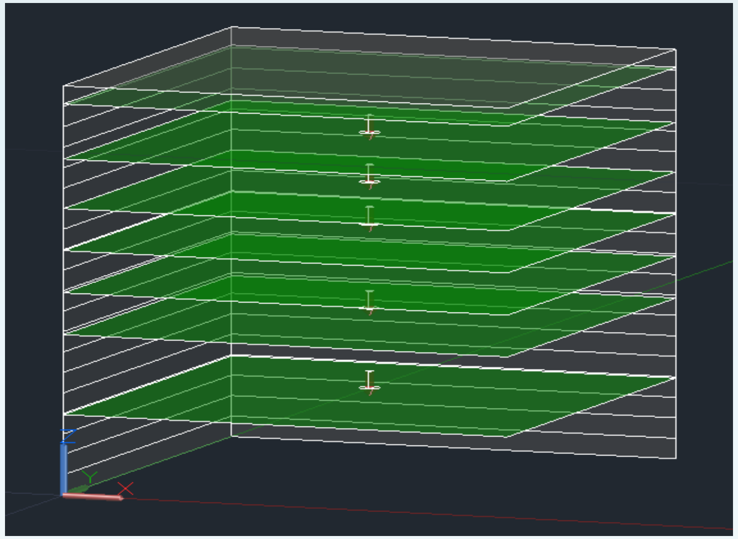
Conclusions:

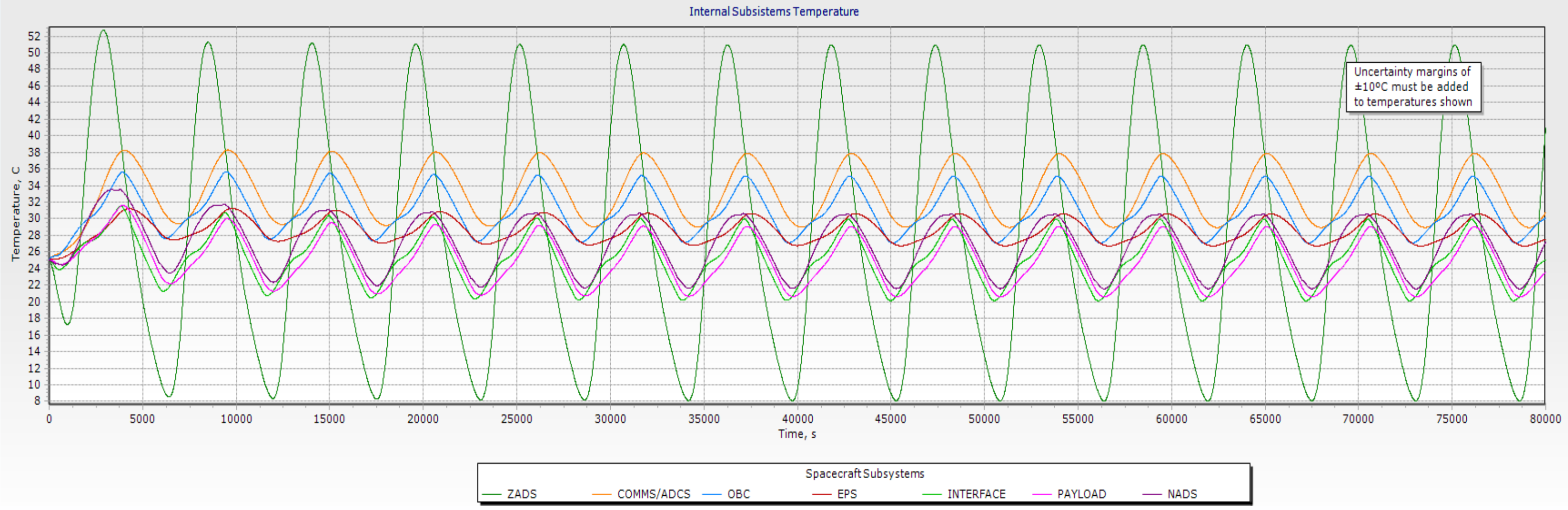
- **Golden coating** (ENIG surface finish) is the best option
- **Active thermal control needed** (e.g. heater)
- More accurate model needed (subsystem level).

2.3. TCS: Radiation Analysis with Thermal Desktop

→ Radiation Heat transfer Analysis

- Entirely in Thermal Desktop
- Objectives:
  - Gain knowledge on the satellite internal thermal behaviour.
  - Create and validate a "base" to develop more accurate models.





Subsystem	Predicted temperature range (ºC)		Operational design temperature range (ºC)	
	Min	Max	Min	Max
ZADS	+8.05	+50.93	–10	+50
COMMS/ADCS	+28.94	+37.85	–15	+65
OBC	+27.07	+35.31	–30	+75
EPS	+26.71	+30.60	+5	+35
INTERFACE	+21.12	+29.96	–30	+75
Payload (FMP)	+20.60	+29.05	–10	+65
NADS	+21.56	+30.62	–30	+75
Upper Solar Panel (+Z)	–25.18	+84.27	–30	+75
Lateral Solar Panels (±X and ±Y)	>–25	<+90	–30	+115

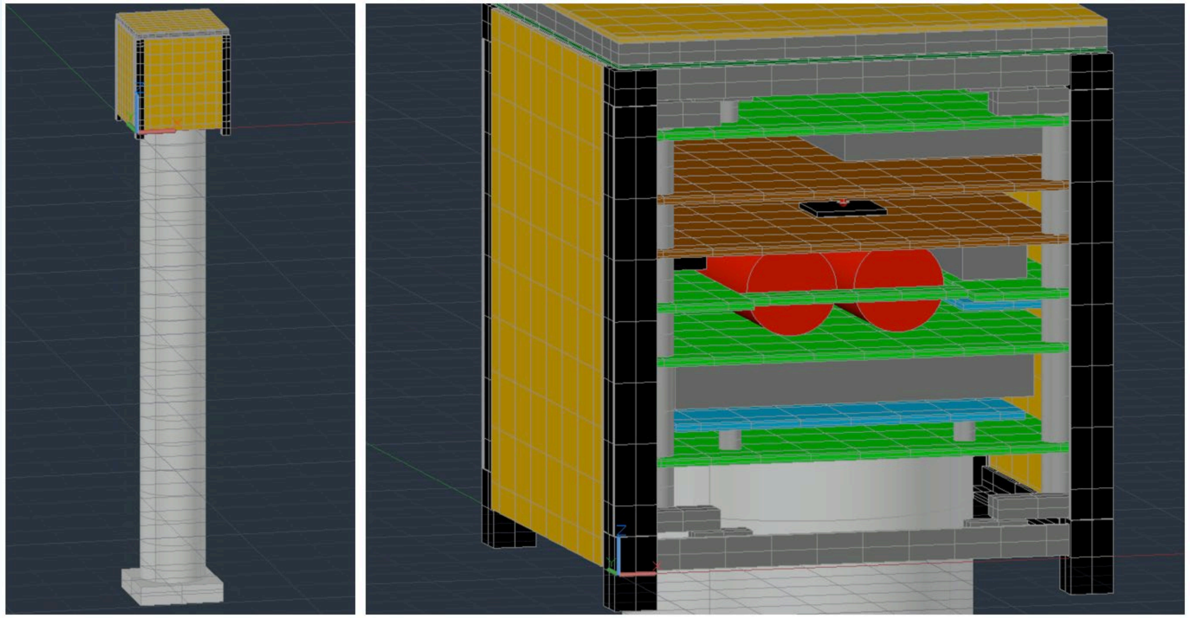
2.3. TCS: Complete Thermal Model - Simulation Analysis

→ Analysis Approach

- Verify the **operational temperature range is respected** by all subsystems during the mission.
- **Worst case** approach.

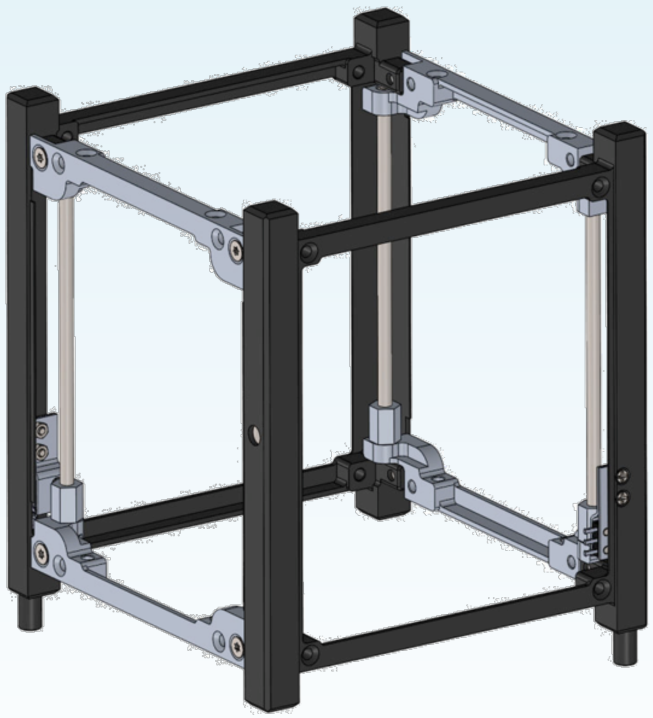
→ [3]Cat-4 Thermal Model

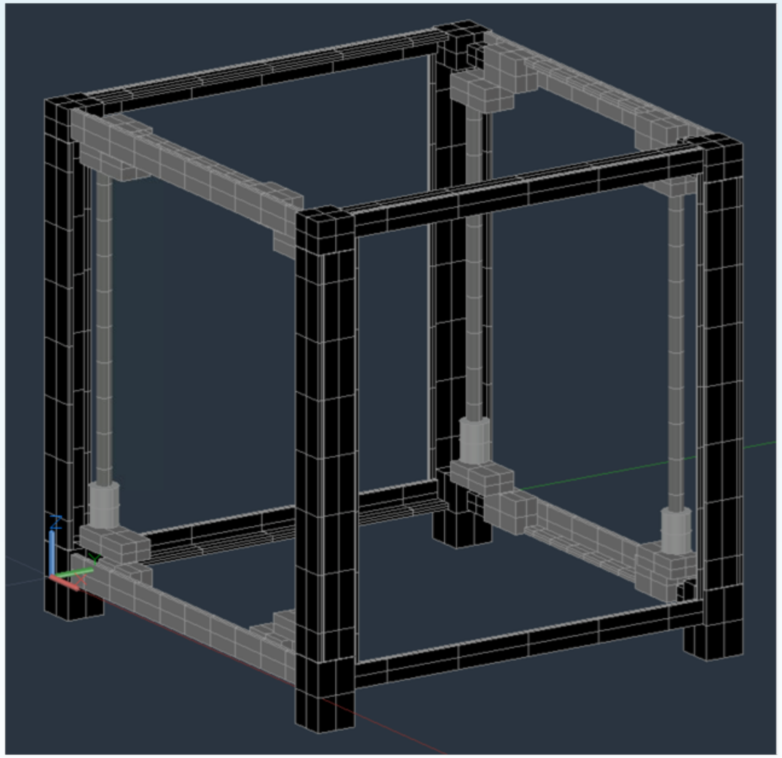
- Modelling of the structure and external faces
- Modelling of the internal PCBs
- Modelling of the CubeSat subsystems



Thermal model of the spacecraft in deployed configuration (left), and view of the internal subsystems (right).

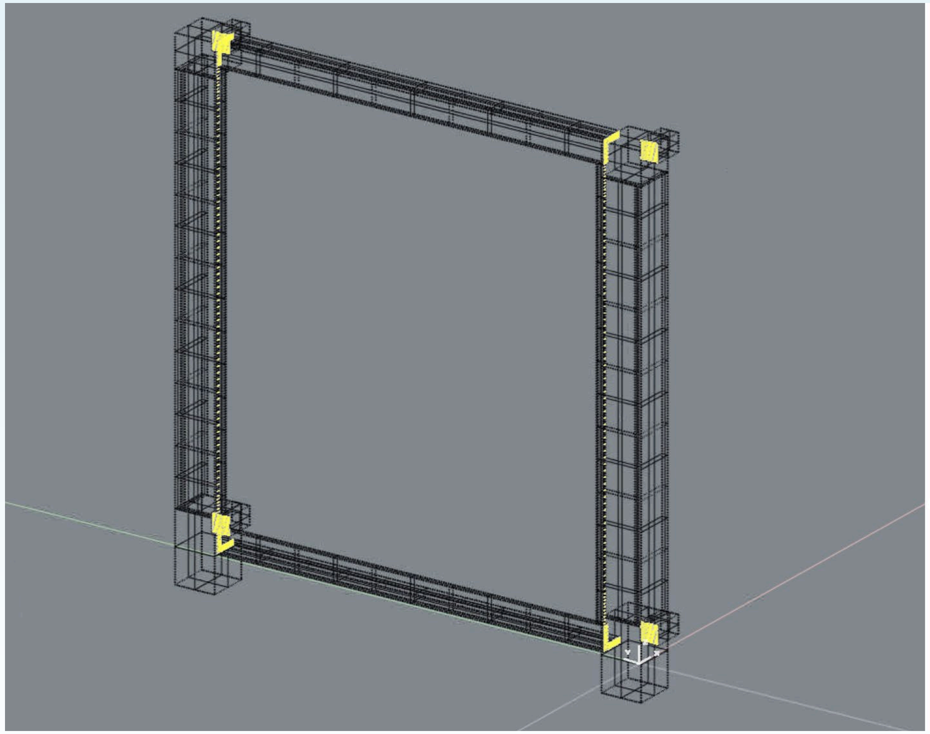
→ **CubeSat structure**

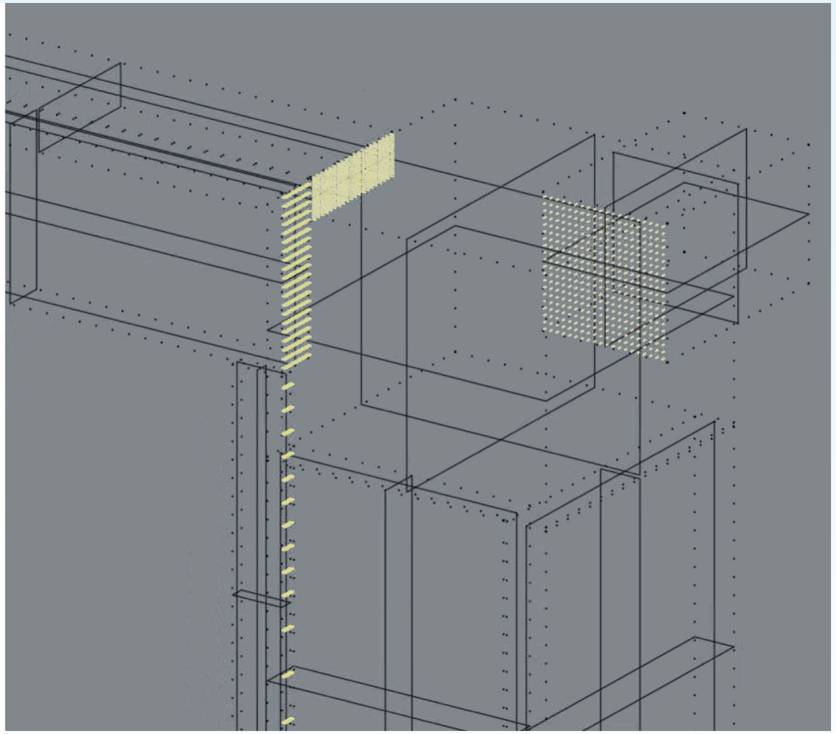




Main structure CAD model (left) and thermal model (right)

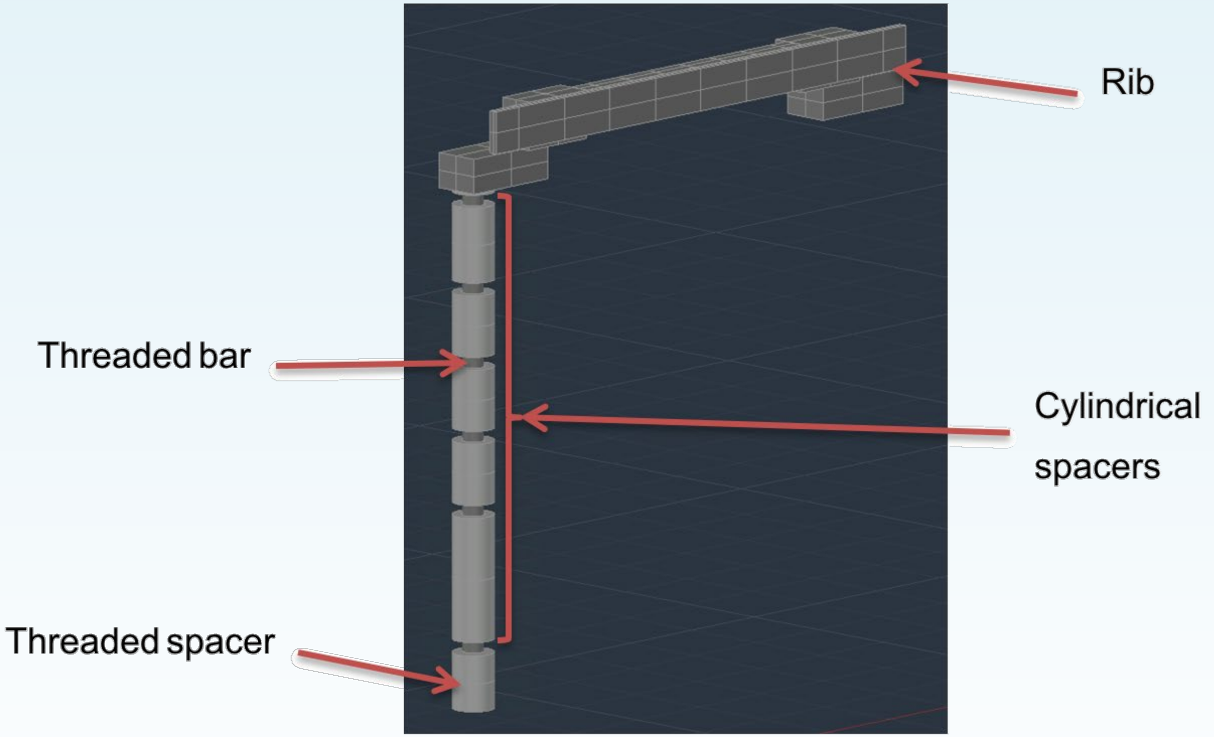
→ CubeSat structure – Side frames

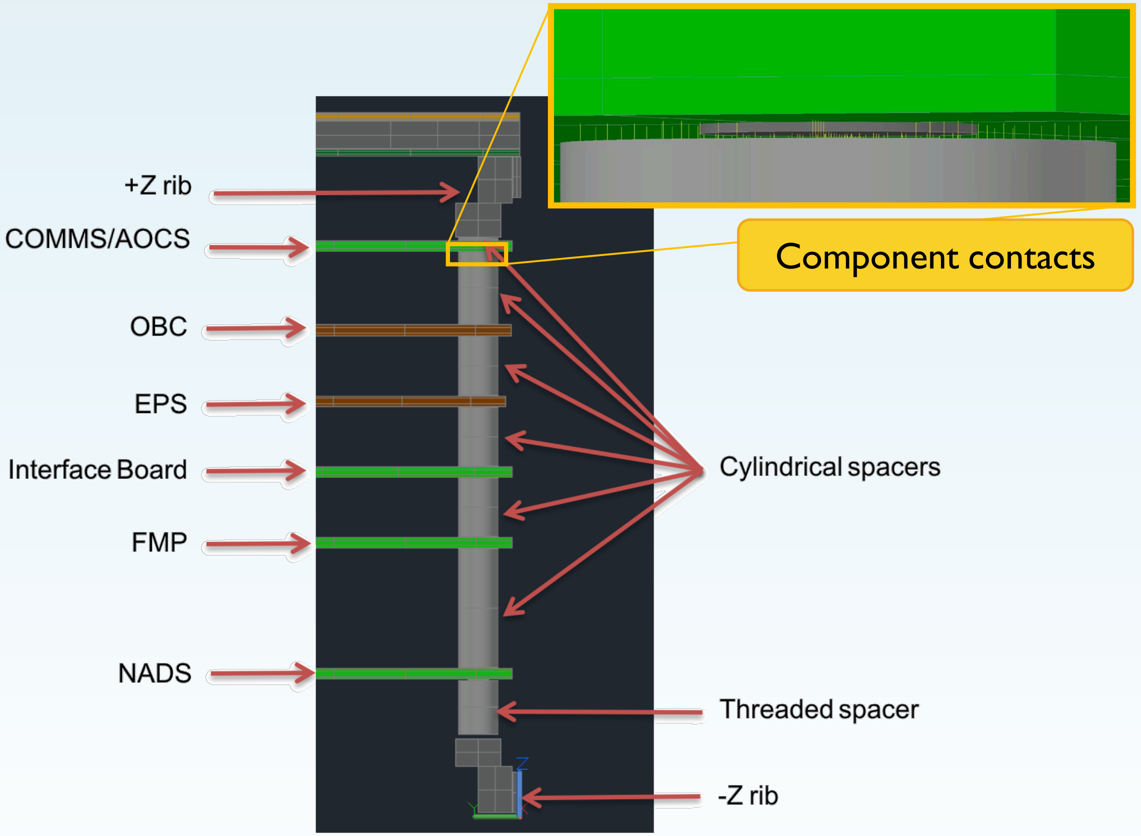




Side Frame contacts amongst some of the internal bricks

→ CubeSat structure



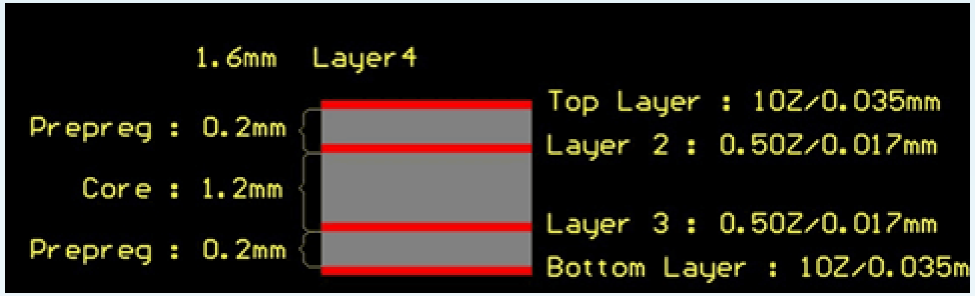


Connections between ribs, threaded bars, spacers and PCBs

→ Modelling of the internal PCBs

PCB	*x*-length (mm)	*y*-length (mm)	Thickness (mm)	# layers	Manufacturer
ZADS	98.00	98.00	1.00	4	ISIS
COMMS/AOCS					
Mainboard	90.20	95.90	1.60	6	Seeed Studio
Daughterboard	*68.00*	*41.00*	*1.60*	*2*	*Seeed Studio*
OBC	90.30	95.40	1.60	6	GOMspace
EPS	89.29	92.93	1.60	6	GOMspace
INTERFACE					
Mainboard	94.20	95.90	1.60	4	Seeed Studio
Daughterboard	*20.00*	*63.00*	*1.60*	*2*	*Seeed Studio*
Payload (FMP)					
Acquisition Board	90.20	95.90	1.60	4	Seeed Studio
*Conditioning Board**	*64.00*	*71.00*	*1.60*	*4*	*Seeed Studio*
NADS					
Mainboard	90.20	95.90	1.60	4	Seeed Studio
Daughterboard	*70.00*	*80.00*	*1.60*	*4*	*Seeed Studio*
Solar Panels					
Upper SP (+Z)	98.00	98.00	1.00	4	Seeed Studio
Lateral SP (±X & ±Y)	98.00	82.80	1.00	2	Seeed Studio

* PCB modelled different. See specific subsystem modelling details in Section 6.3.4.

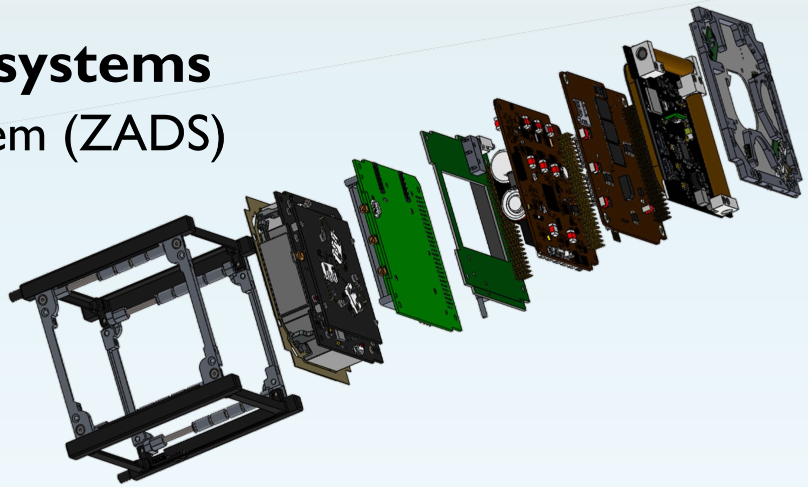


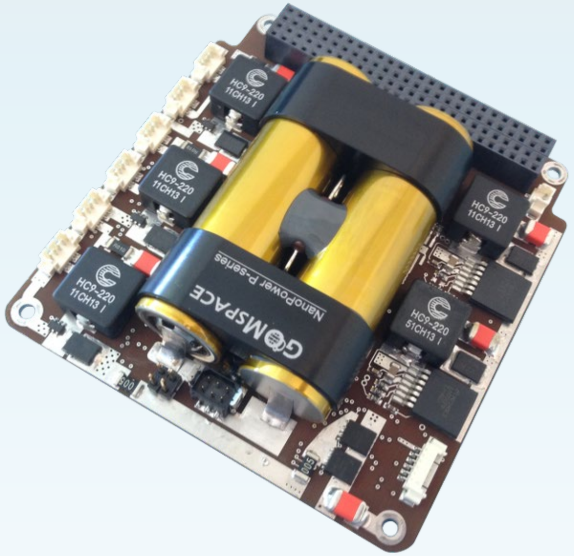
Seeed Studio 1.6 mm, 4 layers PCB

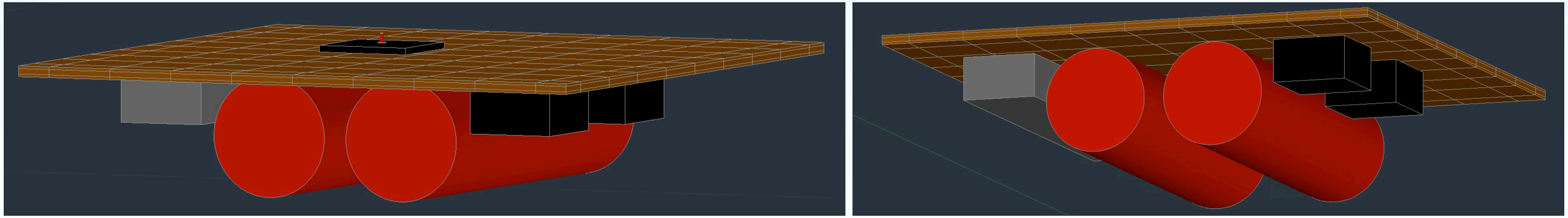
Total thickness [mm]	# layers	ρ [kg/m^3]	c_p [J/kg/K]	k in-plane [W/m/K]	k cross-plane [W/m/K]
Seeed Studio PCBs					
1.00	4	2562.25	932.749	38.2264	0.3201
1.60	2	2194.67	1061.17	17.4587	0.3027
1.60	4	2329.06	1009.52	25.0516	0.3088
1.60	6	2458.19	965.205	32.3475	0.3150
ISIS components PCBs					
1.00	4	2562.25	932.749	38.2264	0.3201
GOMspace components PCBs					
1.60	6	2329.06	1009.52	25.0516	0.3088

→ **Modelling of the CubeSat Subsystems**

- Zenit Antenna Deployment Subsystem (ZADS)
- COMMS
- OBC
- EPS
- Interface Board
- Flexible Microwave Payload (FMP)
- Nadir Antenna Deployment System (NADS)



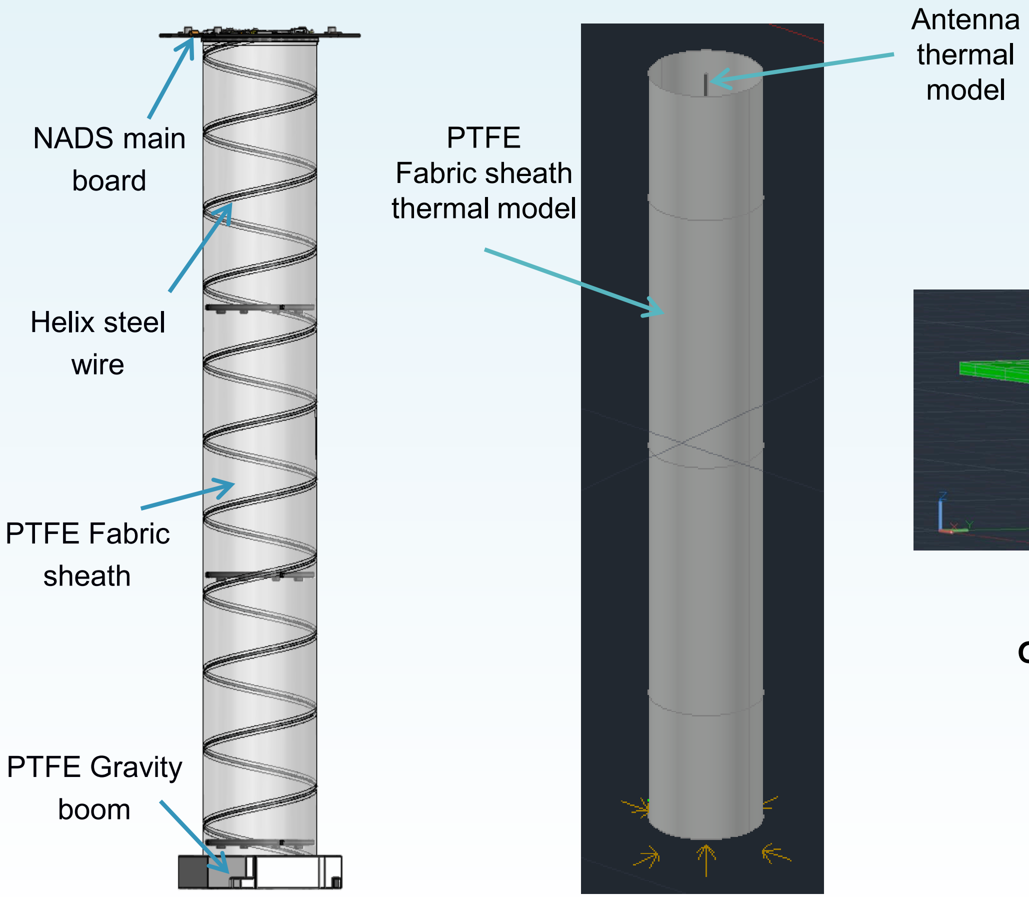


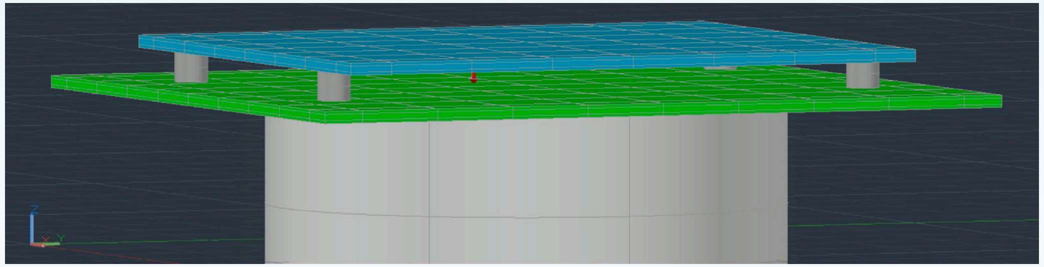


EPS subsystem thermal model. On the upper side the *EPS micro controller* has been modelled with its corresponding *heat dissipation* in accordance with the *Power Budget*. The same applies for the DC/DCs present in the lower side.

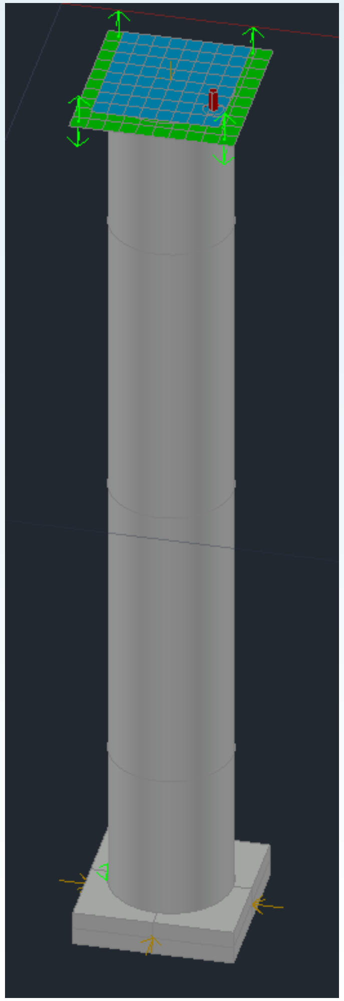
2.3. TCS: Complete Thermal Model-CubeSat Subsystems (ii)

→ Nadir Antenna Deployment Subsystem (NADS)



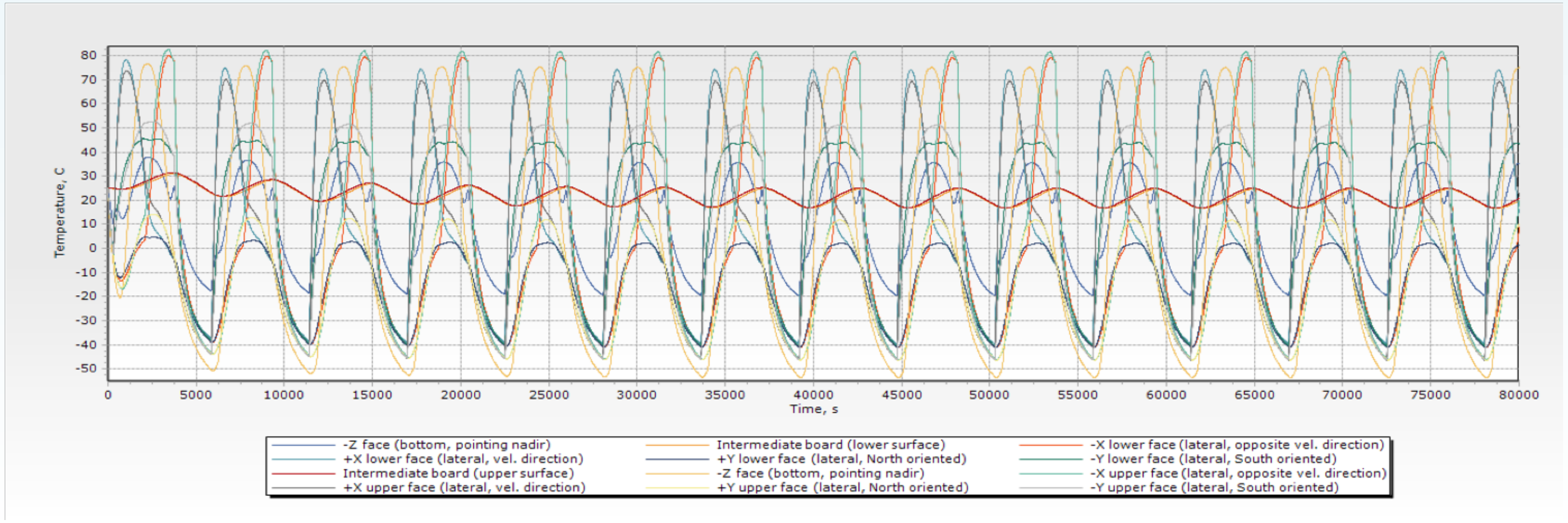


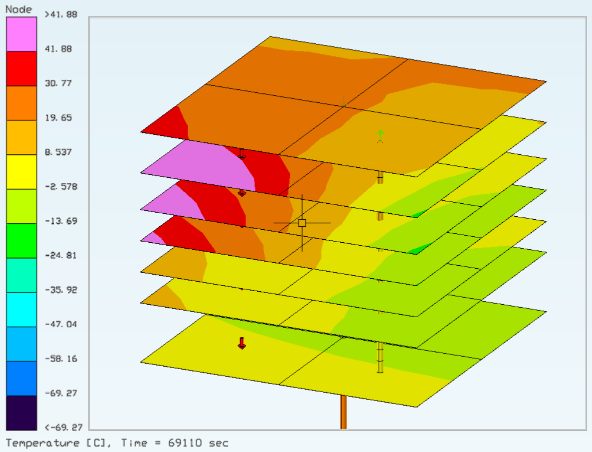
NADS thermal model of the mainboard, daughterboard and spacers between them.

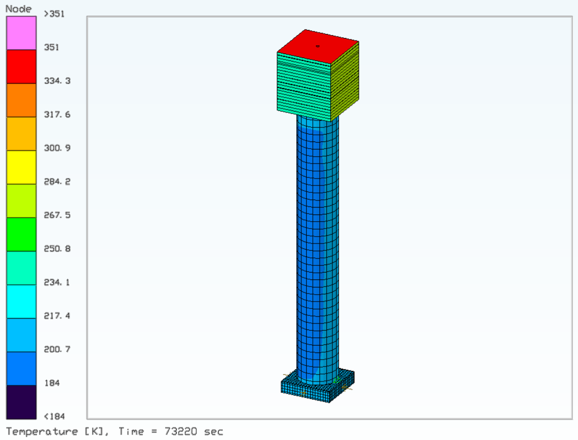


→ **Analysis Results** – Worst Cases

- Hot Case – Nominal Mode, Deployed, and Nadir Pointing
- Cold Case – Sun Safe Mode, Deployed, and Nadir Pointing (+ EPS heaters)
- Cold Case – Sun Safe Mode, Stowed, and Nadir Pointing (+ EPS heaters)







2.3. TCS: Complete Thermal Model - Simulation Results (ii)

→ **Analysis Results – Hot Case** – Nominal Mode, Deployed, and Nadir Pointing

Subsystem	Calculated temperatures (ºC)		Predicted temperatures (ºC)		Design operational temperature range (ºC)	
	Min	Max	Min	Max	Min	Max
Operational Subsystems						
COMMS/AOCS	25.49	41.46	15.49	51.46	-15	65
OBC	30.81	38.71	20.81	48.71	-30	75
EPS board	32.77	34.86	22.77	44.86	-30	75
EPS Batteries (Charge)	35.04	37.13	25.04	**47.13**	5	35
EPS Batteries (Discharge)	35.04	37.13	25.04	**47.13**	-10	50
Interface Board	32.19	22.19	22.19	32.19	-30	75
FMP Mainboard	30.39	20.39	20.39	30.39	-10	65
FMP Daughterboard	33.16	23.16	23.16	33.16	-10	75
NADS Mainboard	25.37	43.57	15.37	23.57	-30	75
Upper SP (+Z)	19.26	36.32	9.26	46.32	-30	115
Upper SP (+Z) Antenna	19.26	36.32	9.26	46.32	-30	75
Lateral SP (±X & ±Y)	16.89	62.12	6.89	72.12	-30	115
Non-operational Subsystems						
ZADS	21.92	41.46	11.92	51.46	-10	50
NADS Antenna Wire	-30.82	34.63	-40.82	44.63	*n/a*	*111*
NADS Sheath	-71.64	8.81	-81.64	18.81	*-63*	*278*
NADS Counterweight	-51.72	-34.22	-61.72	-24.22	*-190*	*250*

2.3. TCS: Complete Thermal Model - Simulation Results (iii)

→ **Analysis Results – Cold Case** – Sun Safe Mode, Deployed (left) & Stowed (right), and Nadir Pointing

Subsystem	Calculated temperatures (ºC)		Predicted temperatures (ºC)		Design operational temperature range (ºC)	
	Min	Max	Min	Max	Min	Max
Operational Subsystems						
COMMS/AOCS	-19.72	14.21	**-29.72**	24.21	-15	65
OBC	-13.05	10.23	-23.05	20.23	-30	75
EPS board	-10.24	-8.25	-20.24	1.75	-30	75
EPS Batteries (Charge)	-7.70	6.55	**-17.70**	16.55	5	35
EPS Batteries (Discharge)	-7.70	6.55	**-17.70**	16.55	-10	50
Interface Board	-12.17	8.10	-22.17	18.10	-30	75
NADS Mainboard	-20.97	13.09	**-30.97**	23.09	-30	75
Upper SP (+Z)	-25.94	27.63	**-35.94**	37.63	-30	115
Lateral SP (±X & ±Y)	-24.63	34.23	**-34.63**	44.23	-30	115
Non-operational Subsystems						
ZADS	-23.88	20.48	-33.88	30.48	-10	50
FMP Mainboard	-14.76	9.16	-24.76	19.16	-10	65
FMP Daughterboard	-6.51	-1.11	-16.51	8.89	-10	75
NADS Antenna Wire	-52.68	6.88	-62.68	16.88	*n/a*	*111*
NADS Sheath	-93.10	-8.01	-103.10	1.99	*-63*	*278*
NADS Counterweight	-68.73	-52.29	-78.73	-42.29	*-190*	*250*
Upper SP (+Z) Antenna	-25.94	27.63	-35.94	37.63	-30	75

Subsystem	Calculated temperatures (ºC)		Predicted temperatures (ºC)		Design operational temperature range (ºC)	
	Min	Max	Min	Max	Min	Max
Operational Subsystems						
COMMS/AOCS	-19.21	13.82	**-29.21**	23.82	-15	65
OBC	-12.75	9.75	-22.75	19.75	-30	75
EPS board	-10.10	8.00	-20.10	18.00	-30	75
EPS Batteries (Charge)	-7.53	6.11	**-17.53**	16.11	5	35
EPS Batteries (Discharge)	-7.53	6.11	**-17.53**	16.11	-10	50
Interface Board	-11.85	7.32	-21.85	17.32	-30	75
NADS Mainboard	-20.00	11.82	**-30.00**	21.82	-30	75
Upper SP (+Z)	-25.54	27.23	**-35.54**	37.23	-30	115
Lateral SP (±X & ±Y)	-23.96	33.15	**-33.96**	43.15	-30	115
Non-operational Subsystems						
ZADS	-23.35	20.00	-33.35	30.00	-10	50
FMP Mainboard	-14.23	8.15	-24.23	18.15	-10	65
FMP Daughterboard	-14.23	8.15	-24.23	18.15	-10	75
NADS Counterweight	-17.10	-23.12	-27.10	13.10	*-190*	*250*
Upper SP (+Z) Antenna	-25.54	27.23	-35.54	37.23	-30	75

2.3. TCS: Complete Thermal Model - Simulation Results (iv)

→ **Analysis Results – Cold Case** – Sun Safe Mode, Deployed (left) & Stowed (right), and Nadir Pointing with *heaters* in the EPS

Subsystem	Calculated temperatures (ºC)		Predicted temperatures (ºC)		Design operational temperature range (ºC)	
	Min	Max	Min	Max	Min	Max
Operational Subsystems						
COMMS/AOCS	-12.55	22.25	**-22.55**	32.25	-15	65
OBC	-3.14	19.46	-13.14	29.46	-30	75
EPS board	3.25	10.79	-6.75	20.79	-30	75
EPS Batteries (Charge)	15.13	17.64	**5.13**	27.64	5	35
EPS Batteries (Discharge)	15.13	17.64	5.13	27.64	-10	50
Interface Board	-0.72	17.82	-10.72	27.82	-30	75
NADS Mainboard	-14.08	19.95	-24.08	29.95	-30	75
Upper SP (+Z)	-19.96	34.33	**-29.96**	44.33	-30	115
Lateral SP (±X & ±Y)	-18.39	40.29	**-28.39**	50.29	-30	115
Non-operational Subsystems						
ZADS	-17.54	27.32	-27.54	37.32	-10	50
FMP Mainboard	-5.64	17.50	-15.64	27.50	-10	65
FMP Daughterboard	1.04	7.23	-8.86	17.23	-10	75
NADS Antenna Wire	-50.64	14.50	-60.64	24.50	*n/a*	*111*
NADS Sheath	-93.02	-4.37	-103.02	5.63	*-63*	*278*
NADS Counterweight	-62.73	-52.29	-72.73	-42.29	*-190*	*250*
Upper SP (+Z) Antenna	-19.96	34.33	-29.96	44.33	-30	75

Duty cycle of the heaters: 36.36 %

Subsystem	Calculated temperatures (ºC)		Predicted temperatures (ºC)		Design operational temperature range (ºC)	
	Min	Max	Min	Max	Min	Max
Operational Subsystems						
COMMS/AOCS	-11.94	22.00	**-21.94**	32.00	-15	65
OBC	-2.70	19.23	-12.70	29.23	-30	75
EPS board	3.5	18.11	-6.5	28.11	-30	75
EPS Batteries (Charge)	15.22	17.73	**5.22**	27.73	5	35
EPS Batteries (Discharge)	15.22	17.73	**5.22**	27.73	-10	50
Interface Board	-0.18	17.42	-10.18	27.42	-30	75
NADS Mainboard	-13.00	19.00	-23.00	29.00	-30	75
Upper SP (+Z)	-18.72	34.12	**-28.72**	44.12	-30	115
Lateral SP (±X & ±Y)	-15.13	38.73	**-25.13**	48.73	-30	115
Non-operational Subsystems						
ZADS	-16.83	27.00	-26.83	37.00	-10	50
FMP Mainboard	-4.96	16.83	-14.96	26.83	-10	65
FMP Daughterboard	-4.96	16.83	-14.96	26.83	-10	75
NADS Counterweight	-20.10	-12.82	-30.10	-2.82	*-190*	*250*
Upper SP (+Z) Antenna	-18.72	34.12	-28.72	44.12	-30	75

Duty cycle of the heaters: 27.78 %

2.3. TCS: Complete Thermal Model - Conclusions

→ Analysis Conclusions:

- Initial simpler models can be rapidly implemented and allow to take some initial key decisions.
- EPS **batteries** *are the* ***most critical component***.
  - In the **cold cases**, heaters may be required with a duty cycle of around a 30%.
  - In the **hot case**, the maximum temperature on *charge mode* may be exceeded.
- The ***EPS heater*** is able to warm up and bring to valid temperatures other subsystems that exceeded their minimum temperatures during the worst cold cases.
- The TCS is able to maintain the temperature of **all components within operational range** during the entire mission, **except for:**
  - the **batteries** of the EPS during the *worst hot case*, and
  - the **COMMS/AOCS** subsystems during the *worst cold case*.

→ Proposed Actions:

TCS design:

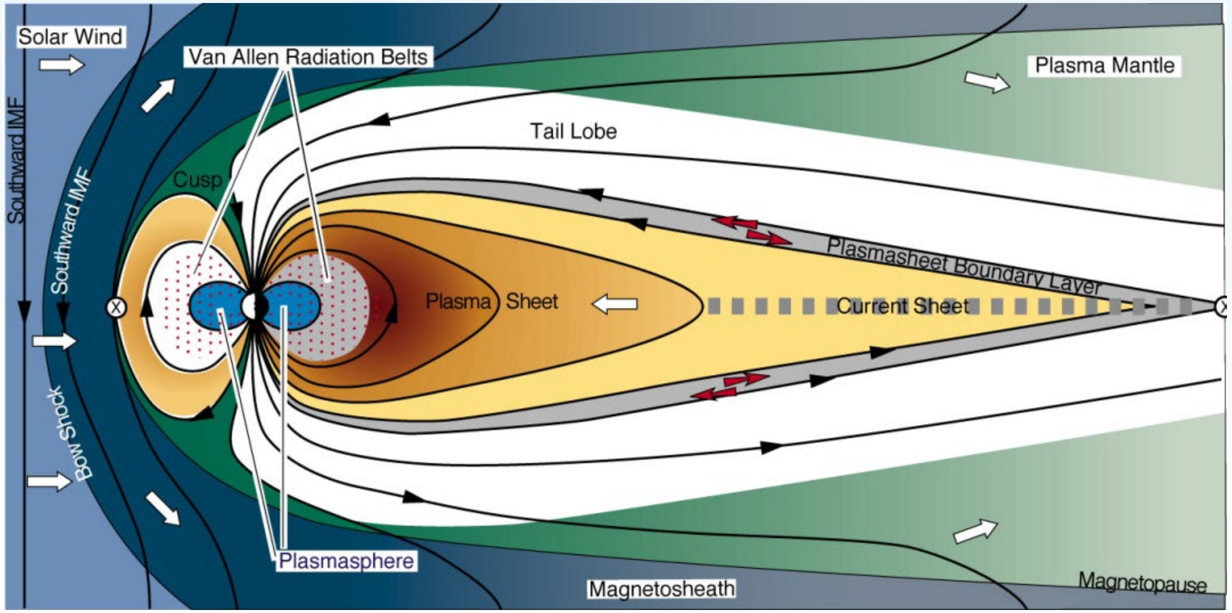
- Use of Passive Thermal Straps
- Internal differential colouring (z-axis)

Thermal Model:

- Better modelling of COMMS/AOCS
- Extremely pessimist situations?

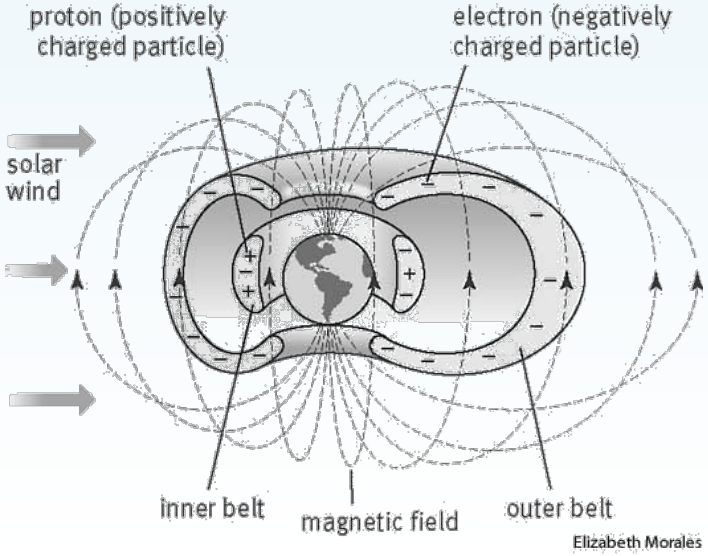
Solar Wind

- Solar Wind dominates space weather
- Consists of a flux of charged particles at 200-800 km/s
- Earth is protected by its own magnetic field that deflects it $\Rightarrow$ solar wind shapes it.
- Particles trapped in the Earth's magnetic field “go” to the Van Allen belts.
- Only observable on Earth when it is strong enough to produce boreal aurorae, geomagnetic storms or plasma tails in comets.



Van Allen Radiation Belts

- Contain energetic particles trapped in the Earth's magnetic field
- Inner belt (100-10000 km) has a larger concentration of protons
- Outter belt (13000-60000 km) consists mainly of electrons
- The effects caused by these particles are
  - degradation of electronics due to accumulated radiation dose
  - degradation of solar array performance
  - single event upsets (SEUs)
  - dielectric discharging



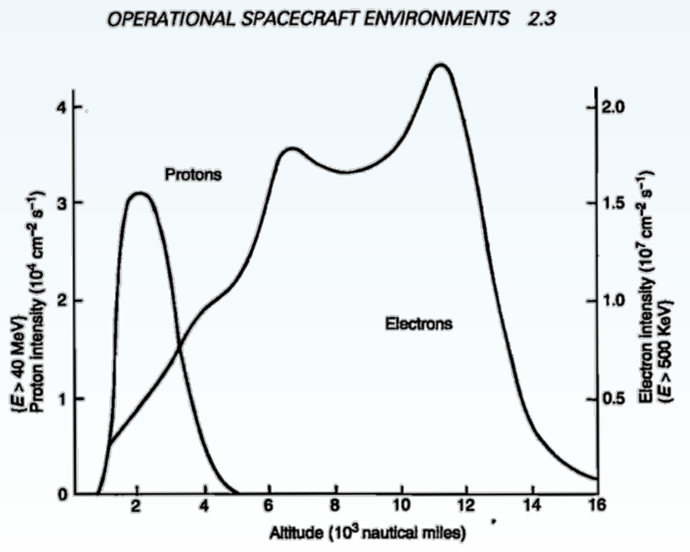
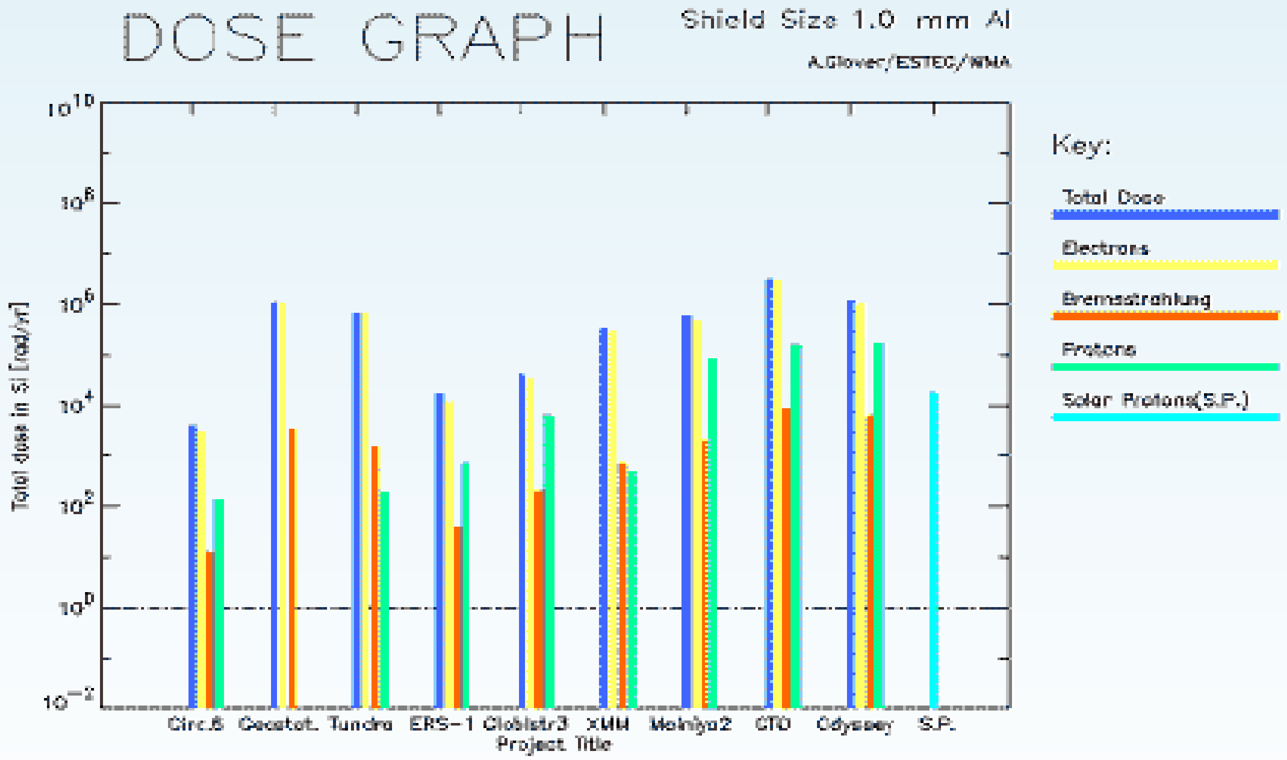


Figure 2.14 Van Allen radiation belts (idealized)

2.3. Radiation Analysis (iii)

Relative radiation level experienced in different orbits (from STMicroelectronics)

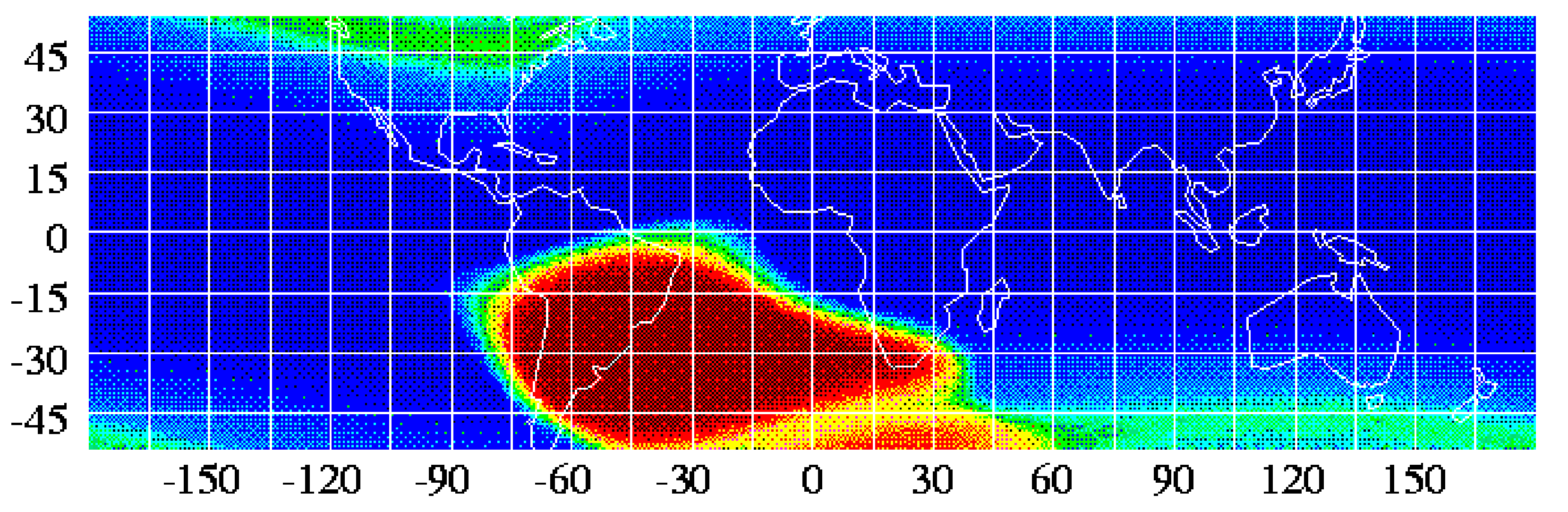


Calculation can be done using software tools such as:

- **SPENVIS (SPace ENVironment Information System)**
  https://www.spenvis.oma.be/

South Atlantic Anomaly: the "Bermuda triangle of the spacecrafts"

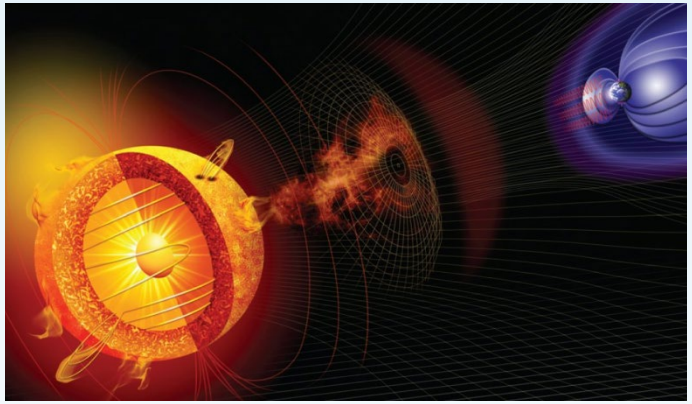
- Region where the inner Van Allen belt is closer to the Earth
- Exposes satellites flying below the belt to higher radiation doses, causing disruptions on systems.
- Caused by the non-concentrity of Earth's magnetic field.



2.3. Radiation Analysis (v)

Geomagnetic Storms

Disturbance of Earth's magnetosphere as a consequence of solar ions caused by disruption



Effects:

- Satellite systems: Particle damage, UV, Atmospheric drag
- Power Systems: Geomagnetically induced currents
- Navigation Systems: Changes in ionosphere
- Communication: Ionospheric irregularities

Single Event Effect

A Single Event Effect is caused by ions or electro-magnetic radiation striking a sensitive micro-electronic device.

- Single event upset (SEU): A change of state or transient
- Sigle event Latchup (SEL): Event causes loss of device funcionality
- Sigle event Burnout (SEB): Device destruction is caused due to a high current state in a power transistor.

2.4. EPS and Power Budget

2.4. EPS Design Considerations (i)

→ **System sizing**

- While operative, primary energy system should be able to
  - Feed all systems
  - Recharge batteries more energy than they will spend
- Batteries should be able to store more energy than which is going to be consumed during eclipse
- Need to know
  - Load power consumption and ON-OFF time
  - Systems power consumption and ON-OFF time
  - Battery capacity
  - Available power
  - Light and eclipse time
  - Subsystems efficiency
- Systems should be oversized because of degradation
- Consider worst case

→ **Required power**

- Required power at EOL (End Of Life) depends on:

$$P_{EOL} = \frac{P_{LOADS}}{\eta_{SD}} + \frac{P_e \cdot t_e}{t_s \cdot \eta_{BCR} \cdot \eta_{BDR}}$$

  - P_{LOADS}: Power required by worst case in sunlight [W]
  - P_e: Power required by worst case in shadow [W]
  - t_e: Eclipse period [s]
  - t_s: Sunlight period [s]
  - η_{BCR}: Battery Charger efficiency (~0,92)
  - η_{BDR}: Battery Discharger (regulators, buses…) efficiency (~0,9)
  - η_{SD}: Shunt dump efficiency

→ Solar array sizing

- Solar arrays must be sized depending on the required power at EOL:

$$P_{EOL} = S \cdot \cos\varphi \cdot \eta_{SC} \cdot F \cdot P_F \cdot A_{SA}$$

  - S = Solar intensity (~1400 W/m^2)
  - cosφ= Angle between Sun line and array normal
    - If we are calculating for more than one array and/or geometry is not planar, we should replace it by "Solar Panel Orientation Coefficient"
  - η_{SC} = EOL cell conversion efficiency **(beware! It degrades with temperature and radiation)**
  - F = Sum of loss factors (~0.75)
  - P_F=Packaging efficiency (~0.85): Part of solar arrays made by solar cells, taking into account void spaces, connections…
  - A_{SA}=Solar Array Surface

2.4. EPS Design Considerations (iv)

→ Solar panel orientation coefficient

- Defines how many solar panels are illuminated pondering
  - Illumination time (% of time under light and in shadow)
  - Incidence angle
  - Number of panels

- Example: Cubesat with all sides with solar arrays, rotating, with one axis fixed towards the Earth's magnetic field
  - Orbit 6 am – 6 pm (100% sun): 1,408 x 1U
  - Orbit 9 am – 9 pm (73% sun): 1,528 x 1U
  - Orbit 12 am – 12 pm (64% sun): 1,473 x 1U

2.4. EPS Design Considerations (v)

→ Battery sizing

- Battery capacity should be chosen according to:

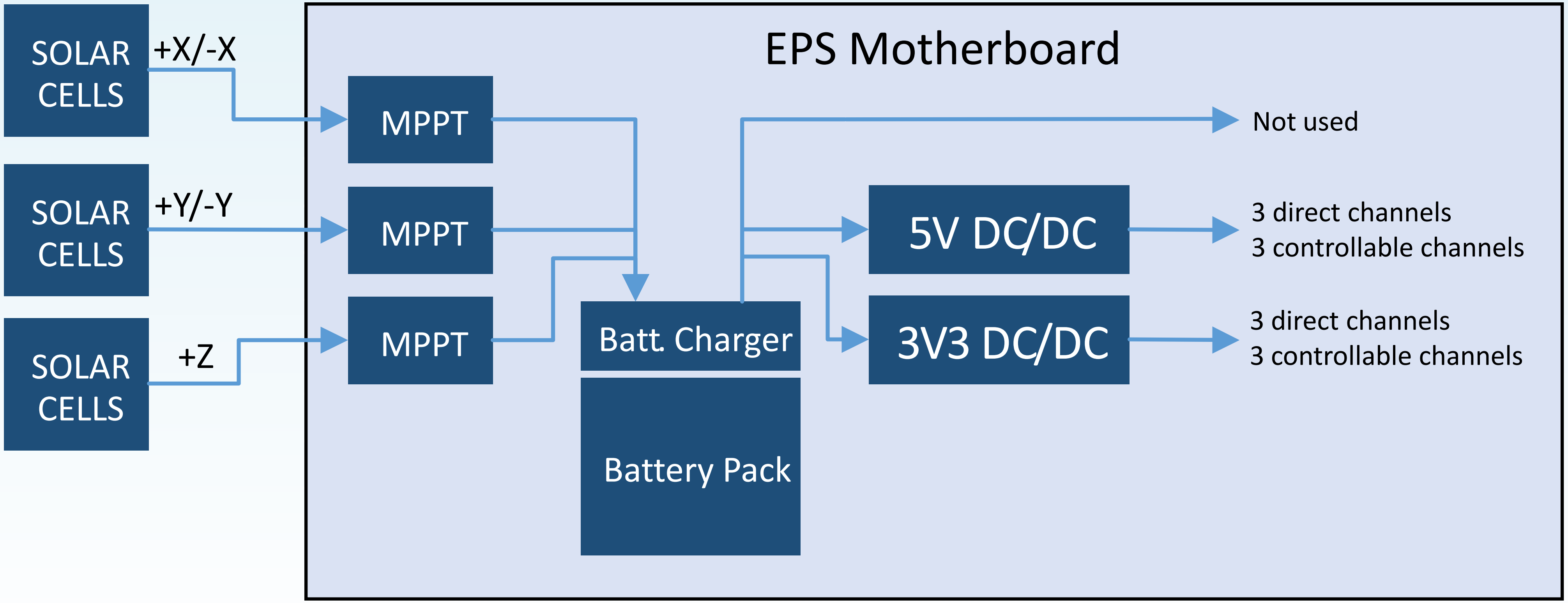
$$E_{BAT} = \frac{P_e \cdot t_e}{N_B \cdot N_C \cdot V_D \cdot DOD \cdot \eta_{BDR}}$$

- E_{BAT} = Battery capacity [A·h]
- N_B = Number of batteries
- N_C = Number of cells
- V_D = Cell discharge voltage [V]
- DOD = Depth of discharge

Material	Cell Volts	Capacity (W·h/kg)	Temperature range	Cycles @ 75% DOD	Cycles @ 25% DOD
Ni-Cd	1.25	30-40	-20° - 45°	800	21000
$Ni\text{-}H_2$	1.30	50-80	0° - 20°	4000	150000
Ag-Zn	1.10	60-70	0° - 50°	100	3500
Ni-MH	1.2	60	0° - 25°	4000	130000
Li-Ion	3.7	100-250	-25° - 75°	700	2700

2.4. EPS – Motherboard (i)

→ EPS Architecture



2.4. EPS – Motherboard (ii)

→ Gomspace NanoPower P31u

- Used and tested in ^{3}Cat-2 mission
- Flight Heritage
- Certified ISS Compliance (€€€)
- Heaters and battery thermal control included

2.4. EPS – Solar Panels

→Solar Panels includes:

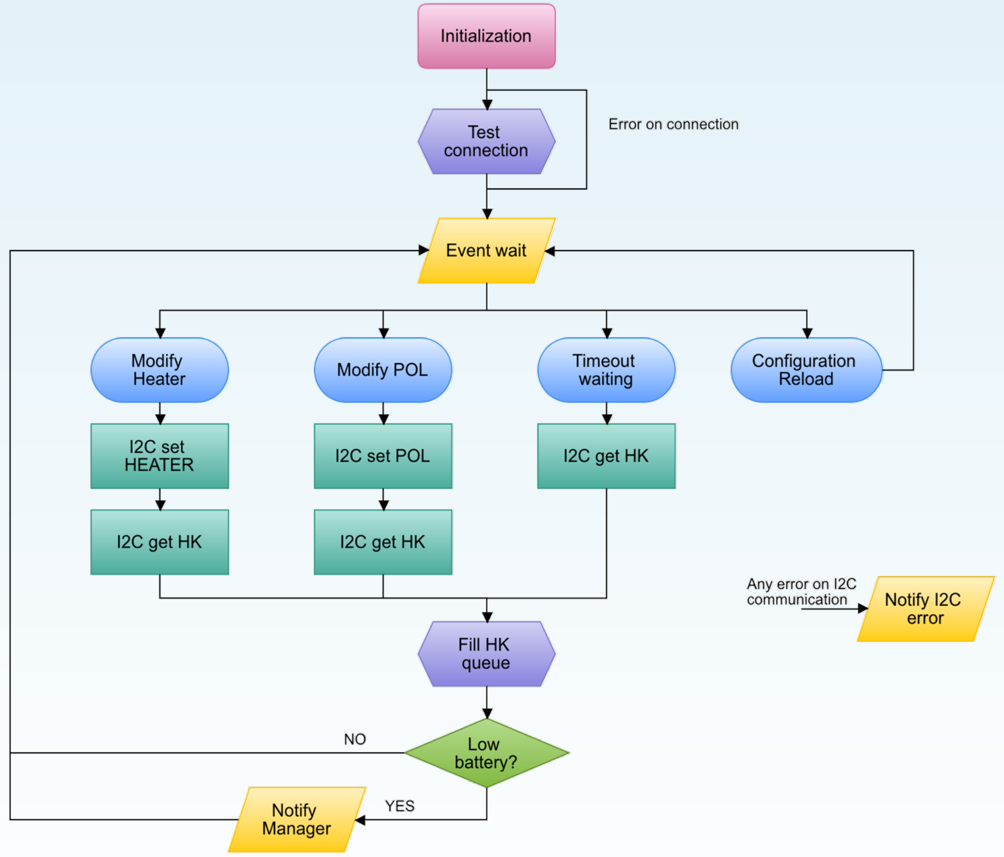
- x2 Azurspace 30% Triple Junction GaAs Solar Cell Assembly (connected in series).
- Photodiode (only the sensor)
- Temperature sensor
- Others (Up-looking antenna, apertures for interface, etc.)

→Final solar panels same technology and identical circuitry used in ^{3}Cat-2 mission.

→Prototype solar panels for electrical testing, thermal characterization and attitude determination test.

2.4. EPS: OBC Software – EPS Task

→ Management of EPS
- COTS from Gomespace
- Commands
  - Heater de/activation
  - Point of Load
  - Watchdog
- Thermal Control → Two thresholds



2.4. EPS: Power Distribution (i)

→ Power distribution

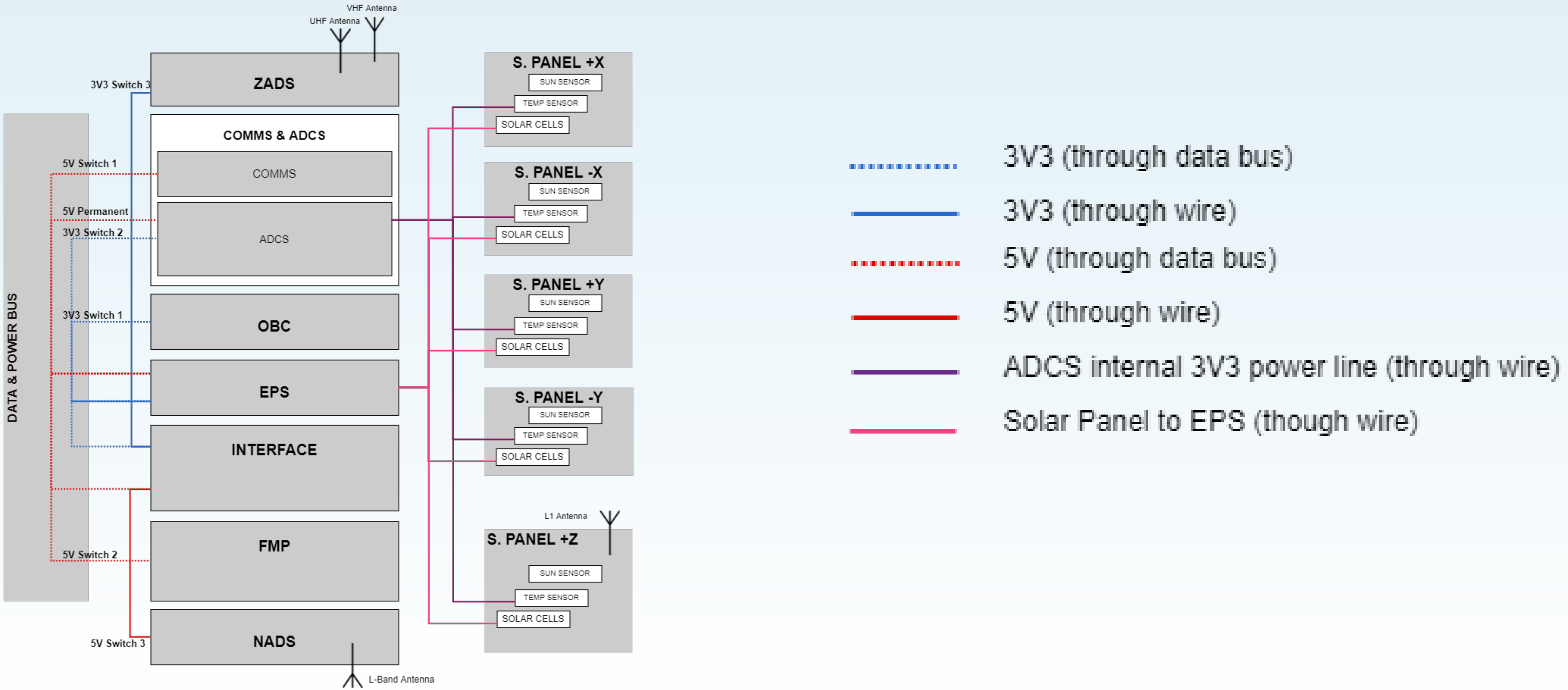
- Provides power to all subsystems in the spacecraft
- Constraints:
  - EPS has 3 switched outputs at 3.3V
  - EPS has 3 switched outputs at 5V

  - EPS has a permanently enabled output at 3.3V
  - EPS has a permanently enabled output at 5V

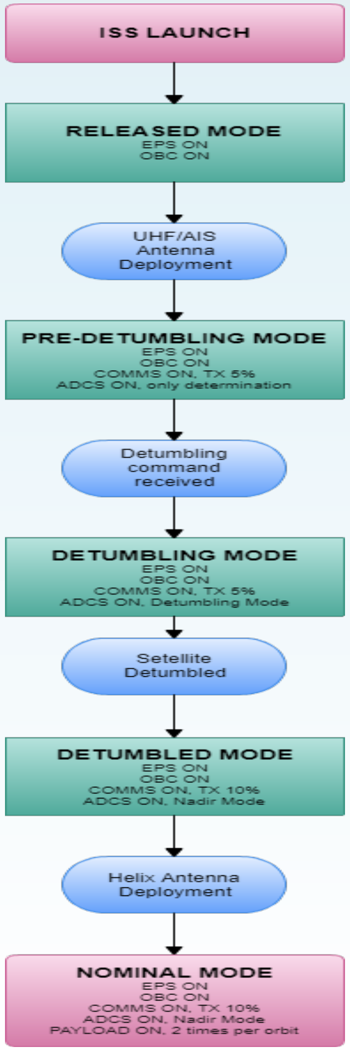
  - EPS has a permanently enabled output directly from the battery

- Power assignment
  - 3.3V switched outputs
    - OBC, ZADS, ADCS (logic)
  - 5.0V switched outputs
    - COMMS, Payload, NADS
  - 5.0V permanently enabled output
    - ADCS (torque rods)

2.4. EPS: Power Distribution (ii)



2.4. EPS: Power Budget (i)



Commissioning power states:

→ Released: Only EPS and OBC active

→ Pre-detumbling: EPS, OBC, COMMS (5%) and ADCS (only determination) active

→ Detumbling: EPS, OBC, COMMS (5%) and ADCS (Detumbling Mode) active

→ Detumbled: EPS, OBC, COMMS (5%) and ADCS (Nadir Mode) active

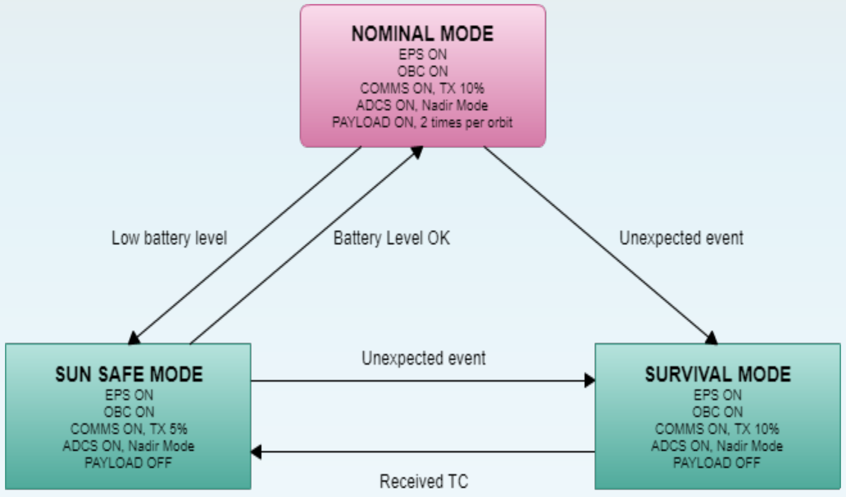
2.4. EPS: Power Budget (ii)

Operational power states:

→ Nominal: EPS, OBC, COMMS (10%), ADCS (Nadir Mode) and Payload active

→ Sun Safe: equivalent to Detumbled state.

→ Survival: equivalent to Detumbled state but COMMS at 10%.



MODE	POWER BUDGET	AVERAGE CONSUMPTIONS						
		EPS	OBC	COMMS	PAYLOAD	ADCS	UHF/AIS DEPLOYABLE	HELIX DEPLOYABLE
Released	6,86E-01	1,60E-01	2,35E-01	0,00E+00	0,00E+00	0,00E+00	4,00E-02	3,75E-03
Pre-Detumbling	4,58E-01	1,60E-01	2,35E-01	2,37E-01	0,00E+00	1,22E-02	0,00E+00	3,75E-03
Detumbling	2,98E-01	1,60E-01	2,35E-01	2,37E-01	0,00E+00	1,62E-01	0,00E+00	3,75E-03
Detumbled (Sun Safe)	4,56E-01	1,60E-01	2,35E-01	2,37E-01	0,00E+00	2,28E-01	0,00E+00	3,75E-03
Nominal	2,53E-01	1,60E-01	2,35E-01	3,46E-01	7,84E-02	2,28E-01	0,00E+00	3,75E-03
Survival	3,38E-01	1,60E-01	2,35E-01	3,46E-01	0,00E+00	2,28E-01	0,00E+00	3,75E-03

2.4. EPS: Power Budget (iii)

→ **Power analysis report (what you should be considering in your design!):**

Including battery heaters…

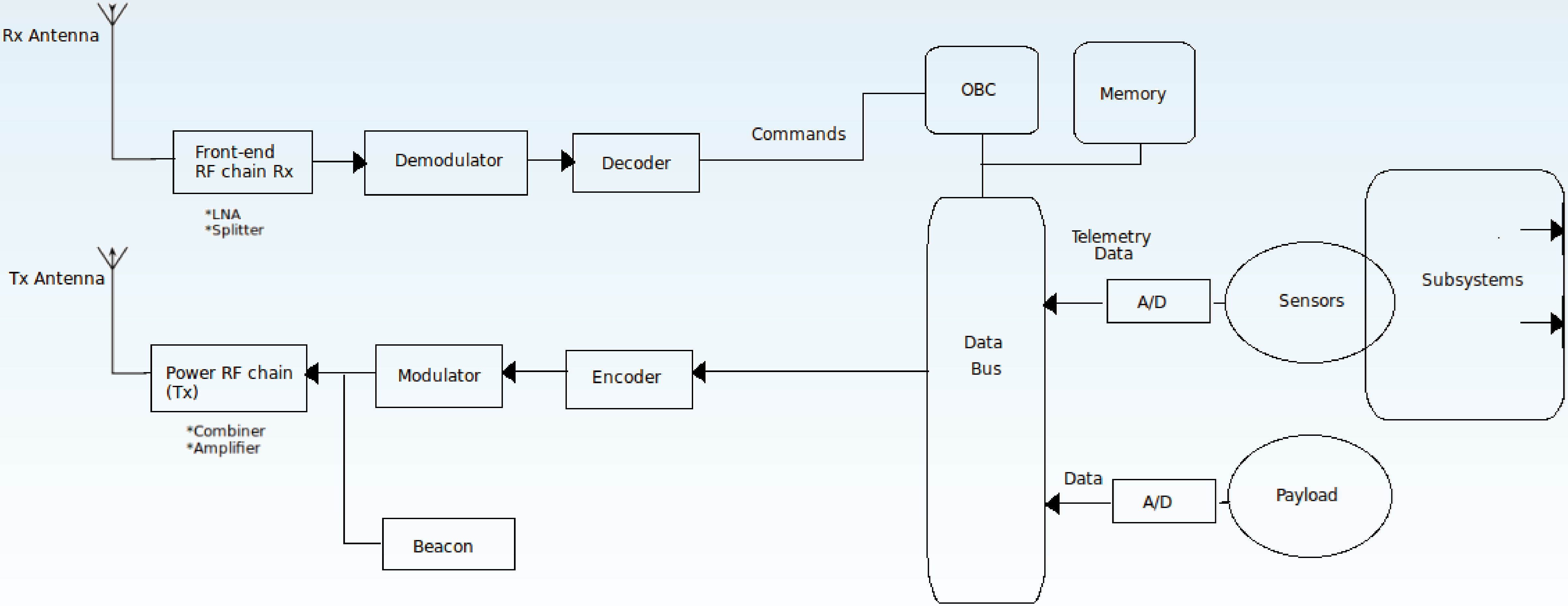
- Expected maximum Depth of Discharge (DoD): 3,48%
- Expected battery lifetime: 191 days to reduce battery capacity at 80%, 233 days to 65%.
- Expected peak currents: 0.22A / 5A in 3.3V bus, 0.89A / 4A in 5.0V bus, 1.16A / 4A in battery bus
- Expected charging times: 24.1h in Nominal, 19.1h in Sun Safe, 12.6 h in Released

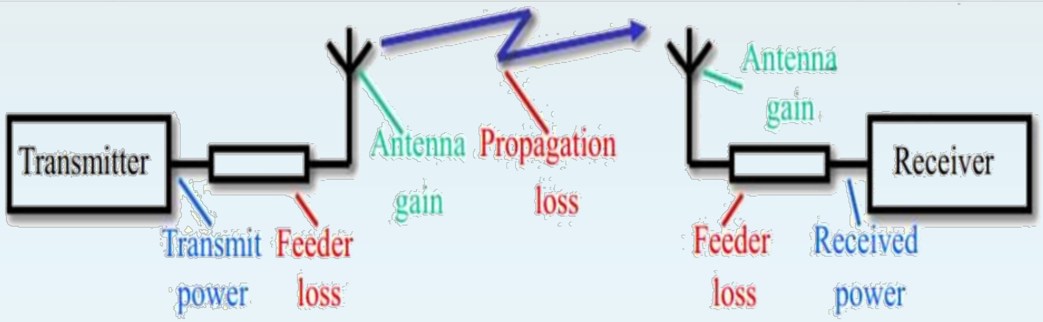
→ **Conclusions:**

- **^{3}Cat-4 operation without loss of performance** is guaranteed for, at least, **8 months (!!) ⇒ needs to be adjusted to mission EOL (= re-entry)**
- **Peak currents** are well **below** the **maximum peak currents supported by the EPS**

2.5. Communications System (COMMS).

2.5. Space Segment Architecture





[A. R. Nasser]

Link Budget Equation:

$$S = P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 r^2}$$

Received noise power:

$$N = kT_{sys}B$$

$$\frac{C}{N} = \frac{E_b}{N_0} \cdot \frac{R}{B}$$

Definitions:

C/N: Carrier-to-noise ratio

Eb/N0 : energy per bit over spectral noise density

R/B: bit rate over bandwidth

EIRP: Effective Isotropic Radiated Power

R: bit rate

B: Bandwidth

k = 1.38064852 × 10^{-23} m^2 kg s^{-2} K^{-1} Boltzmann's constant

$$\frac{E_b}{N_o} = \frac{EIRP \cdot G_r}{kT_{sys}R} \quad (EIRP \triangleq P_t \cdot G_t)$$

$$\frac{R}{B} \leq log_2\left(1 + \frac{S}{N}\right)$$

Shannon's Theorem

2.5. Link Budget (ii)

Additional ITEMS to be considered in the link Budget:

- Frequency
- Transmitter Power
- Transmitter Line Loss
- Peak Transmit Power Antenna
- Effective Isotopic Radiated Power
- Transmitter Antenna Half Power Beamwidth
- Transmitter Antenna Pointing Error
- Transmit Antenna Pointing Loss
- Free Space Path Loss
- Propagation & Polarization Losses
- Faraday rotation
- Receiver Antenna Peak Gain
- System Noise Temperature
- Data rate
- Bit Energy/Noise Spectral Density
- Bit Error Rate
- Required Ratio
- Implementation Loss, Atmospheric losses
- Margin

Increasing the transmission robustness:

- **Convolutional codes**

Protect information by adding redundant bits.

- **Reed-Solomon code**

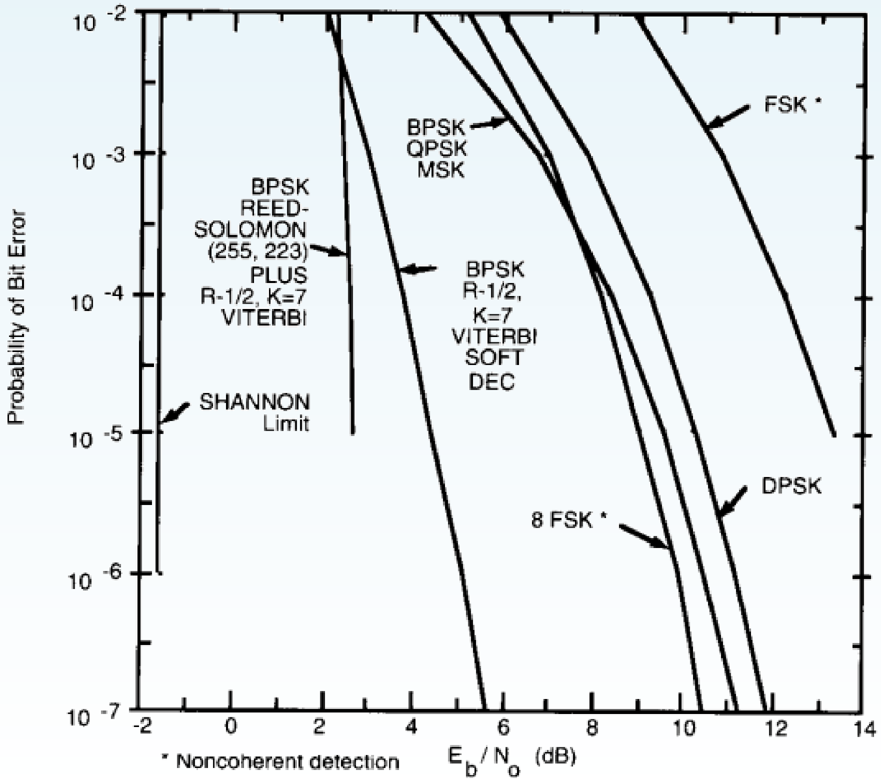
Achieve largest possible code minimum distance for any linear code with the same encoder input and output block lengths. Particularly useful for burst-error correction $\Rightarrow$ *effective for channels with memory.*

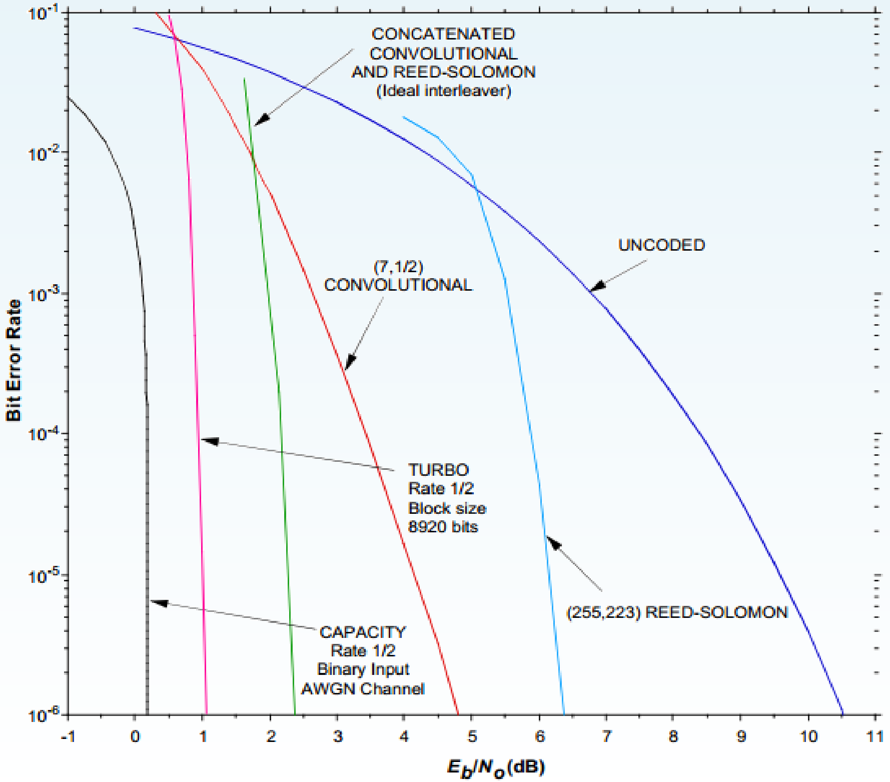
- **Turbo Codes: Encoding with Interleaving**

Parallel concatenation of two codes separated by an interleaver

2.5. Link Budget (iii): Modulations

- Bit error rate as a function of the Eb/N0, and the number of bits per symbol used in a given modulation scheme.
- The more levels are used, the more energy per bit is needed (Eb/N0) ⇒ smaller distance between symbols in I/Q plane, and larger error probability.





2.5. Link Budget (iv): Other considerations

Band	Frequency	Service
Ka	17,3..30 [GHz]	Sat.com (fixed), High-speed communication
Ku	10,3..14,7 [GHz]	Sat.com (fixed), Exploration
X	7..8,5 [GHz]	Sat.com (fixed), Military Sat
C	3,4..7,0 [GHz]	Sat.com (fixed), Aviation radio navigation
S	1,7..2,7 [GHz]	Sat.com (fixed), Aviation radio navigation
L	1,2..1,7 [GHz]	Sat.com (mobile),
UHF	300..3000 [MHz]	Amateur HAM, data
VHF	30..300 [MHz]	FM Broadcast, TV Broadcast, Mobile radio, Amateur HAM

2.5. Regulatory

- **Frequency Filing** (as it is now)

1. Frequency coordination for amateur radio satellites is provided in 145.8-146 and 435-438 MHz by the IARU through its Satellite Advisor: https://www.iaru.org/reference/satellites/

Amateur-satellite service. Amateur stations meet the requirements of the radio regulations, RR 1.56. and 1.57.

RR 1.56 *amateur service:* A *radiocommunication service* for the purpose of self-training, intercommunication and technical investigations carried out by amateurs, that is, by duly authorized **[licensed]** persons **[individual natural people]** interested in radio technique solely with a personal aim **[for themselves]** and without pecuniary interest **[compensation]**. (NOTE: Explanatory terms in brackets are not part of the treaty text.)

RR 1.57 *amateur-satellite service:* A *radiocommunication service* using *space stations* on earth *satellites* for the same purposes as those of the *amateur service*.

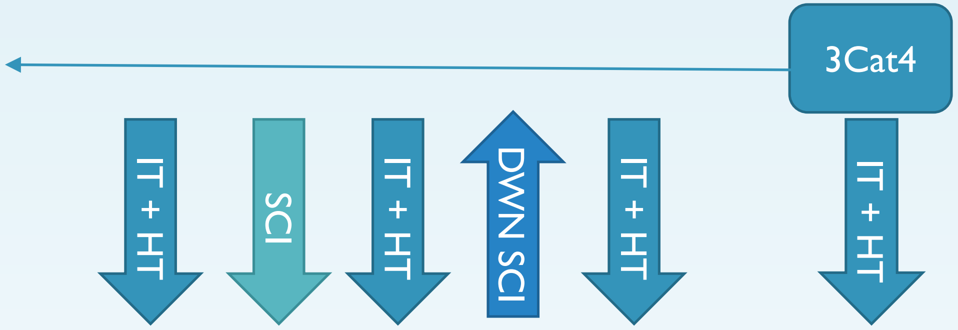
The radio regulations are annexed to and part of a treaty, the International Telecommunication Convention, to which nearly every country in the world is a signatory party. See: http://www.itu.int/pub/S-CONF-PLEN-2011.

2. It is a mandatory requirement for the IARU coordination that the licensing administration notifies the ITU with the selected frequency assignments/bands for the proposed satellite (ref RR Article 9, sub-section IA3). The licensing administration files the Advanced Publication Information (API) with ITU.

Radio Regulations : https://www.itu.int/pub/R-REG-RR-2016

2.5. Concept of Operations (i)

- → During GS contact
  - Automatic IT + HT transmission
  - Specific Telecommands
  - Requested Downloads
- → Target areas
  - Uploaded through telecommands
- → Specific Telecommands
  - Deploy Payload Antennas
  - Exit survival mode
  - Download scientific data

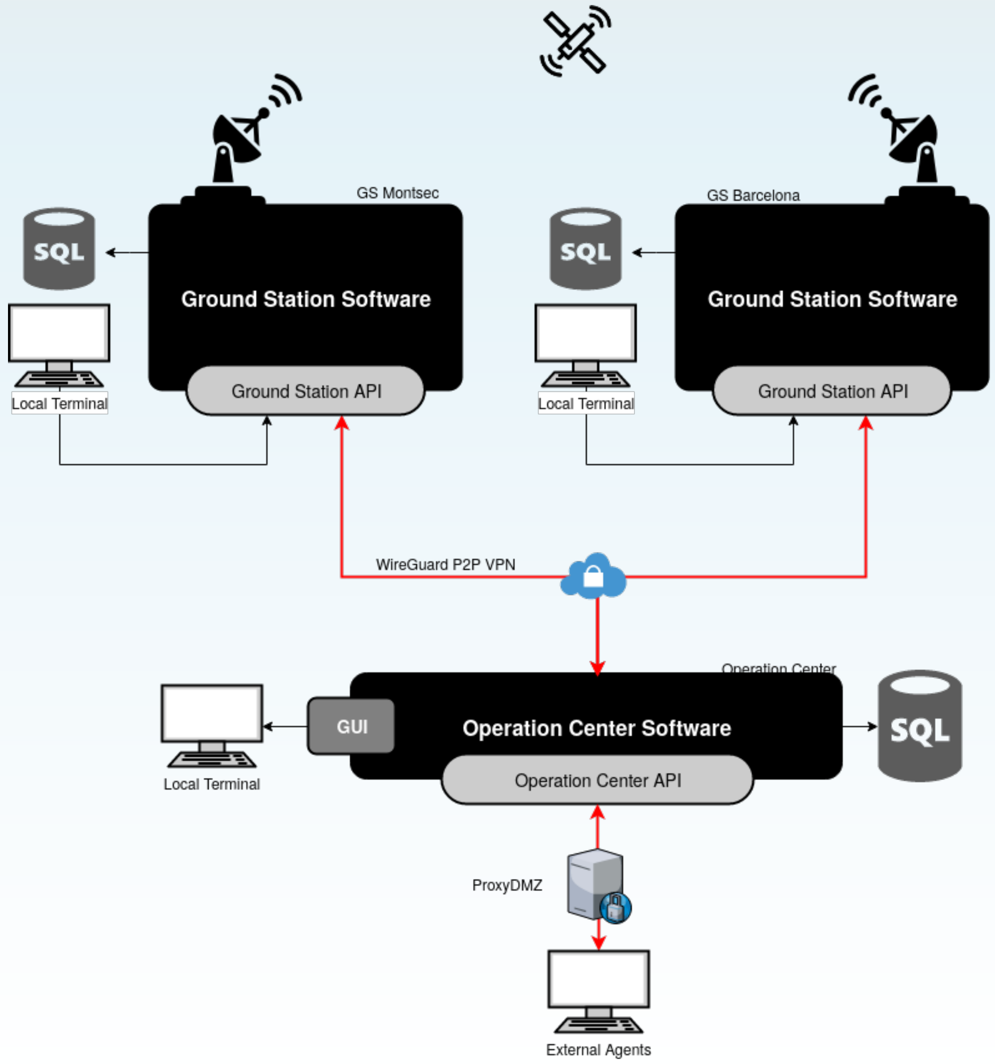


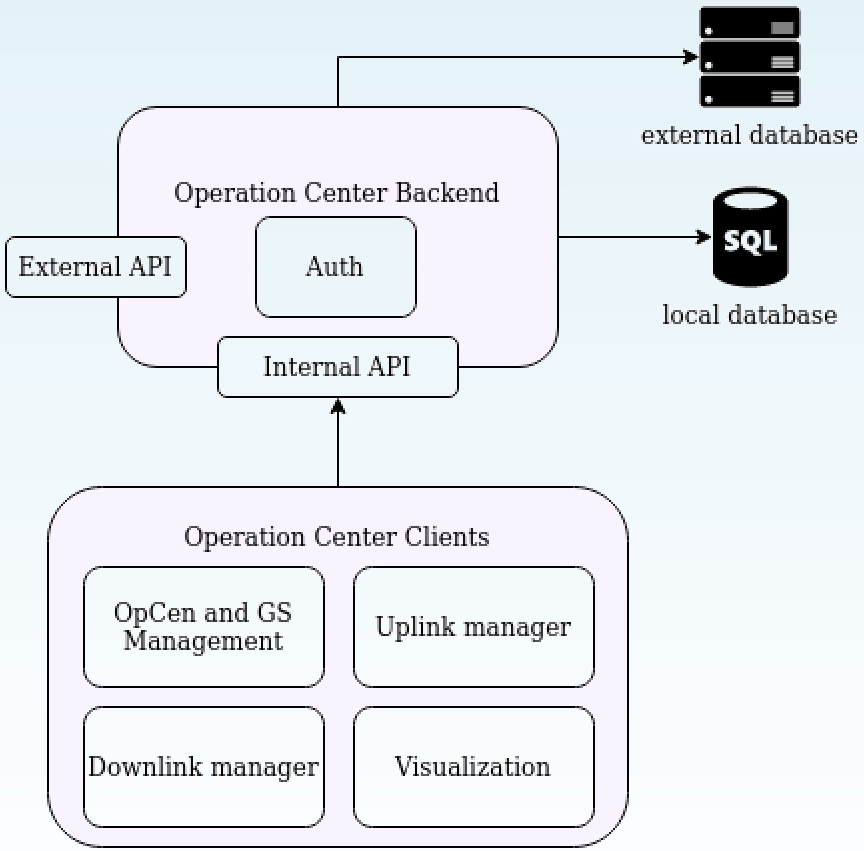
2.5. Concept of Operations (ii): Ground Segment

- RF reception and transmission verification
  - ³Cat-1 used the same transceiver as 3Cat-4 for UHF Uplink and Downlink
    - Complete receiving and transmitting chain has thus been verified
  - GOMX1 has also been received successfully, and it is currently used for testing purposes
  - Update to the new control software did not affect the RF Chain, so it is considered an upgrade
- Validation and testing of the new control software completed for the FSSCat mission
- Testing with the ³Cat-4 Comms subsystem to be performed, including:
  - End-to-end testing of uplink and downlink using the QM
  - Routine testing of the VHF/UHF antennas
    - Movement, pointing, reception, infrastructure
  - Scheduling tests using the new software architecture

2.5. Concept of Operations (iii): Ground Segment

- Significant improvements have been made to Operations
  - Development of a distributed software architecture to remotely control multiple Ground Stations from our Operation Center.
  - Automated pass scheduling, data flows and testing
    - Any number of passes can be scheduled from the Operation Center, and the corresponding Ground Station will prepare and execute them, even if Internet connection is lost after scheduling.
    - Data is recorded in the Ground Station and streamed back to the Operation Center for real-time decoding to aid the Operating Personnel. Uplink can be scheduled or sent on-request.
    - Automated tests (Antenna movement, SDR performance, etc.) are performed routinely to check health status.





- External Database
  - Synchronization with each Ground Station data
- Local database
  - Information about the Ground Station network
  - Passes scheduling information and telecommands planification
- Back-end
  - Main part of the software. Controlls all the logic and communicates with the databases and the Ground Stations. Can be accessed through an API.
  - Authorization management to make it secure
- Operation Center Clients
  - Webpage applications with separate functionalities

Operations Center Management User Interface

→ Satellites management interface
- Add/edit/delete satellites from the Operations Center database
- Satellite's TLE autoupdates automatically from Celestrak

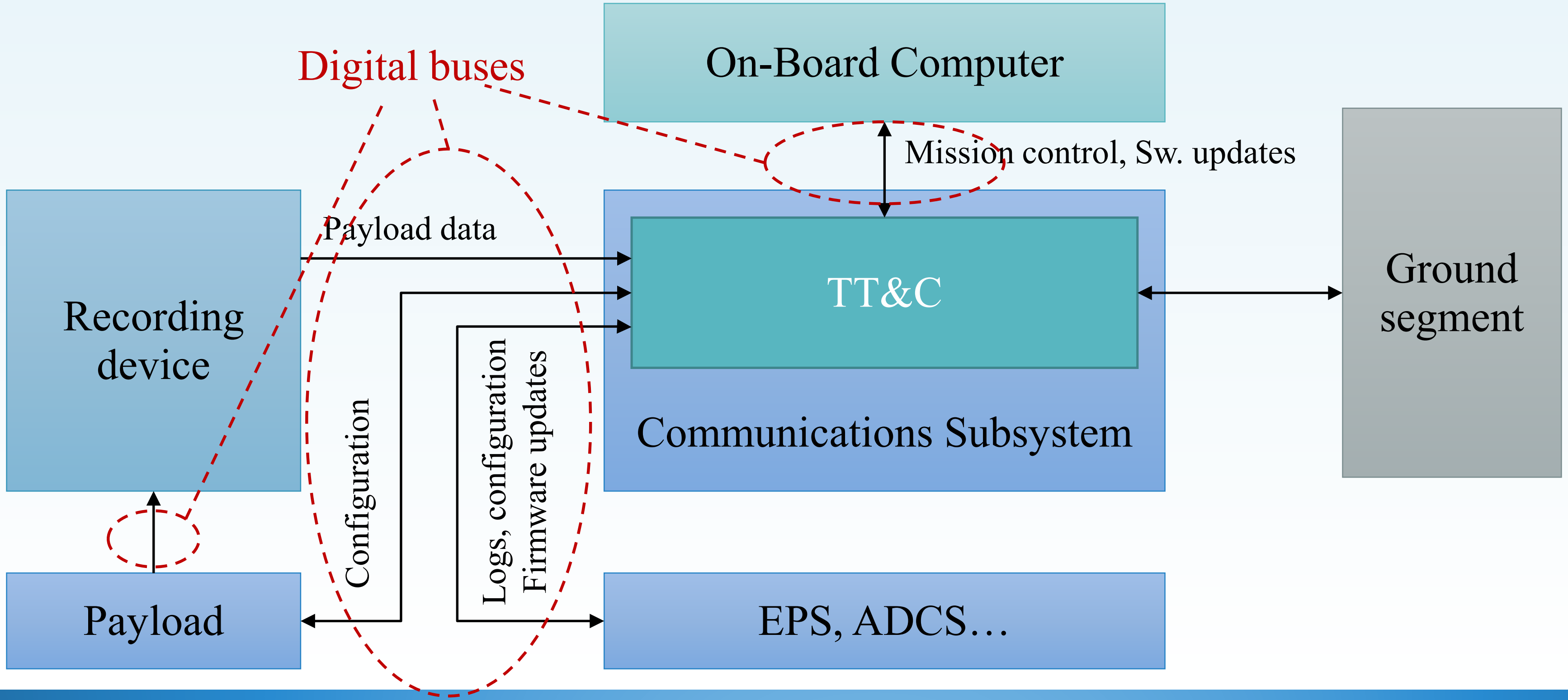
→ Ground Stations management
- View Ground Station's cameras
- Remote Antennas movement and current position display

→ Passes Scheduling
- Schedule new passes from the satellites stored in the database
- Different scheduling modes (next pass, next N passes, all passes in a time interval, etc.)

2.6. On Board Data Handling System (OBDH).

Introduction

- Involved subsystems.
- Types of data, requests, actions….
- Flight software and On-Board Computer: architecture, OS, CPU.



2.6. On Board Data Handling System (OBDH) (ii)

Telemetry data – housekeeping (example)

Type	Source	Analog / Digital
Temperature	Solar panels, batteries, OBC	Analog (thermistors, RTD, Ics,…)
Voltages & currents	Power supplies solar panels, power buses	Analog (sensing circuitry)
Operation modes	Payload status, heaters (on/off)	Digital
Actuation / deployment mechanisms	Solar panels and antennas deployment	Digital

2.6. On Board Data Handling System (OBDH) (iii)

Telemetry data – housekeeping data, considerations

- **Number of required acquisition channels**

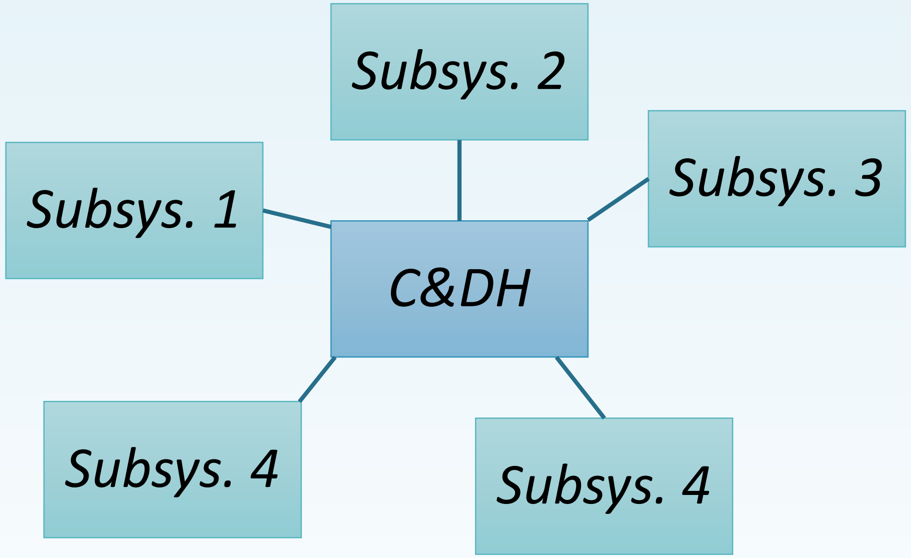
- **Accuracy required**
  - Precision of any telemetry channel shall allow an assessment of the nominal or out-of-tolerance status of the monitored parameters
  - Sufficient telemetry shall be available to allow the verification of:
    - Power budget with accuracy better than e.g. ±5%
    - Temperature with an accuracy better than e.g. ±1%

- **Types of sources**

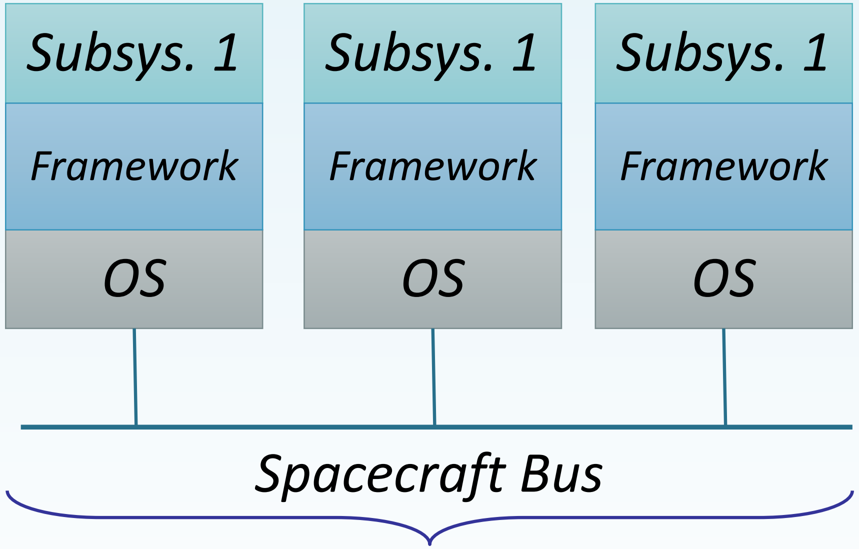
- **Format and storage** (*standardization* is critical):
  - e.g. Analog voltage 0 to 5 V_{DC}: units are [V] or [mV]?
  - Storage type: 8/16/32-bit integer, floating point, ASCII ("5123" = 5.123 V)

→Spacecraft Flight Software: general architecture.

- Common topologies: ***centralized*** or ***distributed***.



Integral modules (hardware) connected through digital buses or **software modules** interfacing with OBDH core.

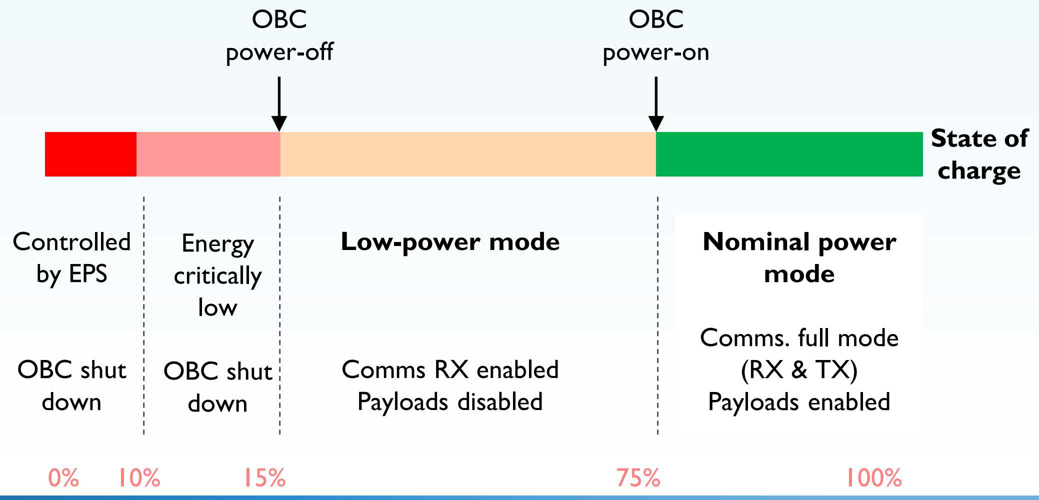


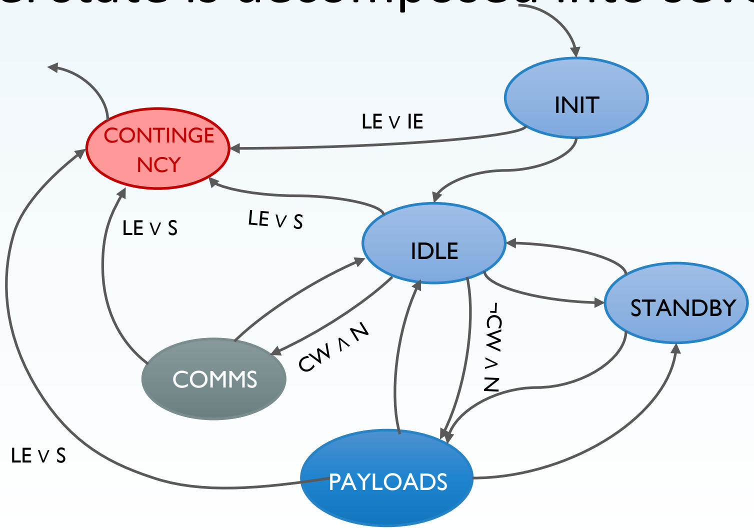
e.g. Voyager, Galileo (NASA's outer planetary spacecraft), AAUSAT3 (nano-satellite mission)

2.6. On Board Data Handling System (OBDH) (v)

Spacecraft Flight Software:

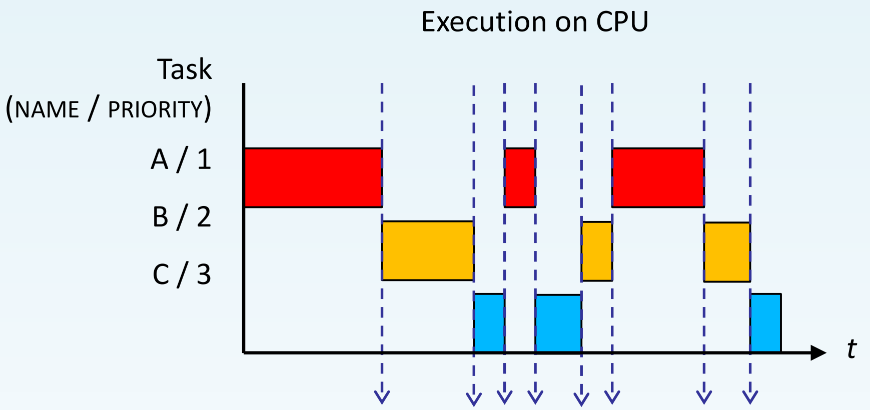
- Implementation of **multiple-level Finite State Machines**.
- High-level mission states → internal sub-states → subsystem modes → device commands.
- Should always guarantee spacecraft safety, i.e. tend to be complex and should be automatically analyzable.
- E.g. if contingency: **SYSTEM RESET** *(may take from several* ***seconds*** *to some* ***hours****)*, **SAFE STATE** *(only critical subsystems are enabled)*.
- E.g. [3]Cat-1 energy and system FSM (each high-level state is decomposed into several routines):





→Spacecraft Flight Software:

- **Real-time** operating systems (RTOS):
  - Deterministic latencies RT scheduler: predictable execution.
  - RT ≠ fast computing.
  - Priority-based. Preemptive / non-preemptive.
  - Programming aspects: kernel manages Real-Time Tasks (similar to threads).
  - Examples of RTOSes used in spacecraft:
    - ✓ **VxWorks**: proprietary.
    - ✓ **RTEMS**: open source, free license.
    - ✓ Micrium **uC/OS-III**: open-source.
    - ✓ **QNX**: proprietary.
    - ✓ **LynxOS**: proprietary.
    - ✓ **FreeRTOS**: open-source, free license.
    - ✓ **Xenomai** (Linux patch): soft-real-time, open-source, free license.
    - ✓ **PREEMPT_RT** (Linux patch): soft-real-time, open-source, free lic.



Task context switches are managed by the kernel scheduler (i.e. they are deterministic, **predictable**).

- Common frameworks and standards:
  - NASA cFS/cFE (Open Source, Free License) (*). Available for RTEMS, Linux, VxWorks…
  - TSP: Time and Space Partitioning (Avionics Application Standard Software Interface ARINC 635 standard.)

(*) http://opensource.gsfc.nasa.gov/projects/cfe/

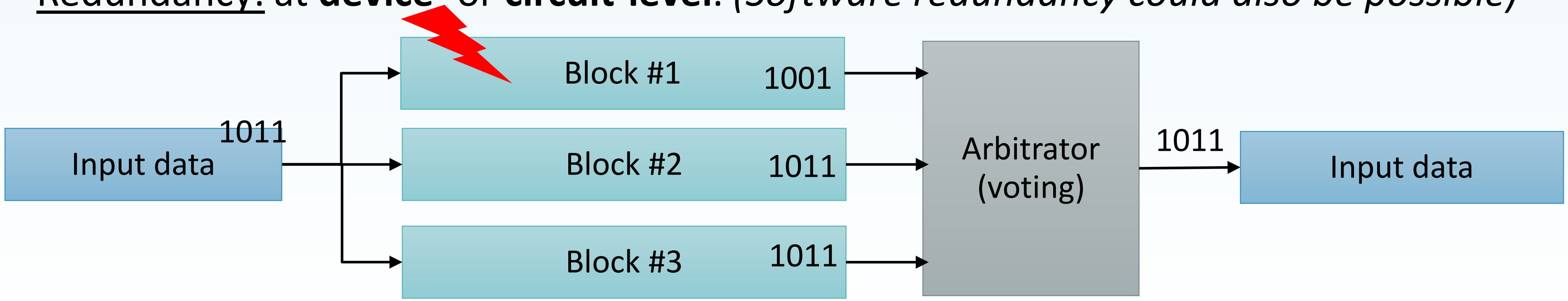
2.6. On Board Data Handling System (OBDH) (vii)

Issues affecting OBDH (i)

- **Radiation;**
- <u>Total dose:</u> for a unit installed externally of the ISS a total dose of 3 kRad for a 3-years mission is foreseen with a box thickness of 3 mm Al equivalent, safety margins applied
  - Total dose mainly due to X-rays and Gamma-rays.
  - Components sensitive to total dose present functionality anomalies (power consumption abnormal increase, ….)
  - **Single event effects**:
  - **SEE**: generalized category of anomalies resulting from a single ionizing particle
  - **SEU:** Single event upset (non-destructive), **SEL** single event latchup (destructive), **SEGR** single event gate rupture (destructive), …
  - **Radiation effects on design**:
  - Radiation limits the number and the type of components available to the designer : uController, CPUs, FPGA Field Programmable Gate Arrays , EEPROMs, Amplifiers, Voltage regulators, etc

Issues affecting OBDH (ii)

- **Radiation: solutions**
  - Radiation-hardened devices:
    - Tolerate higher radiation doses.
    - Special manufacturing techniques.
    - Bipolar technology (not CMOS)
    - Shield components.
    - On CPU: usually SPARC or PowerPC architectures.
      - E.g. SPARC-V8 **LEON3** (VHDL-synthezizable, free license), project started by ESA.
  - Error-Correcting Codes, e.g. NAND-Flash with 4-bit BCH ECC.
  - Redundancy: at **device-** or **circuit-level**. *(Software redundancy could also be possible)*



Issues affecting OBDH (iii)

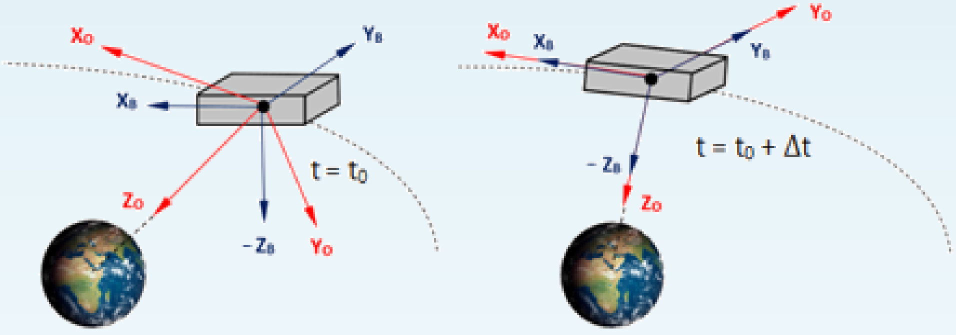
- **Thermal Constraints:**
  - Thermal environment and vacuum limits the types and number of components available to the designer.
  - Typical operational temperature range for a spacecraft OBDH unit could be –20°C to +50°C
  - **Electronic components** are usually classified and sold in three different families:
    - *Commercial* range: 0 to +70 °C (plastic package)
    - *Industrial* range : –40 to +80 °C
    - *Military* range : –55 to +125 °C (ceramic package) [sometimes for automotive applications as well]
  - Heat from electronic components can be removed only **by conductive paths** (heat pipes, no fans, no finned heat sinks....) or **by radiation**

2.7. Attitude Determination and Control System (ADCS) Design

2.7. ADCS Strategy

Scientific experiments require a pointing status to retrieve useful data.

Desired pointing → in the spacecraft body axes, the –Z face pointing towards Nadir.



ADCS process:

→ **Determination process** → determination of spacecraft current attitude w.r.t. reference frame.

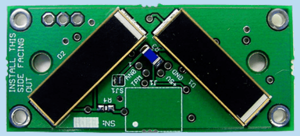
→ **Control process** → control algorithm to bring the spacecraft current state to a referenced one.

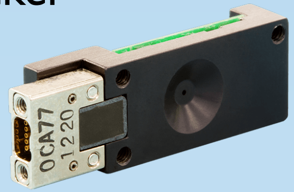
→ **Actuation process** → physical execution to compensate the attitude state.

ADCS modes: Detumbling → Nadir pointing without GB → Nadir pointing with GB

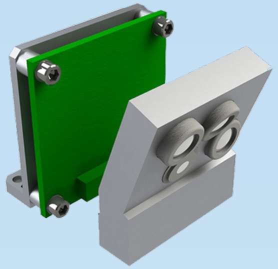
2.7. ADCS - Sensors and actuators (i)

Star tracker



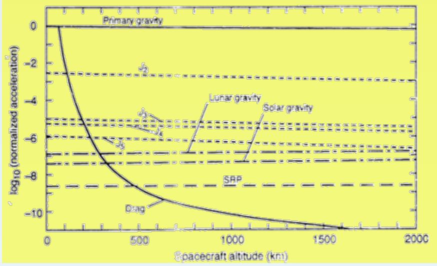


Sun sensors



Earth sensors

magnetometers & gyroscopes



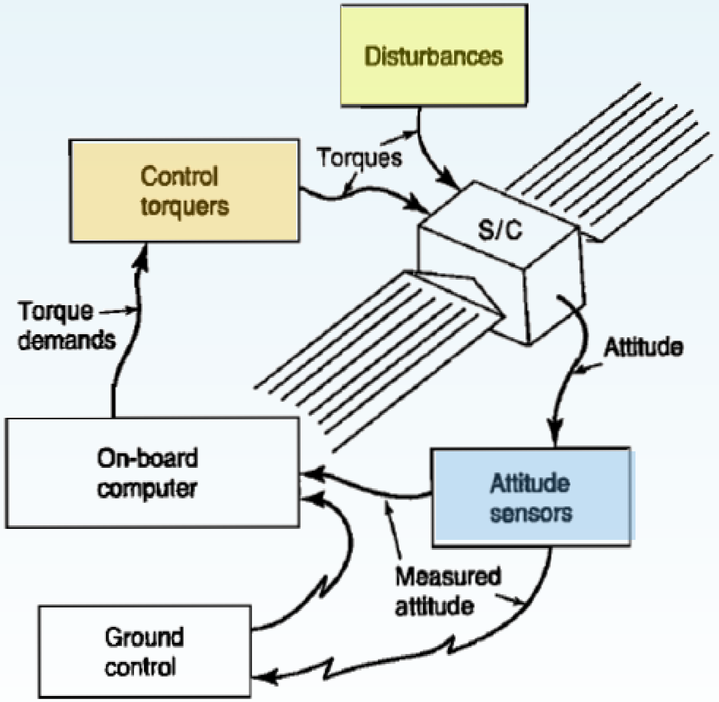
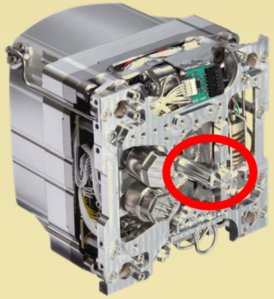
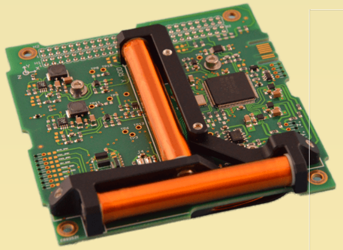
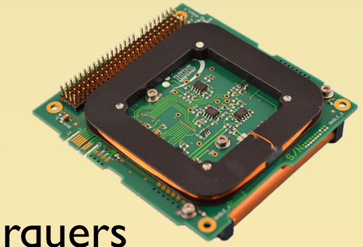


Figure 9.2 Block diagram for an attitude-control system

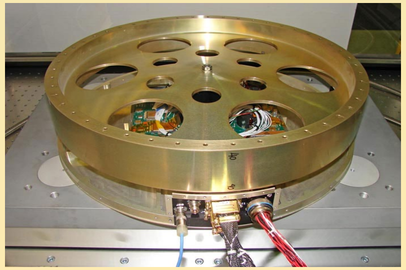


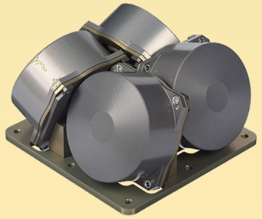
thursters





magnetorquers





reaction wheels

2.7. ADCS - Sensors and actuators (ii)

Sensors used for spacecraft attitude determination:

Sensor	Model	Description
Gyroscope	2x ADXRS290	Enable the measurements of the angular speed.
Magnetometer	1x TIDRV425	Enable the measurements of the magnetic field.
Sun sensor	5x SLCD-61N8	Enables the definition of the sun vector w.r.t. spacecraft body frame.

Actuators used for spacecraft attitude control:

Actuator	Model	Description
Magnetorquer	2x NSS Magnetorquer Rod 1x MT01 Compact magnetorquer	Enable the generation of torque from its interaction with the Earth magnetic field.

Main goal of the Detumbling Control:

→ Reduce the initial angular speed of the spacecraft due to the injection to below 2 °/s.

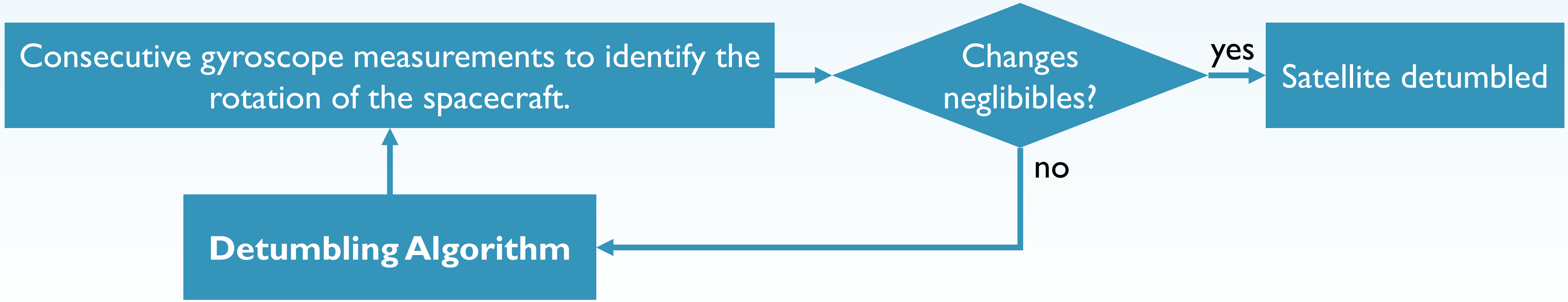
Must be performed in a **fully autonomous way** and to minimize the risk of failure, the involved **actuators, sensors, and algorithms** must be **simple, but very reliable.**

Detumbling Algorithm

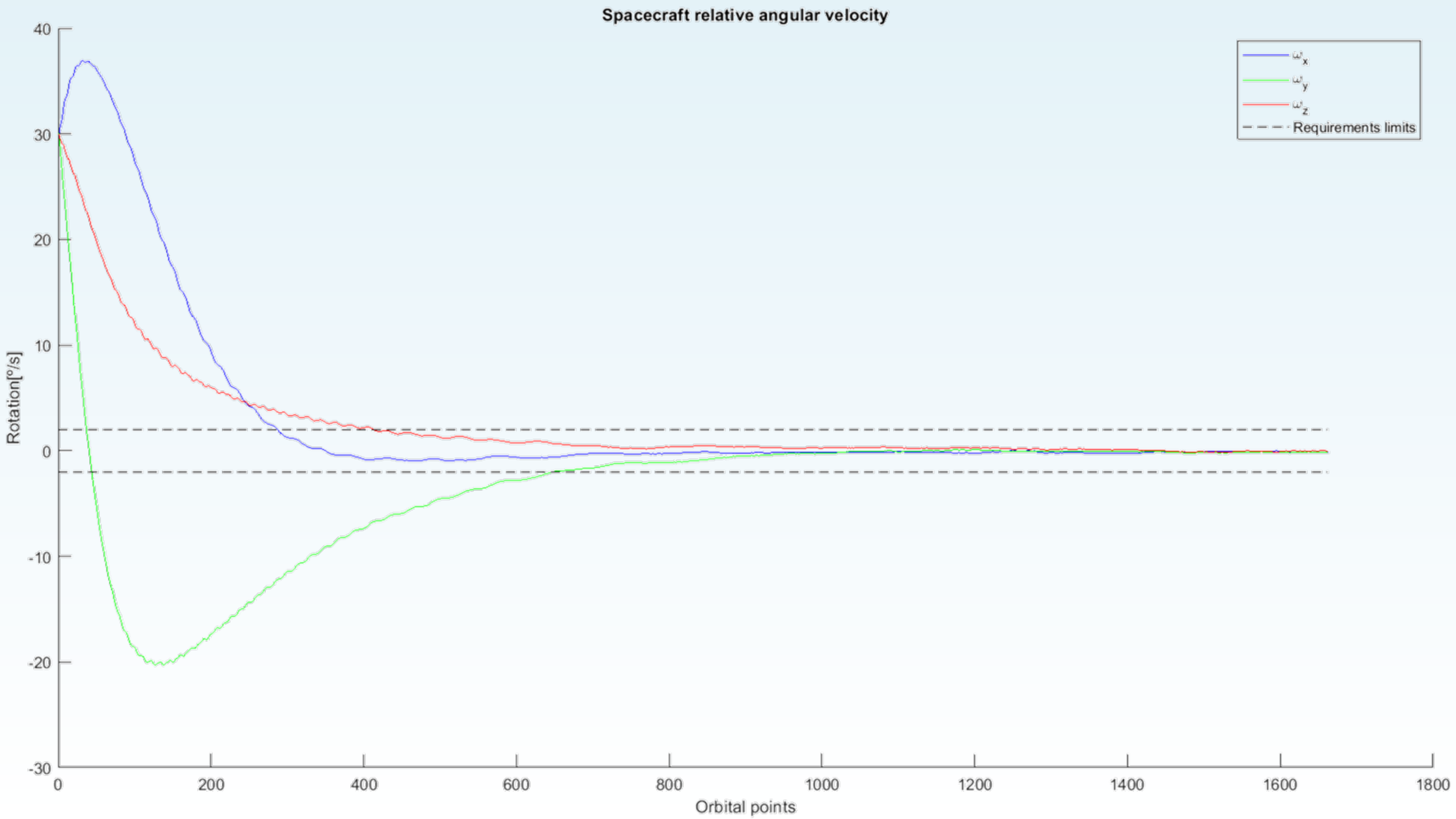
$$\mathbf{m} = \frac{k}{\|\mathbf{B}\|}\omega \times \mathbf{b}$$

k = positive scalar gain
w = angular velocity
B = magnetic field

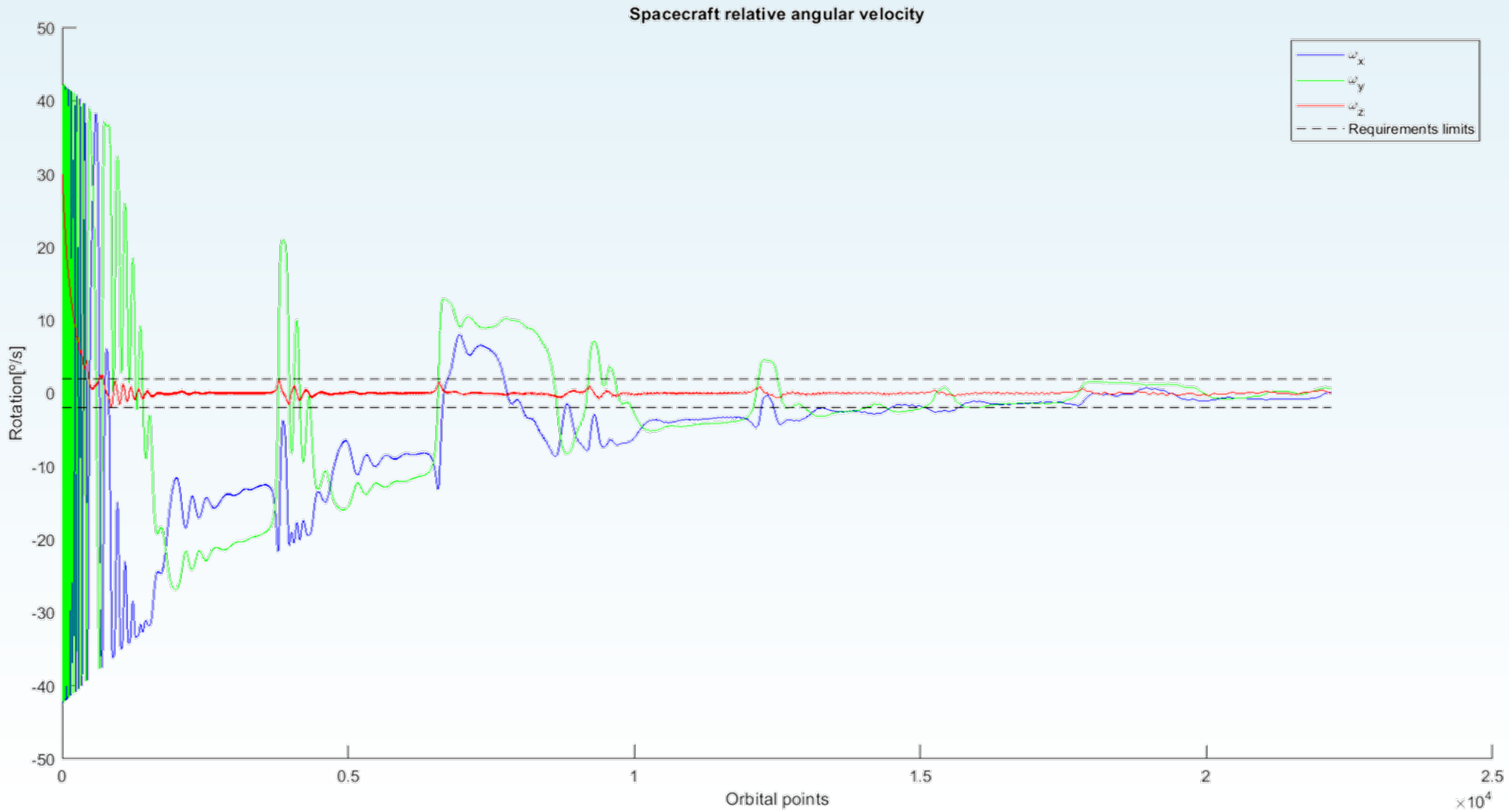
Requirement ID	Description
ADCS-FUNC-014	The DM (Detumbling Mode) shall stabilize the satellite attitude when tumbling uncontrolled after its deployment.
ADCS-FUNC-015	The DM shall be able to recover from angular speed of up to 30°/s in each axis to a final angular speed lower than 2°/s in each axis after 24 hours.



Detumbling in Stowed Configuration

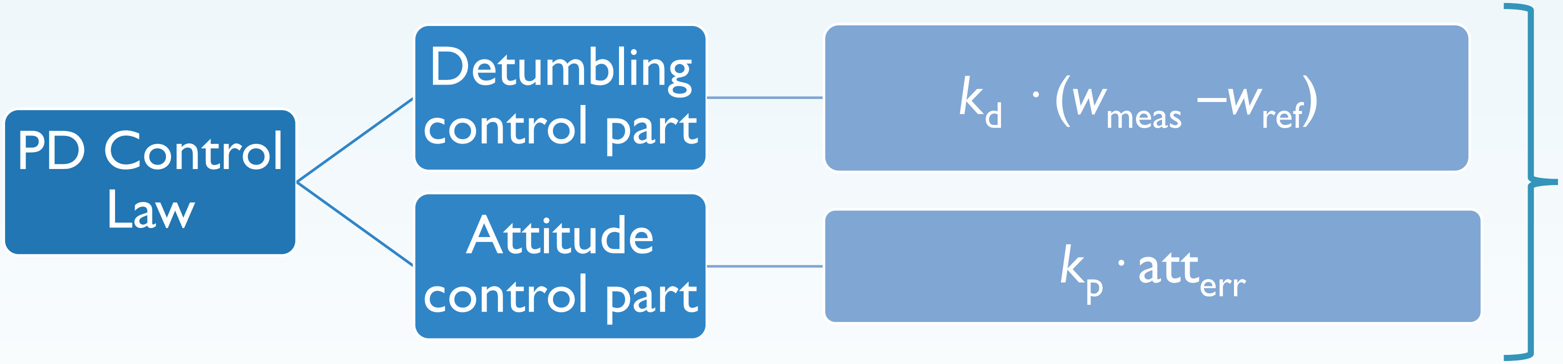


Detumbling in Deployed Configuration



Main goal of the Nadir Pointing Control:

→ Align the spacecraft –Z axis with the Z axis of the orbital frame (defined to point towards the centre of the Earth) with a pointing accuracy of 10°.



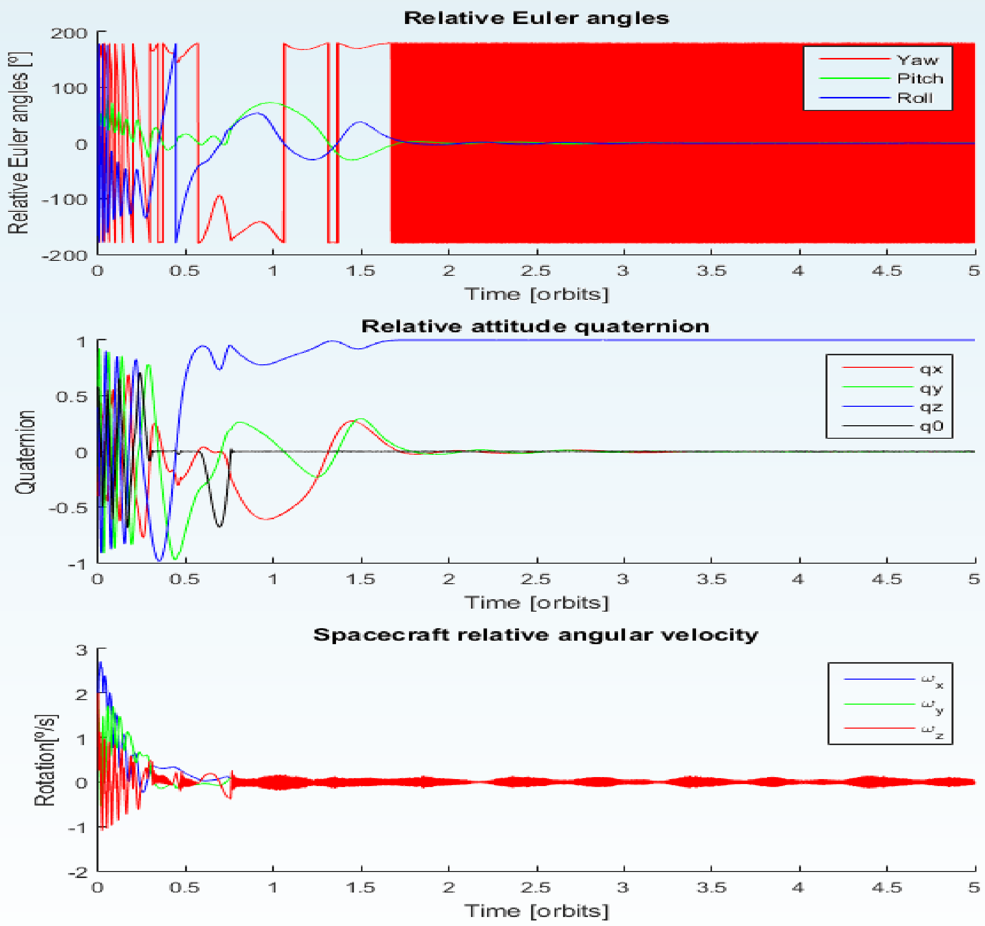
$$\mathbf{L} = -k_p\, \boldsymbol{\delta} \mathbf{q}_{1:3} - k_d\, \boldsymbol{\omega}$$

2.7. ADCS - Nadir Pointing Control (ii)

Requirement ID	Description
ADCS-FUNC-016	The NPM (Nadir Pointing Control) shall ensure the correct satellite attitude state in order to well-execute the satellite payload (the –Z face to Nadir-pointing).
ADCS-FUNC-017	The NPM shall ensure the following attitude flight domain: ▪ Attitude range 10° from Nadir ▪ Angular rate < 0.5°/s
ADCS-FUNC-020	If the nadir pointing is lost, the NPM shall consider a specific procedure to recover the nominal behavior.

Fully magnetic attitude control + GG passive stabilization

2.7. ADCS - Nadir pointing control (iii)



Roll and **Pitch** axes go to **zero**. Thus, **-Z** axis is **aligned with the Z axis of the orbital frame**

Angular velocity decreases below 0.5 °/s

Main goal of the determination part:

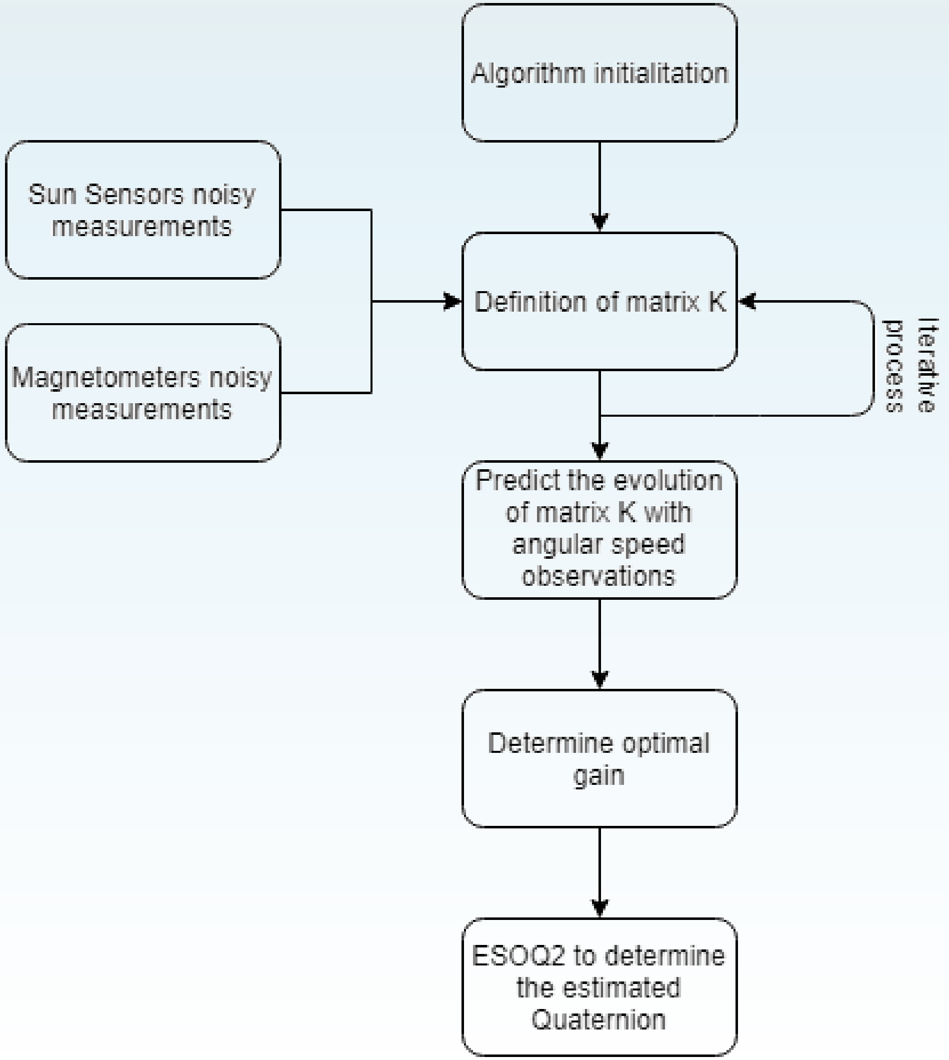
→ Obtain an estimated Quaternion that differs from the real one less than 10^{-3} using the Optimal REQUEST method.

How to estimate Quaternion attitude from vector observations?

→ With the EStimator of the Optimal Quaternion (ESOQ2) and the Optimal REQUEST algorithm.

What is Optimal REQUEST algorithm?

→ Embedding REQUEST in the framework of Kalman filtering.



Algorithm Summary

The Optimal-REQUEST algorithm presented in this section can be summarized as follows:

Initialization:

$$K_{0/0} = \delta K_0 \tag{65}$$

where δK_0 is computed using the first vector measurement according to Eqs. (12) and (13).

$$P_{0/0} = \mathcal{R}_0 \tag{66}$$

$$m_0 = \delta m_0 \tag{67}$$

where δm_0 is a positive weighting factor.

Time update:

$$K_{k+1/k} = \Phi_k K_{k/k} \Phi_k^T \tag{68}$$

$$P_{k+1/k} = \Phi_k P_{k/k} \Phi_k^T + \mathcal{Q}_k \tag{69}$$

where the matrix $\mathcal{Q}_k$ is computed according to Eqs. (24), (25), and (44).

Measurement update:

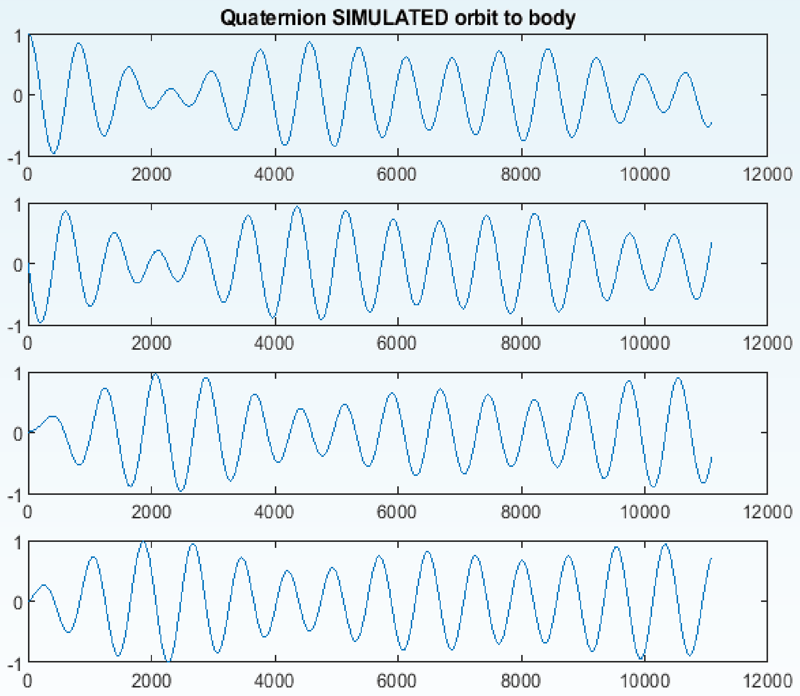
$$\rho_{k+1}^* = \frac{m_k^2 tr(P_{k+1/k})}{m_k^2 tr(P_{k+1/k}) + \delta m_{k+1}^2 tr(\mathcal{R}_{k+1})} \tag{70}$$

$$m_{k+1} = (1 - \rho_{k+1}^*) m_k + \rho_{k+1}^* \delta m_{k+1} \tag{71}$$

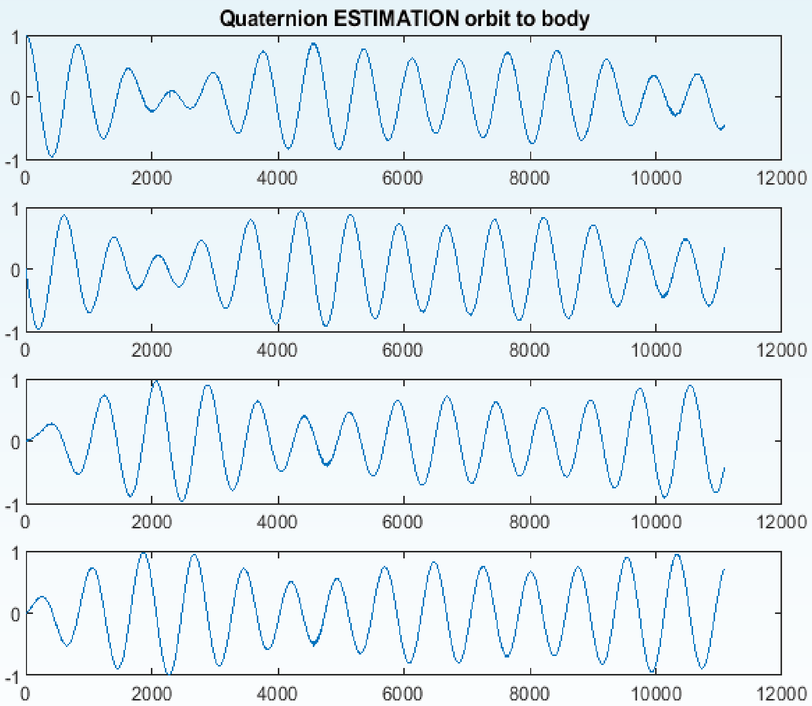
$$K_{k+1/k+1} = (1 - \rho_{k+1}^*) \frac{m_k}{m_{k+1}} K_{k+1/k} + \rho_{k+1}^* \frac{\delta m_{k+1}}{m_{k+1}} \delta K_{k+1} \tag{72}$$

$$P_{k+1/k+1} = \left[(1 - \rho_{k+1}^*) \frac{m_k}{m_{k+1}} \right]^2 P_{k+1/k} + \left(\rho_{k+1}^* \frac{\delta m_{k+1}}{m_{k+1}} \right)^2 \mathcal{R}_{k+1}$$

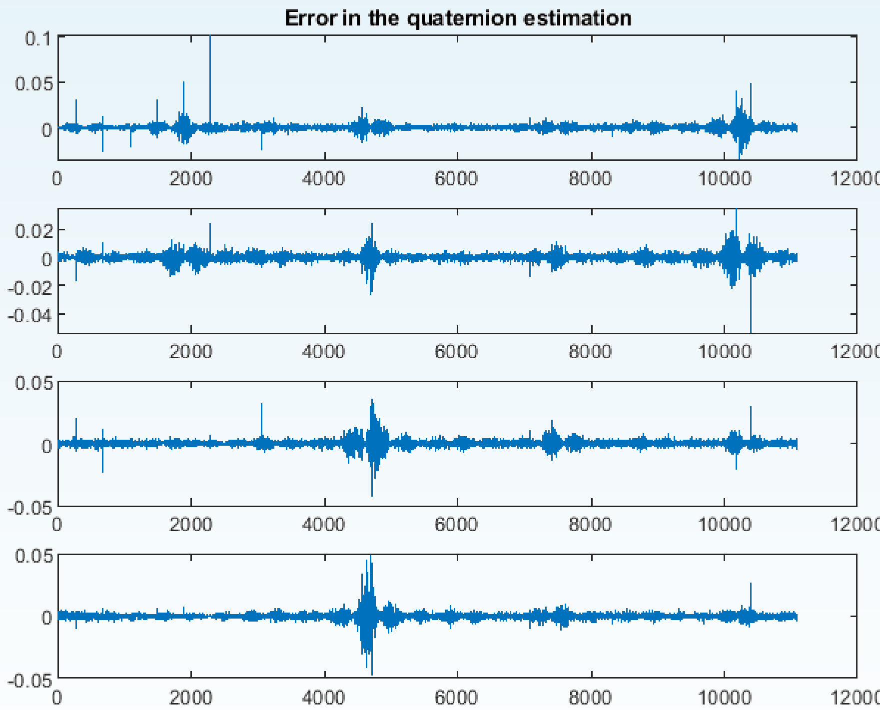
Reference Quaternion



Estimated Quaternion



Error in the Quaternion estimation



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Sources of external disturbances

- **Gravity Gradient disturbance** — By the Earth gravitational field
- **Aerodynamic disturbance** — By the atmospheric particles at LEO
- **Solar Radiation Pressure disturbance** — By the photons radiated from the Sun
- **Magnetic Residual Moment** — By the S/C electronics

External disturbance	Stowed configuration[1]		Deployed configuration	
Altitude	400 km	350 km	400 km	350 km
Gravity Gradient	$0\ Nm$	$0\ Nm$	$1.03 \cdot 10^{-7} Nm$	$1.06 \cdot 10^{-7} Nm$
Aerodynamic	$3.94 \cdot 10^{-9} Nm$	$1.03 \cdot 10^{-8} Nm$	$1.59 \cdot 10^{-6} Nm$	$5 \cdot 10^{-6} Nm$
Solar radiation pressure	$1.687 \cdot 10^{-10} Nm$	$1.687 \cdot 10^{-10} Nm$	$4.791 \cdot 10^{-8} Nm$	$4.791 \cdot 10^{-8} Nm$
Magnetic Residual Moment	$4.83 \cdot 10^{-6} Nm$	$4.92 \cdot 10^{-6} Nm$	$4.83 \cdot 10^{-6} Nm$	$4.92 \cdot 10^{-6} Nm$
Total	$\mathbf{4.83 \cdot 10^{-6} Nm}$	$\mathbf{4.93 \cdot 10^{-6} Nm}$	$\mathbf{6.83 \cdot 10^{-6} Nm}$	$\mathbf{1.00 \cdot 10^{-5} Nm}$

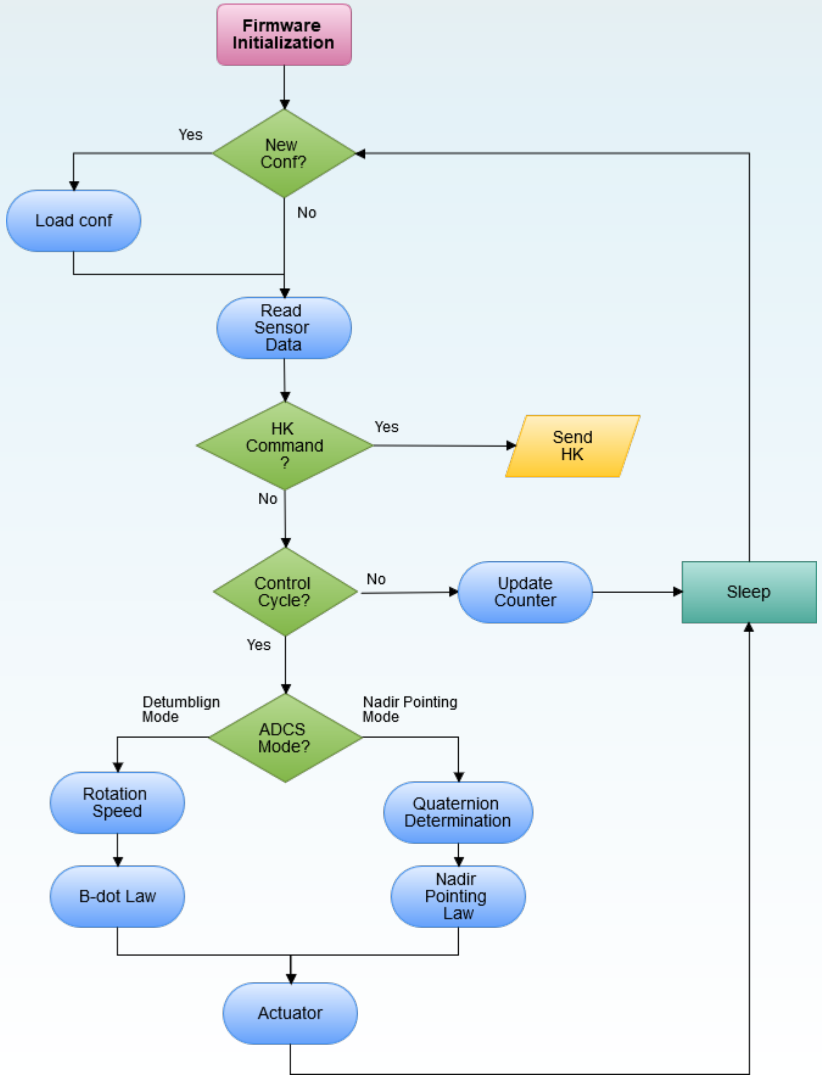
2.7. ADCS Firmware

→ Single Board with STM32L4

→ Sequential execution → Depending on mode
- Retrieve Sensor data
- Quaternion Determination
- Control Law
- Actuator activation

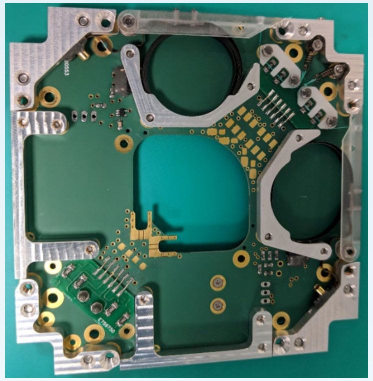
→ ADCS Control
- Detumbling
- Nadir-Pointing

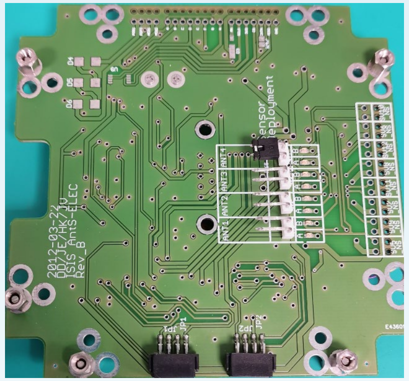
→ ADCS Determination
- Optimal REQUEST



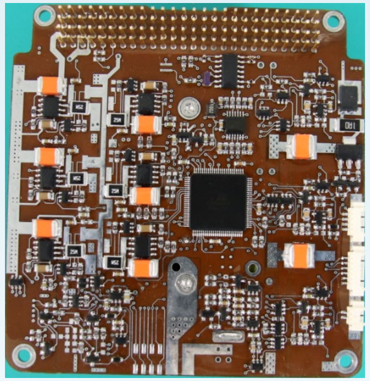
2.8. Assembly, Integration, Verification and Testing

Zenith & Antenna Deployment Subsystem

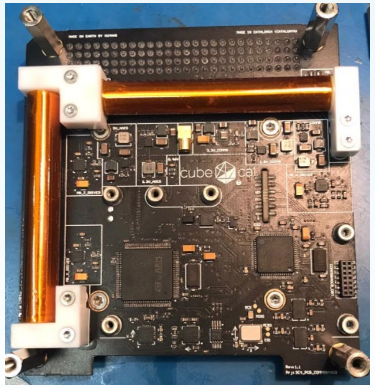


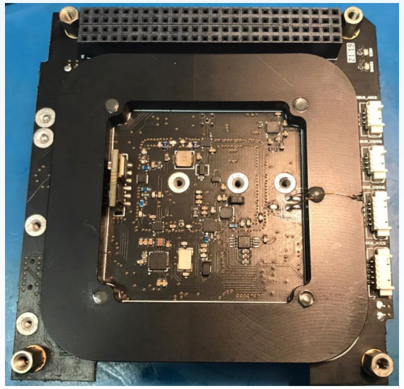


EPS board

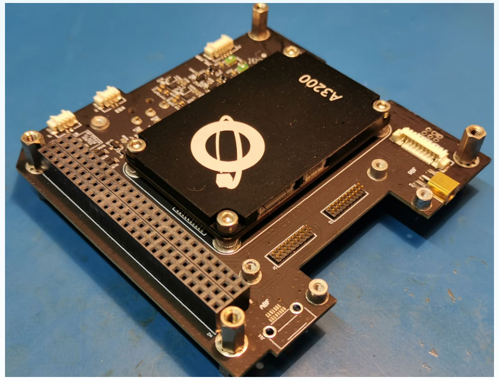


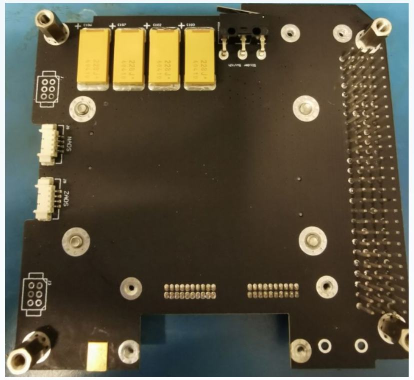
ADCS board

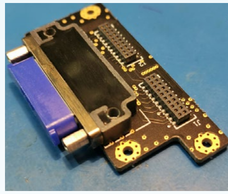




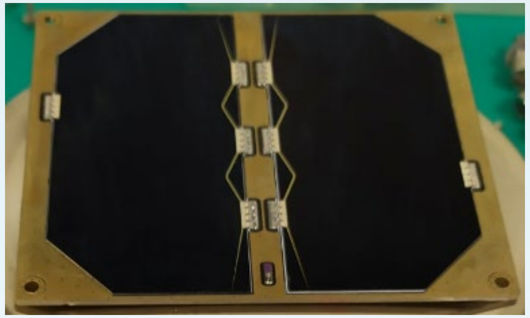
OBC and I/F boards



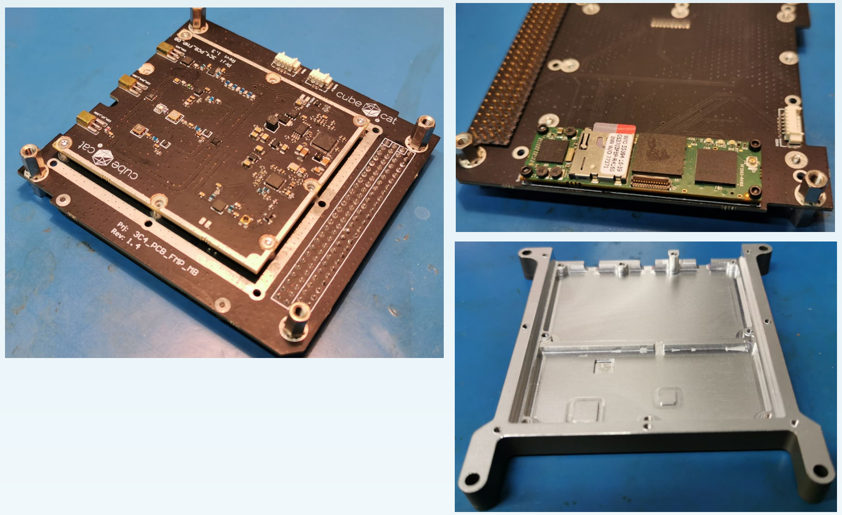




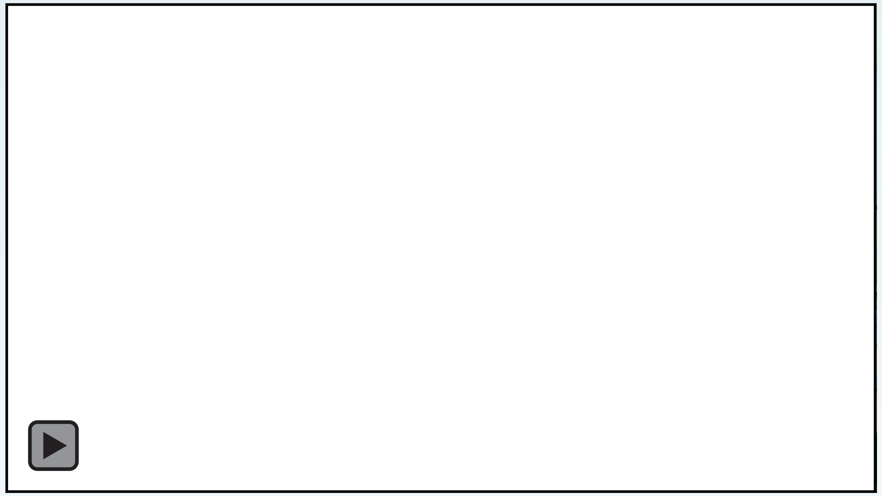
Solar panels

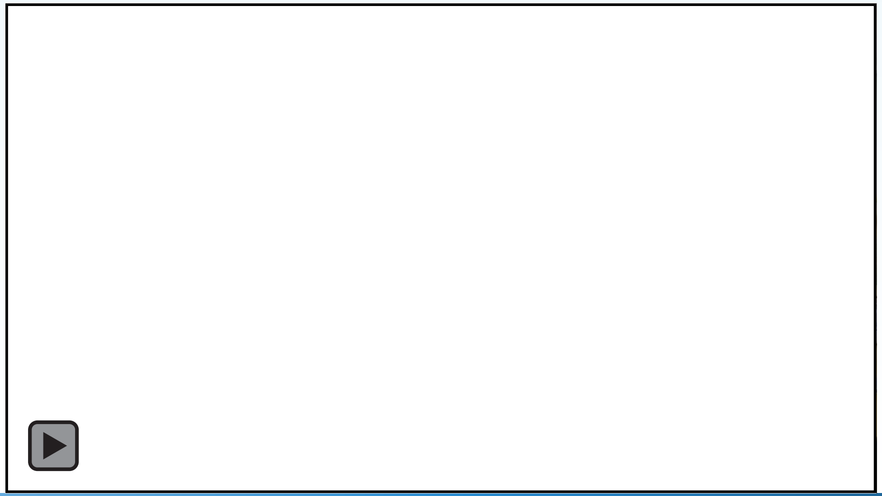


FMPL-1 payload

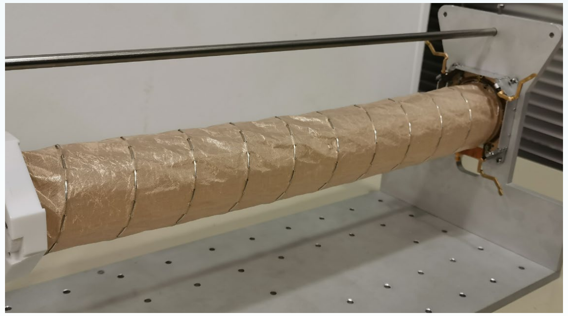


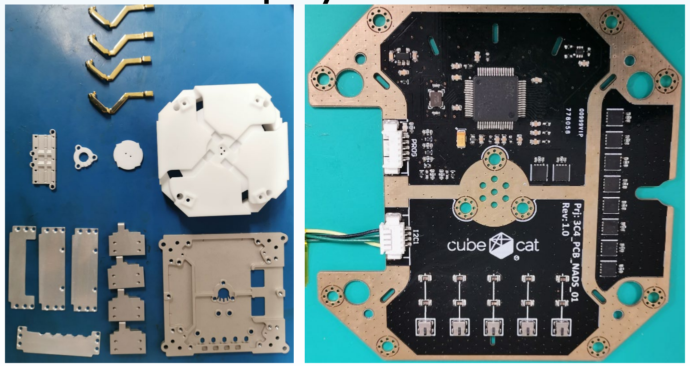
Deployable antenna testing



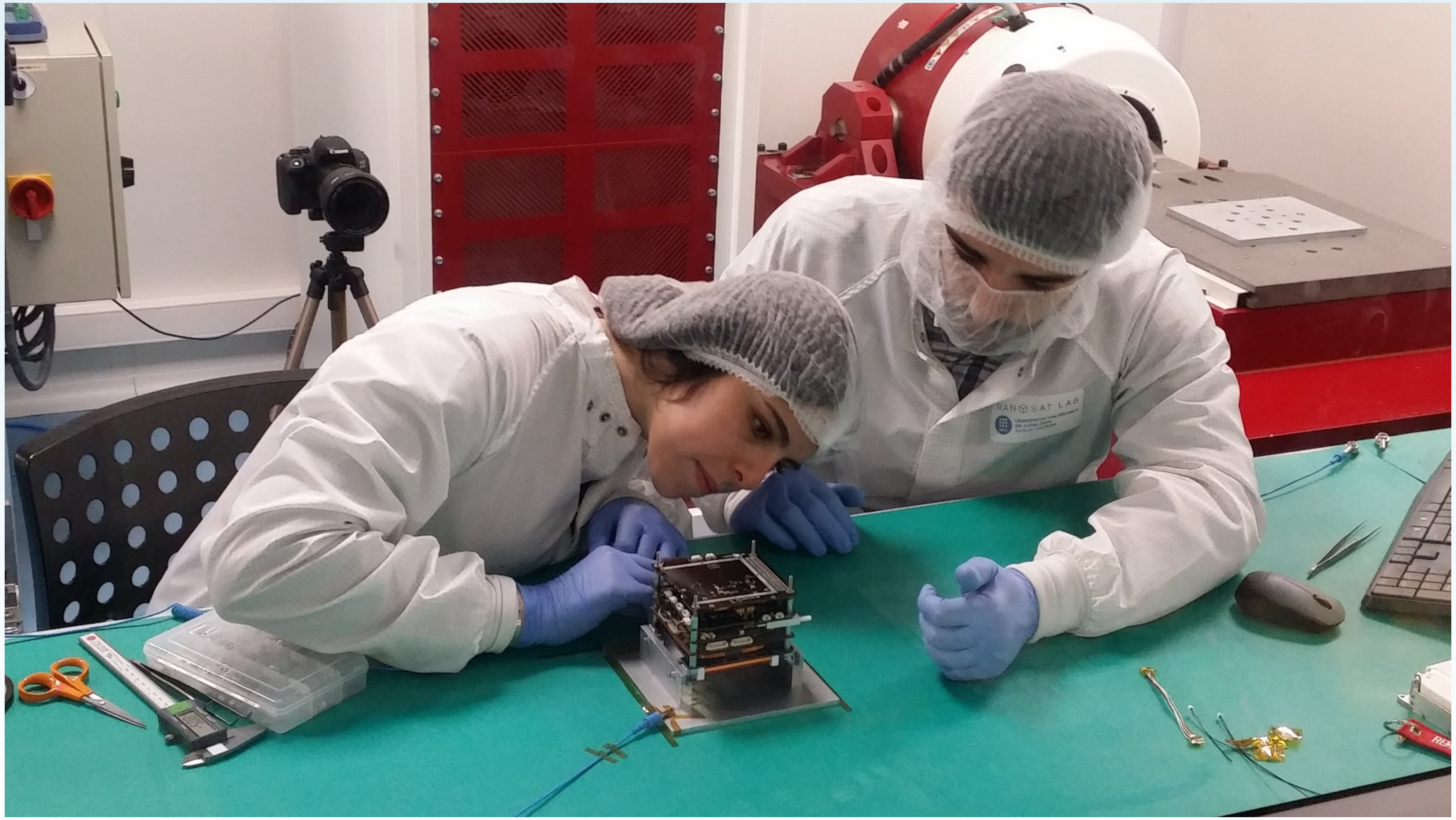


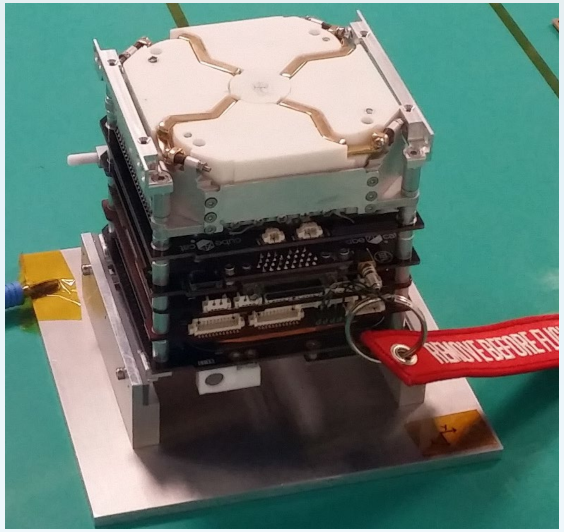
NADS board and deployable antenna

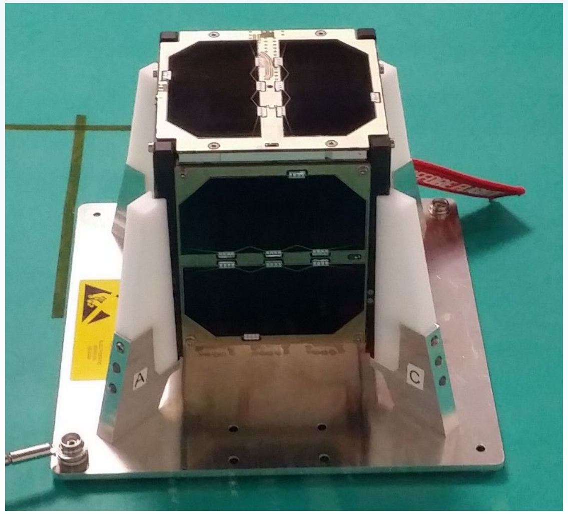




2.8. Assembly, Integration, Verification and Testing (ii): Integrated ^{3}Cat-4 S/C







Useful resources:

- **Power budget:** http://www.amsatuk.me.uk/iaru/Small_Spacecraft_Power_Budget-Rev3.1.xls
- **Mass budget:** www.amsatuk.me.uk/iaru/Small%20Satellite%20Mass_Budget_Rev1.2.xls
- **Link budget:** http://www.amsatuk.me.uk/iaru/AMSAT-IARU_Link_Model_Rev2.5.5.xls
- **Radio Regulations :** https://www.itu.int/pub/R-REG-RR-2016
- **IARU frequency coordination for amateur bands:** https://www.iaru.org/reference/satellites/
- **Simple reentry calculator:** http://www.lizard-tail.com/isana/lab/orbital_decay/
- **Radiation analysis SPENVIS:** https://www.spenvis.oma.be/
- **Orbit calculation (+ power + communications budgets) to be used during the hand-on session at the end of this tutorial**

  - Request a free OpenApp Trial (if possible before the tutorial): https://www.open-cosmos.com/open-app/#free-trial
- **UPC CubeSat Simulation tool:**

  https://drive.google.com/file/d/1MGIz5emMXfz944fBv6R8RMwbuGO05rt7/view?usp=sharing
- **FOSSASAT-1 github (open source PocketQube):** https://github.com/FOSSASystems/FOSSASAT-1
- **To know more on CubeSats status and applications:**

https://www.intechopen.com/online-first/nanosatellites-and-applications-to-commercial-and-scientific-missions

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NANOSAT LAB

Thanks everybody!

... stay tuned for the launch of FFSCat mission (^{3}Cat-5/A and /B) on March 24th!

https://nextspaceflight.com/launches/details/407

Live stream: https://www.rocketlaunch.live/launch/ssms-poc

and I hope to see you at the next GRSS Student Grand Challenge on CubeSats!!

UPC: The NanoSat Lab & CubeSat Missions

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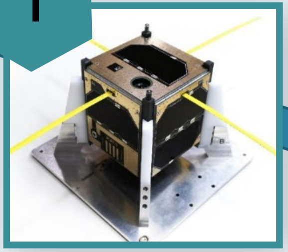
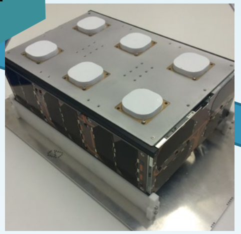
1

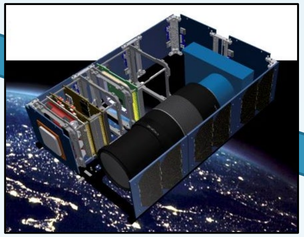


^{3}Cat-1 FM: 7 small P/Ls
Launch: PSLV, 29/11/2018

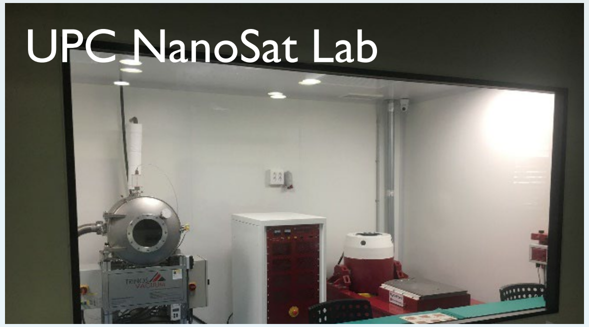
2



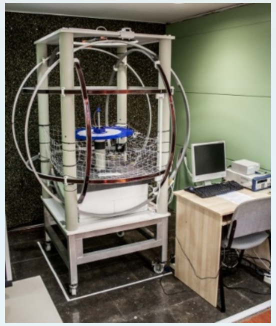
^{3}Cat-2 FM:
PYCARO: GNSS-R P/L: L1+L2, R&LHCP, GPS, Galileo, Glonass
Launch: LMD2, 15/8/ 2016



^{3}Cat-3 (artists view): Multispectral imager
Mission: in stand-by

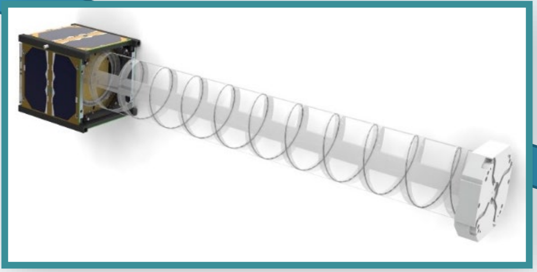


Clean Room facility (class 8): TVAC & shake table



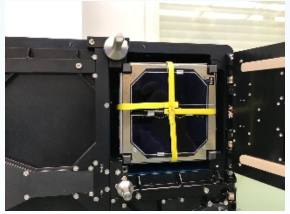
Helmholtz coils & air bearing

Montsec VHF-UHF + S-band ground station

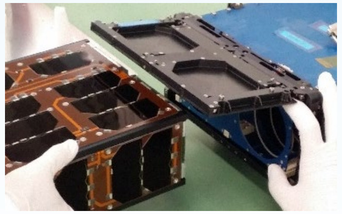


^{3}Cat-4:
ESA Academy: Fly your Satellite program
FMPL-1: GNSS-R + uW radiometer + AIS
Launch: ISS, H2-2019 (TBC)

FSSCAT: Copernicus Masters winner
^{3}Cat-5/A: FMPL-2: GNSS-R + uW radiometer
^{3}Cat-5/B: Hyperscout
Launch Vega SSMS, H1 2019



Integration: 19/7/2018



Integration: 21/6/2016

European Commission — EGEM — EUROPEAN GNSS-R ENVIRONMENT MONITORING