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Open Source CubeSat Workshop 2018

Formation Flying, an opportunity to enhance microwave cosmology with CubeSats

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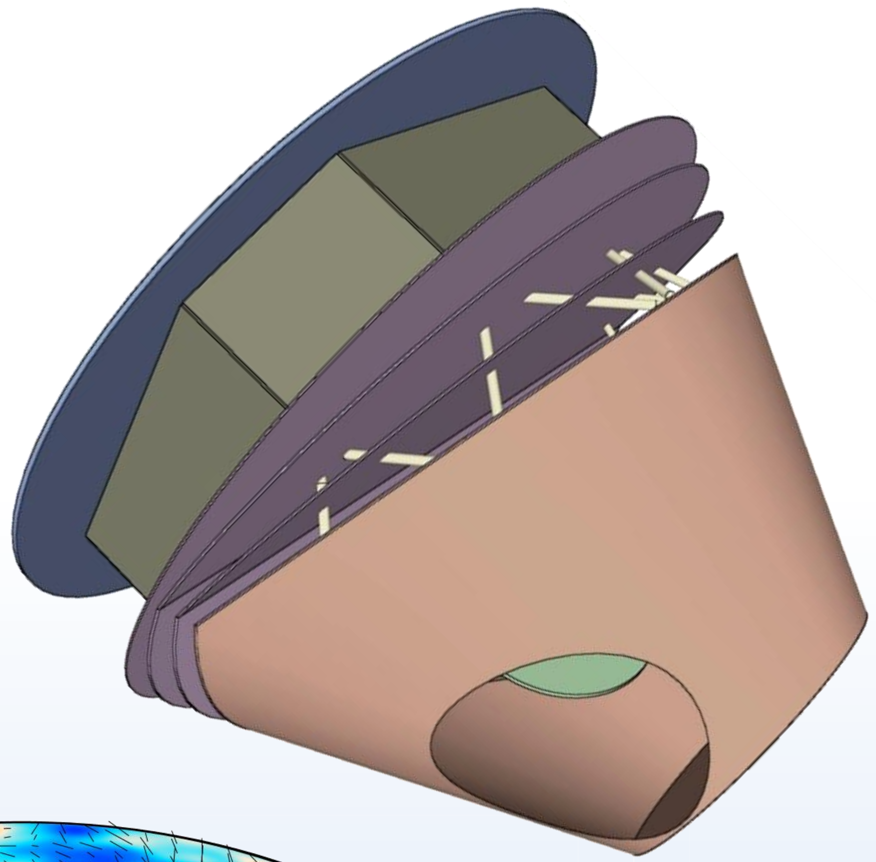
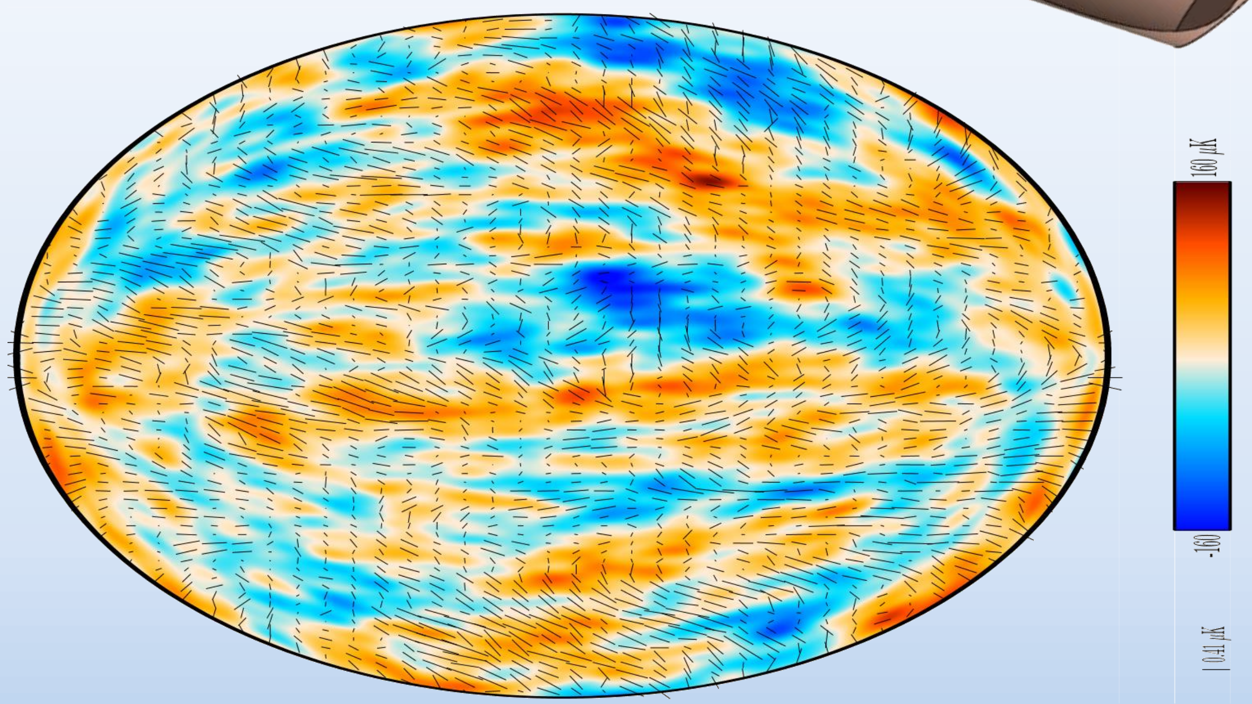
CMB L2 Space Missions



The main goal of the next CMB missions is the cosmological study of the physics of the early universe and structure formation by the precise observation of the Cosmic Microwave Background (CMB) polarization in all sky and in a wide frequency range (~ 40-400 GHz).

Specific Goals:

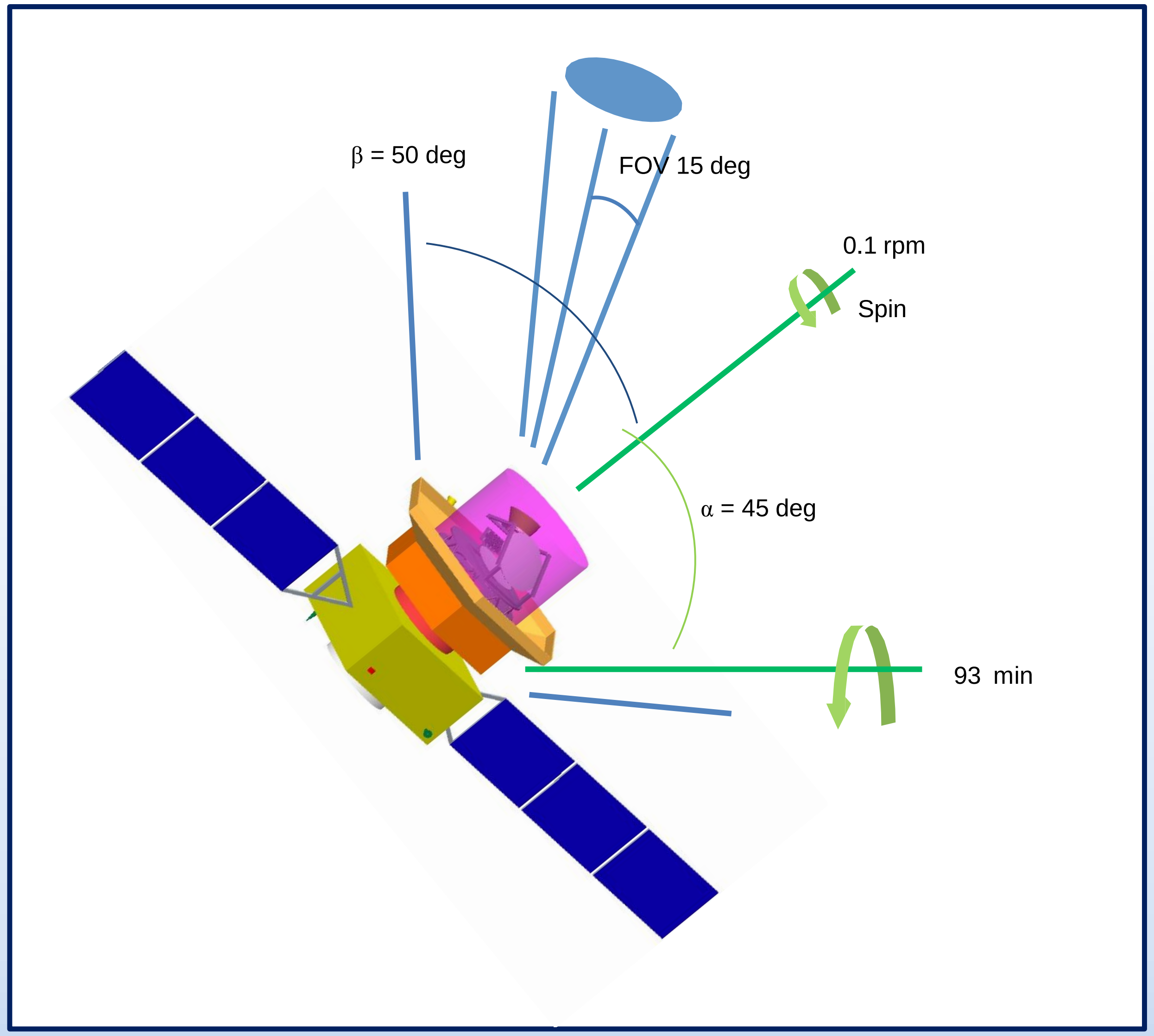
- Probe the physics of inflation
- Determine the number of relativistic species
- Determine the neutrino mass
- Provide information on the Dark Energy and Dark Matter
- Precise determination of the reionization epoch



CMB Temperature and Polarization. ESA and the Planck collaboration. 2018

Sky Coverage

Example of Observation Strategy



Telescope sweeps the sky due to its double rotation

If period of intrinsic rotation is not multiple of period of precession, the axis of the instrument tends to cover the entire hemisphere except a hole in the centre with angular radius

https://www.geogebra.org/m/Nj4SAAvD#material/nQWXemqX

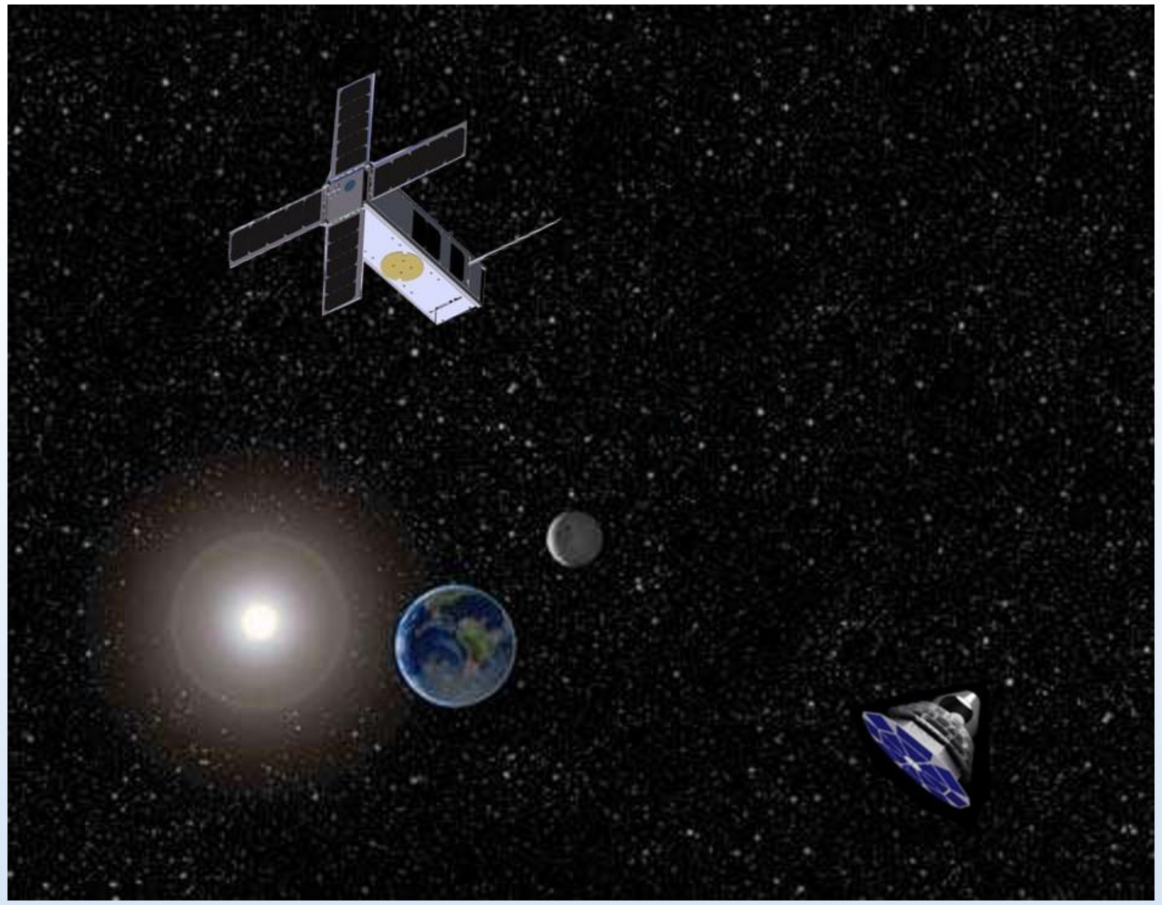
CMB telescopes

- Need a calibration method providing control over **intensity**, **polarization** and **radiation pattern.**

- This **limits the accuracy** on the CMB science.

- Space telescopes have reached unprecedented sensitivity levels, resulting in systematic effects being the major source of uncertainty**.**

The CubeSat flies calibration sources within view of the main satellite experiment, emitting mw radiation from the telescope's far field.



Artist's view of two satellites in FF. Calibration system in 3U CubeSat (Up-Left). CMB polarization measurements spacecraft (Down-Right). From Federico Nati.

CalSat

- Calibration system for the calibration of CMB space telescopes in L2.

- Formation flying between calibrator and the CMB telescope.

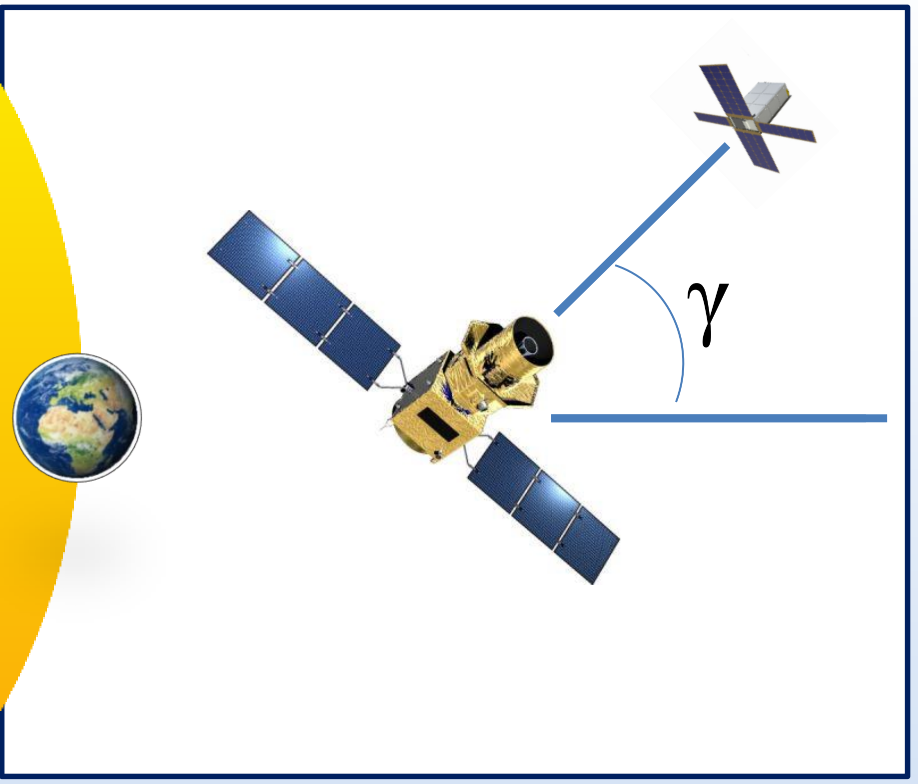
- Launched as a piggy-back.

- Exploring the feasibility of an ancillary calibration satellite.

- Operating from the far field of the telescope (hundreds to thousands of metres).

Relative position Telescope-CalSat

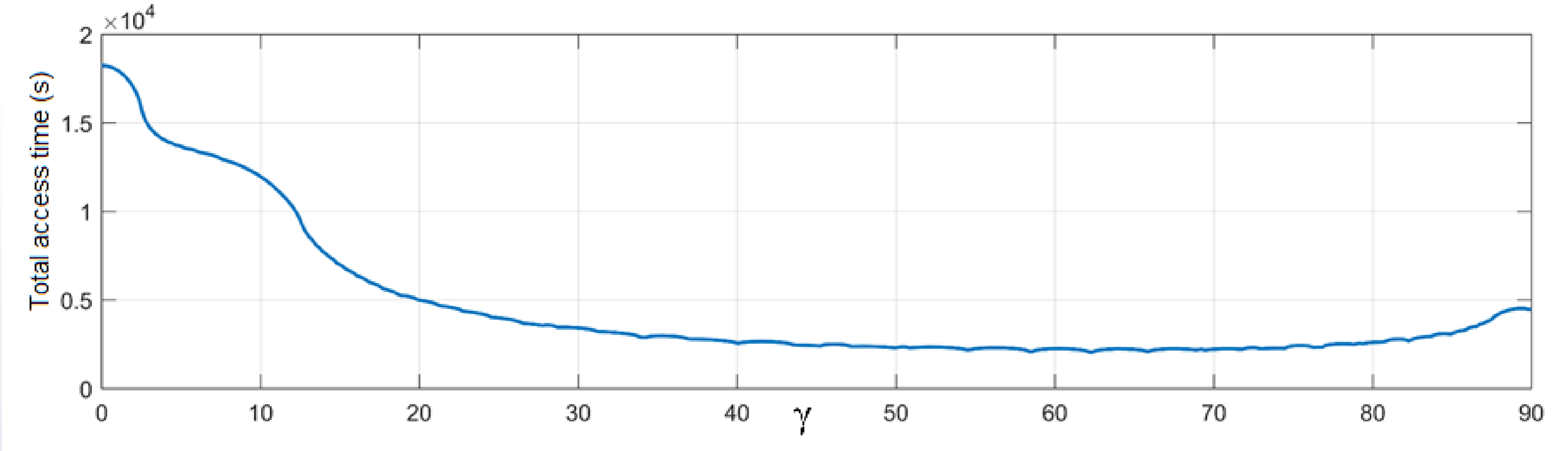
Where to place CalSat?



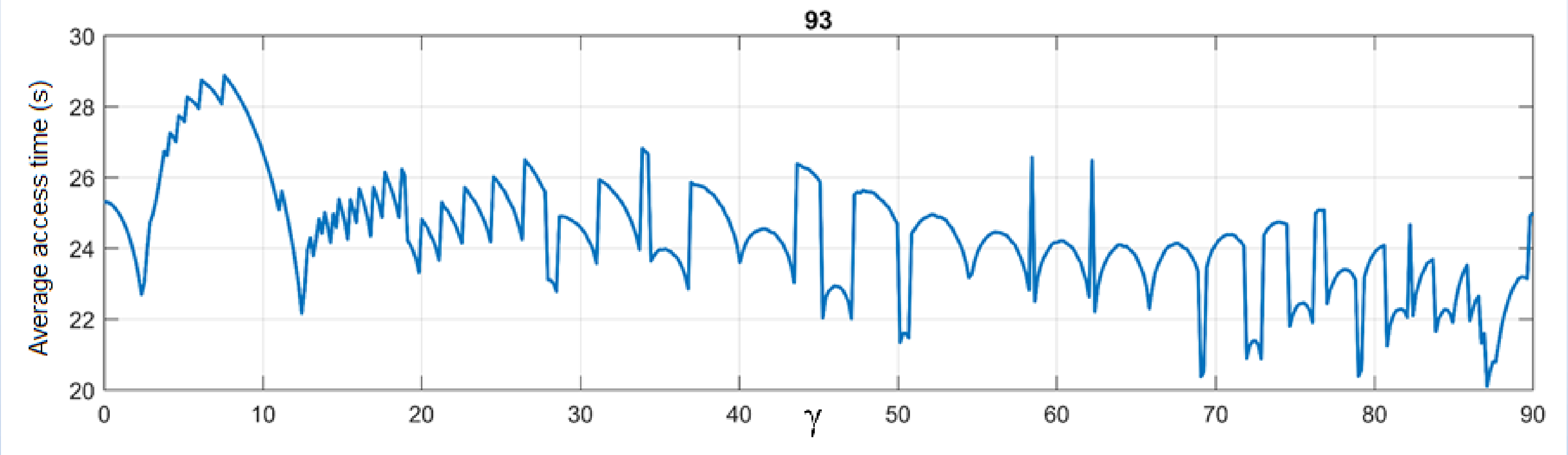
- For long times, better positions for maximizing access only depend on γ and FOV.

- The point in the anti-sun direction is never crossed by the instrument axis, but if
- $\beta - \alpha <$ FOV the instrument sees it in every turn

- For different γ, the number of times that the CalSat is inside the instrument FOV changes.



Total access time during one day depending on γ



Average access time during one day depending on γ

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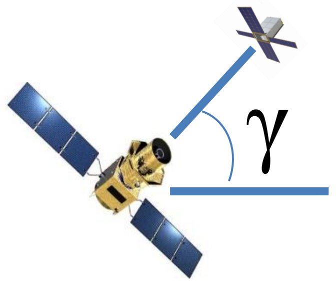
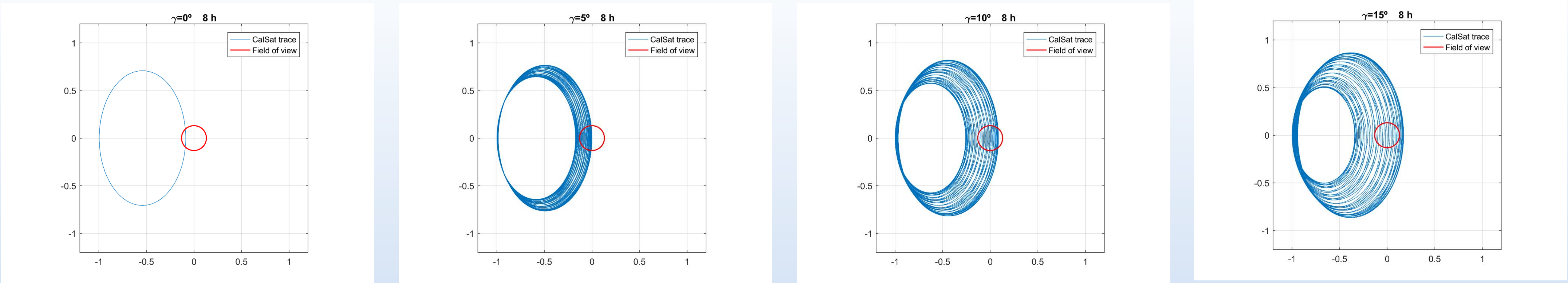
Relative position Telescope-CalSat

Where to place CalSat?



During calibration process the CalSat should cross the FOV several times and through different areas to allow a complete calibration of the sensor.



CalSat trace in sensor frame for different values of γ

Due to the geometry, the pointing of CalSat only crosses all the FOV if γ > FOV

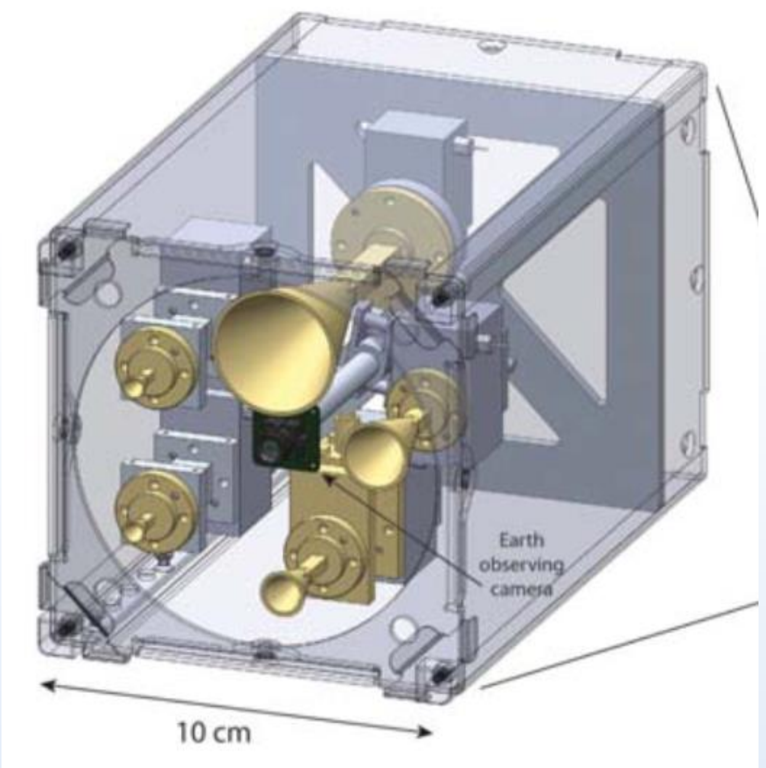
Payload of CalSat

Calibration Source

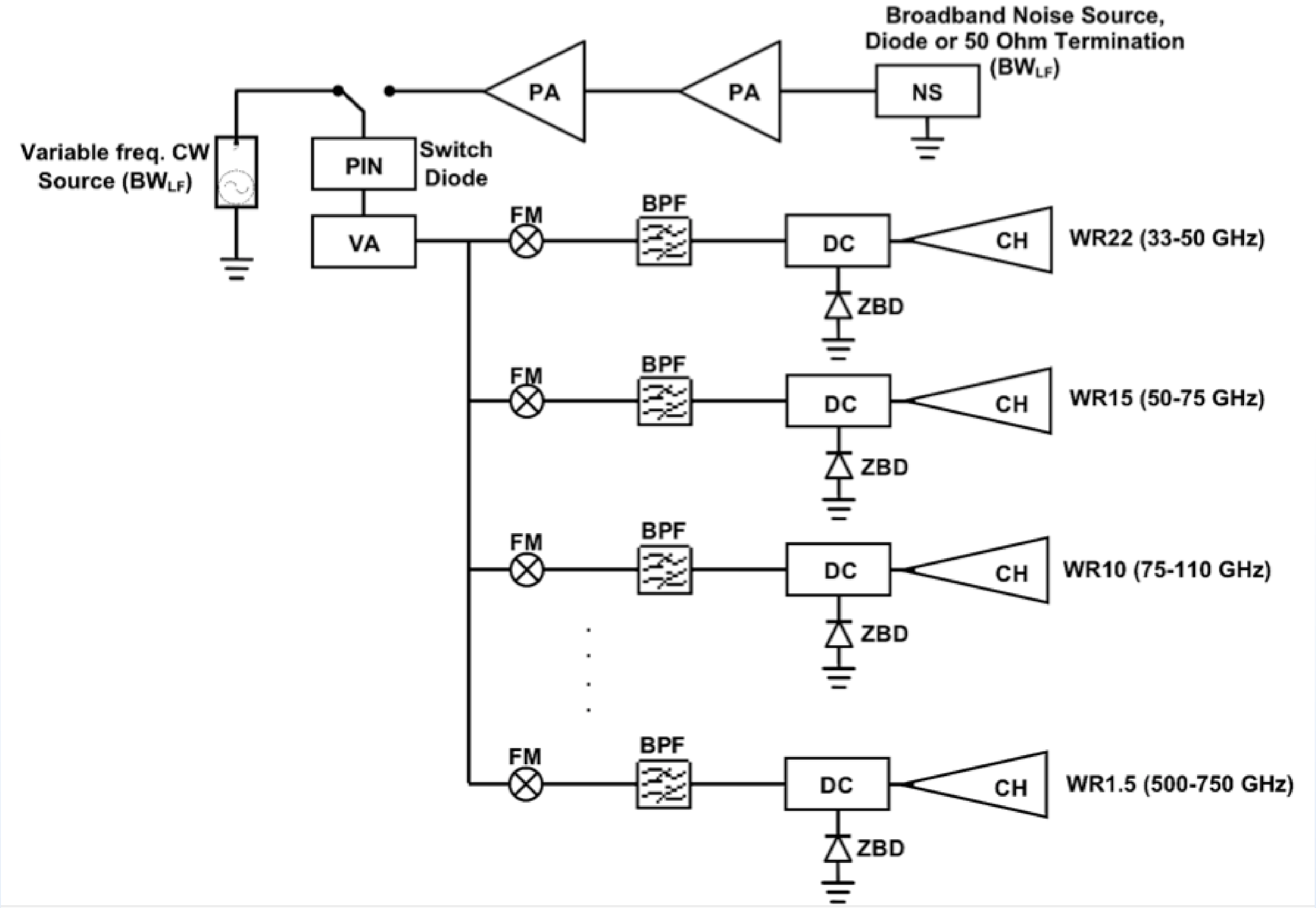
- Adjustable output power & low power consumption.

- High polar purity (about -60 dB x-pol.) and low polar angle error (< 1 arcmin.)

- Wideband covering the proposed space-missions (Typically 40-400 GHz)



Calibration Source* representation with a 1.5 U volume.
We assume 2U volume for our case.



Calibration Source scheme covering 33-750 GHz bandwidth. Low-frequency noise and variable CW signals are up-converted using frequency multipliers and filters

* from [1] Bradley R. Johnson et Al.

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Mission requirements summary

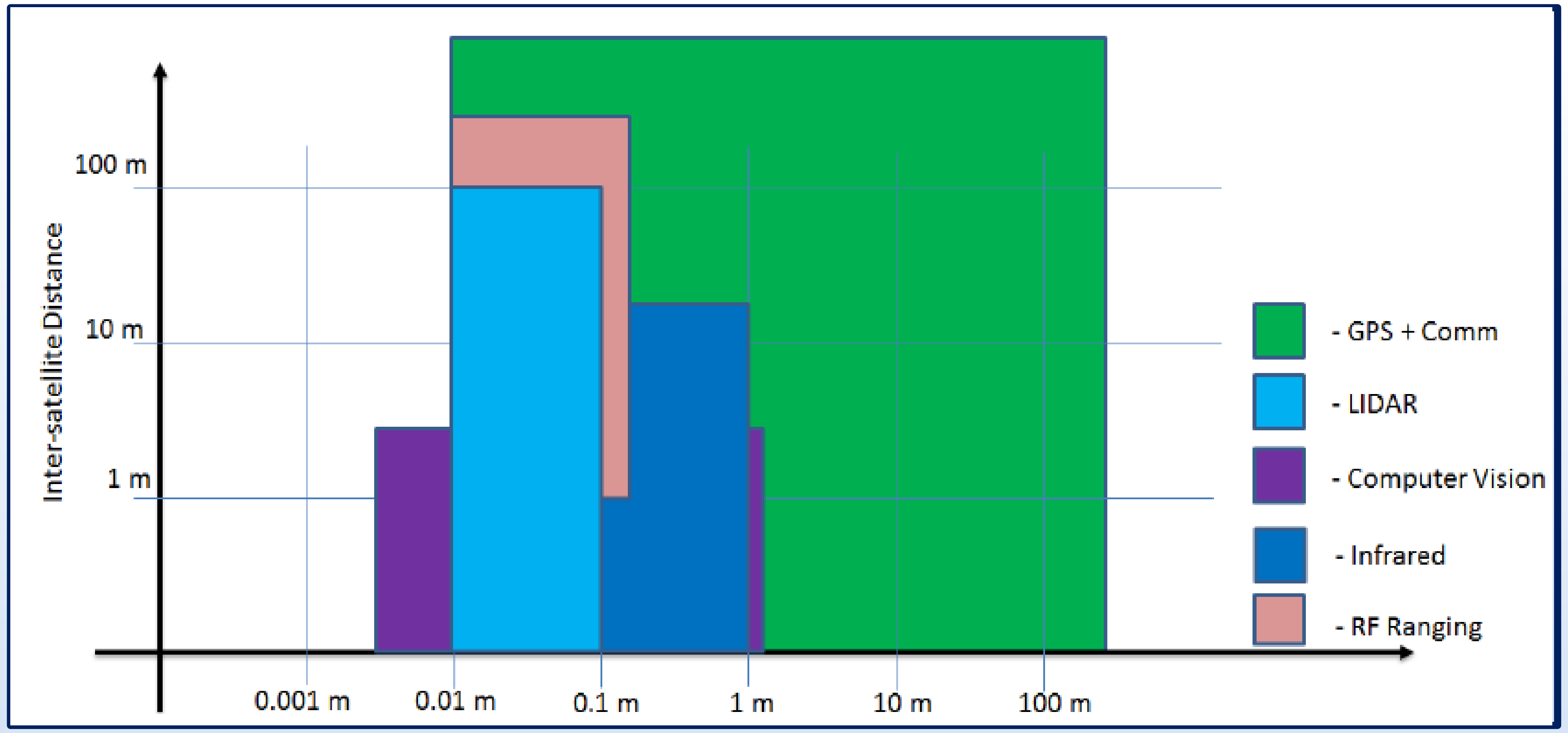
Requirements	Value
The CalSat shall maintain the orbit during 3 years	3 years
The CalSat shall be at a distance d from the main telescope vehicle	240 < d < 300m
The CalSat shall maintain a distance during the calibration	270 ± 2.7m
The sensors shall locate the direction of the main vehicle	error < 10’
The CalSat shall point to the telescope	error < 3’
The sensors shall know the CalSat orientation	error < 1’
EPS shall provide enough energy allowing 2 calibrations per month	> 28W
The distance sensor shall be able to calculate the distance between	error < 13.5 cm
Propulsion system shall be able to provide orbit and attitude control	

Critical Technologies

Relative position determination

The precision needed in relative position determination is very high (dozens of cm) for the desired distance (~300 meters)

- GPS is not available in L2
- The available power is limited
- The computational capacity is limited
- The Main Satellite should collaborate as little as possible



[2] G. Subramanian et al

Proposed Hardware

Relative position determination

RF ranging in S-band

- Allows distances and precision that we need
- Communications with the same instrument

Commercial example: Swift RelNav

- Relative Range Measurements: < 0.1 m (1-σ)
- Relative Attitude Measurements: < 1.0˚ (1-σ)
- >1 year LEO mission design life
- 86x45mm (0.375U) w/chassis
- 400 grams (with 4 antennas)
- Flexible mounting options
- 6-36V unregulated DC
- Duty cycle dependent power consumption
  Approx. 10W @ 100%

Swift RelNav

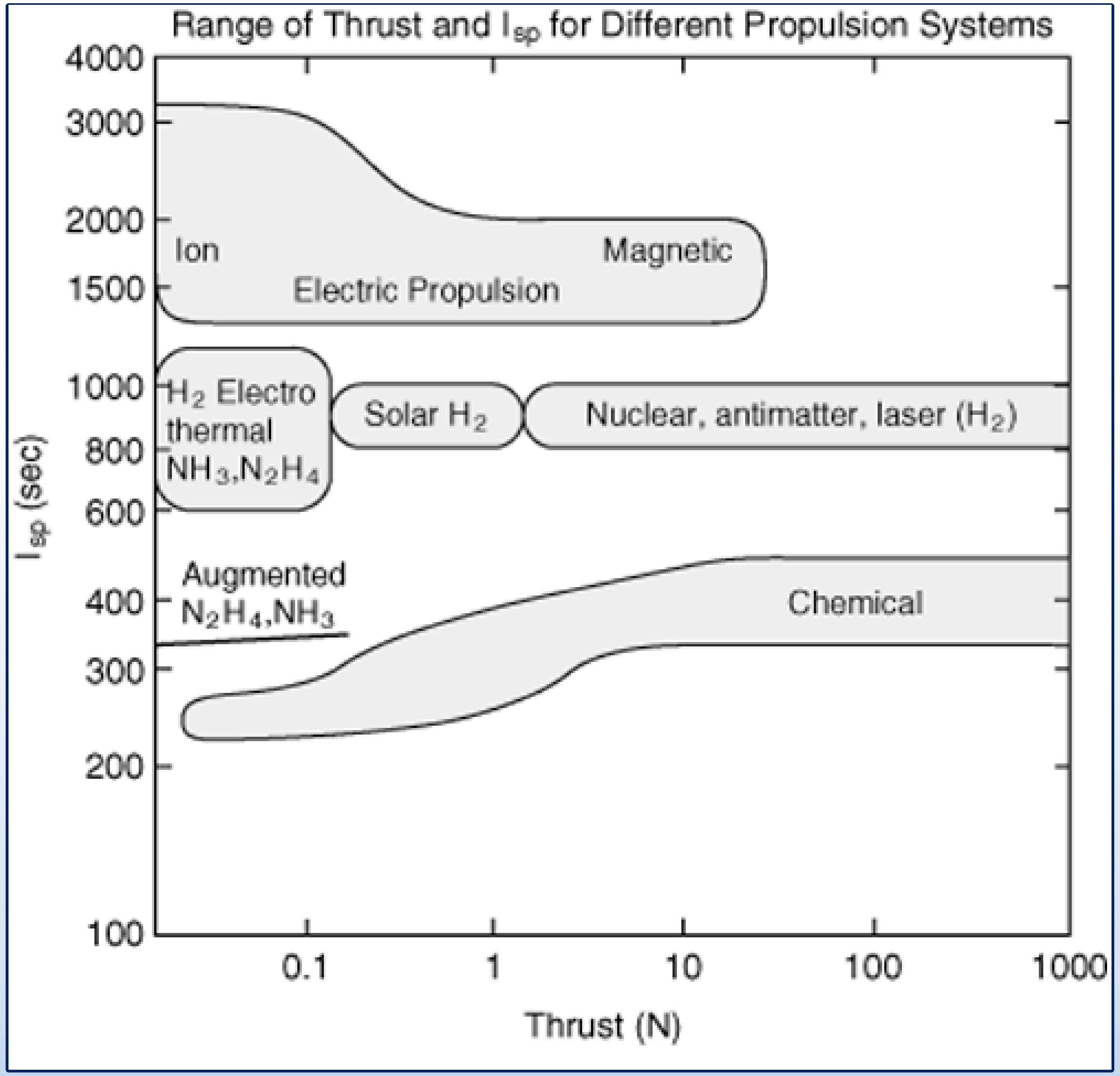
[3] Tethers Unlimited

Critical Technologies

Propulsion

The needed thrust for precision FF of CubeSats is very small.

- **The total Δv for the mission is relatively high because it needs FF and orbit corrections**
- **But the minimum impulse needed is very small**
- **Precise thrusters with small thrust like ionic thrusters are big, expensive and consume a lot of power**



NASA

Proposed Hardware

Propulsion

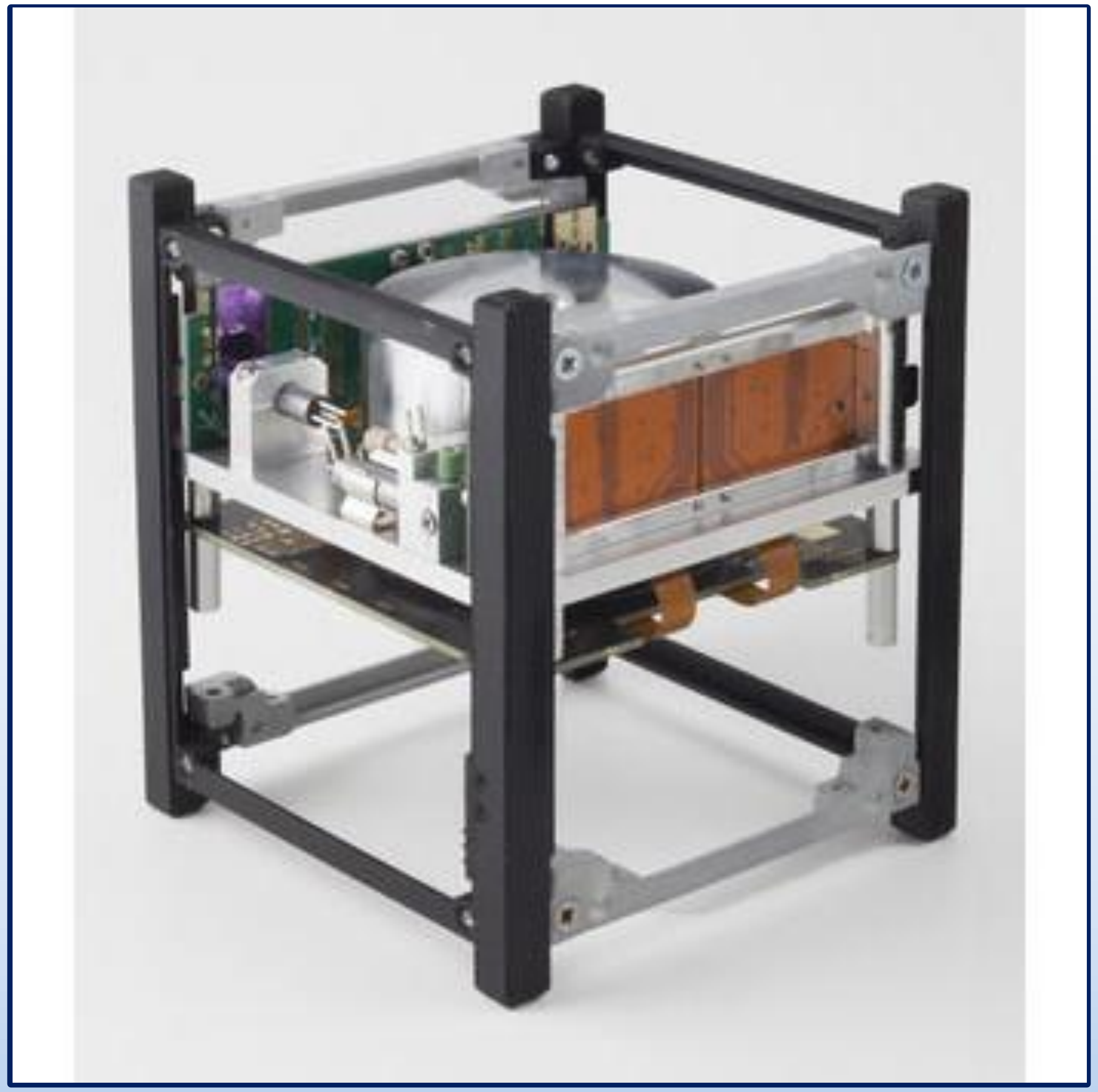
Cold Gas Propulsion

- Allows small and precise impulses (mN)
- Enough total impulse
- Low power consumption

Commercial example: NanoProp CGP3

- Thrust: 1mN
- Thrust resolution: 10 μN
- Specific impulse: 60-110 sec
- Total impulse 40 Ns
- Power consumption < 2W (average)
- Mass 300/350 g (dry/wet) (butane)
- Operating pressure: 2-5 bar
- Temperature range 0º to 50º C
- 100x100x50 mm (including electronics board)

GOMSPACE NanoProp



[4] GomSpace

CubeSats FF Mission Examples

Chinese Academy of Science proposal
12 3U CubeSats FF in L2
Ultra-Low Freq. Antenna 3-100 MHz

Pros

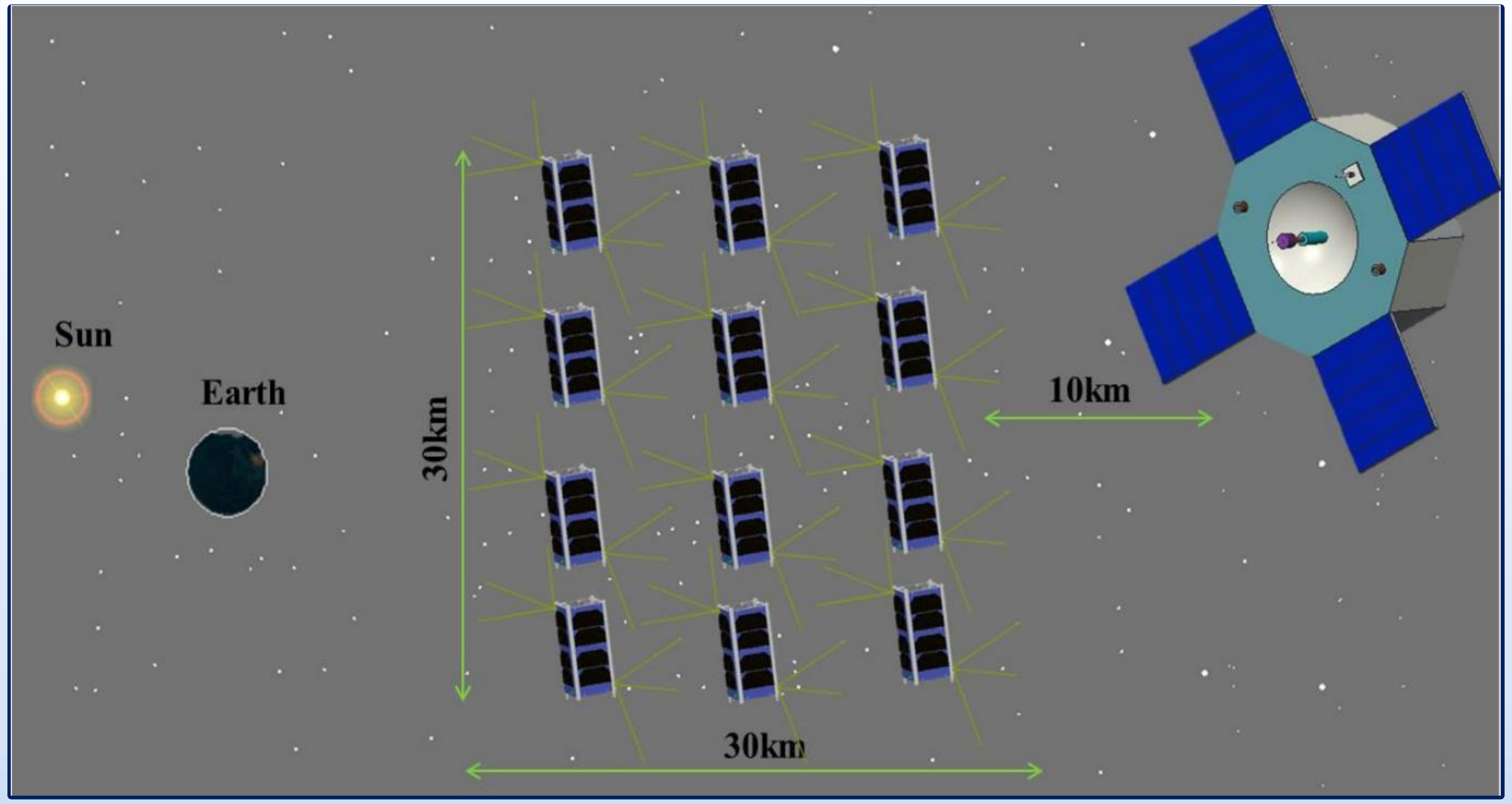
- Similar needs of position determination
- **S-Band ranging**
- **Butane micro-thrusters**

Cons

- Not tested or approved
- Constellation

SULFRO

Space Ultra-Low Frequency Radio Observatory



[5] S. Wu

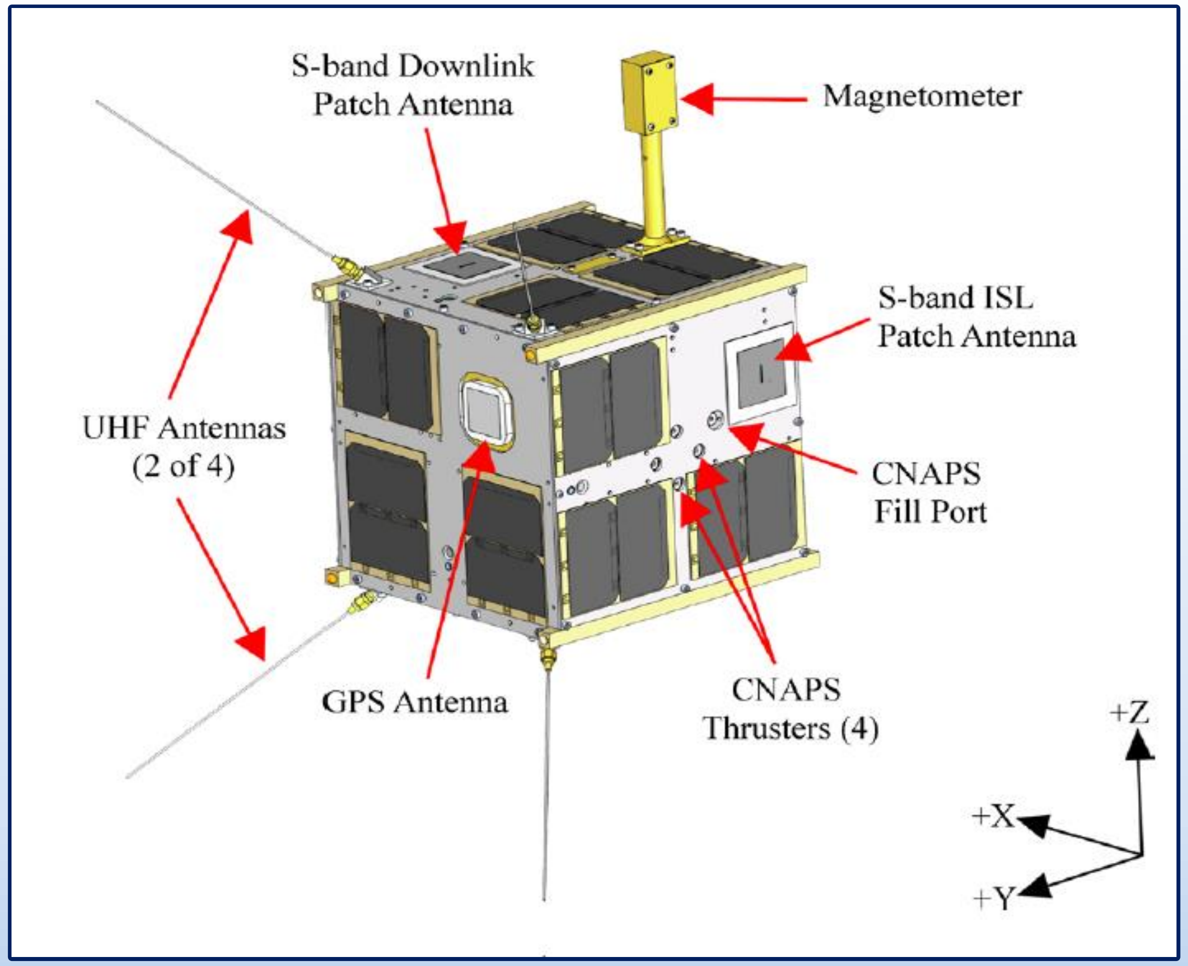
CubeSats FF Mission Examples

Toronto University Mission
2 8U CubeSats FF in LEO
FF demonstrador

Pros
- **Successfully tested**
- Similar needs of position determination
- SF_6 micro-thrusters
- S-Band communication

Cons
- GPS position determination

CanX 4-5

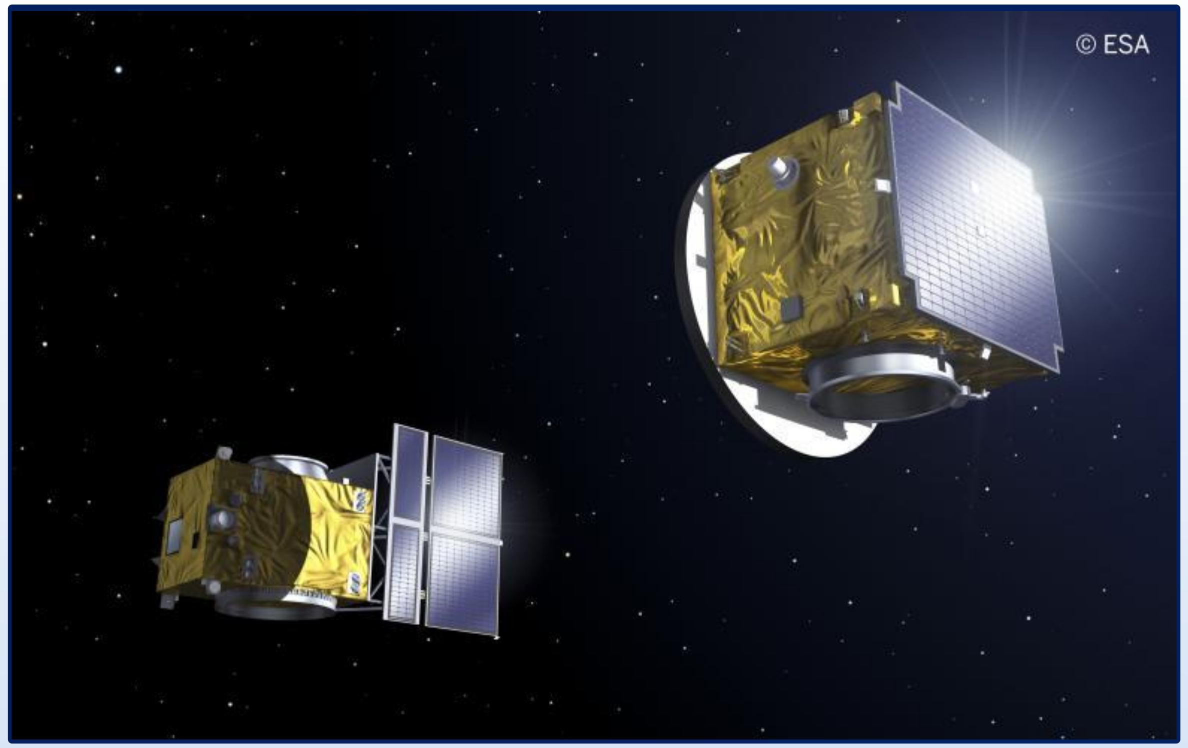


[6] N. Roth

CubeSats FF Mission Examples

ESA Mission
2 Spacecrafts FF in highly-elliptical orbit
FF demonstrador & solar coronagraphy

PROBA 3



[7] J. Llorente

Pros

- Higher needs of position determination (sub mm)
- Progressive metrology GPS→CLS→ FLLS (Laser)
- Cold gas thrusters (10 mN) among others

Cons

- Not tested yet, but advanced stage
- **Not a CubeSat mission**

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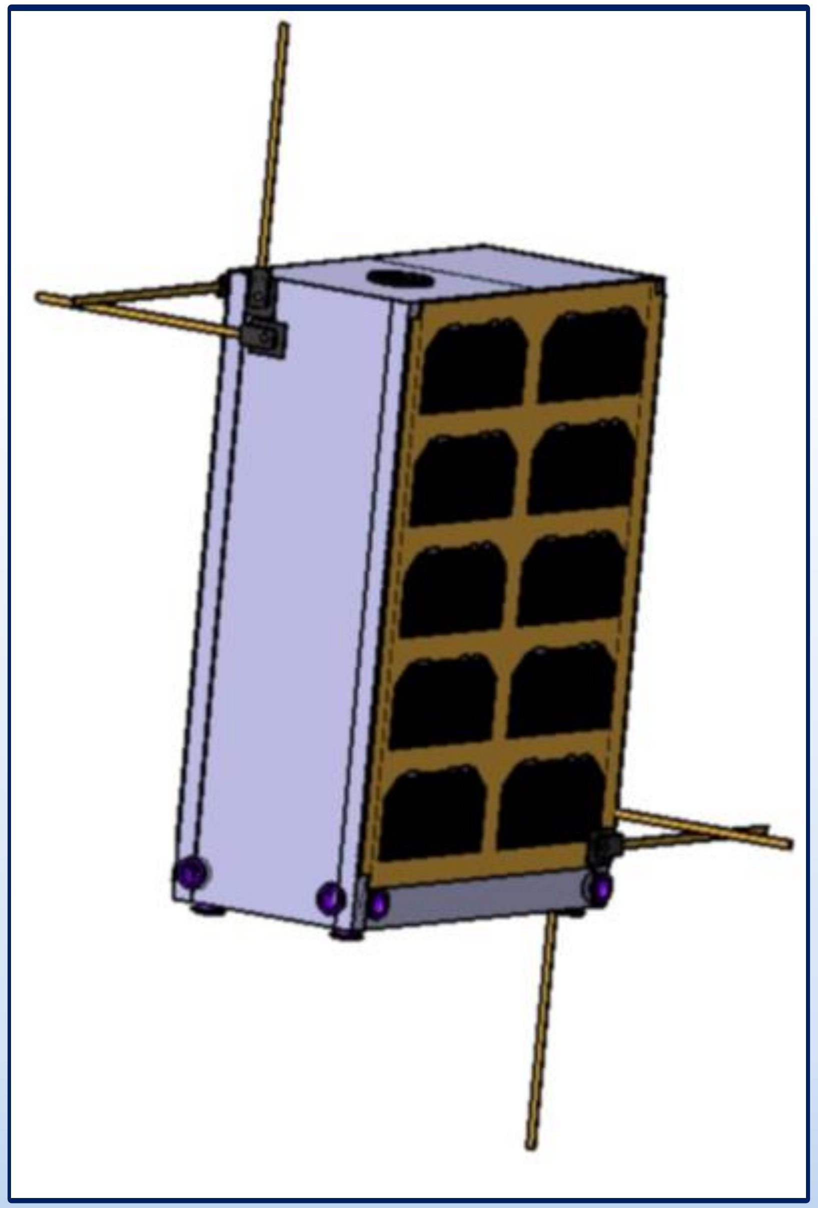
CalSat predesign



Design in CDF Facility

- 12 Workstations
- ESA client / server software OCDT
- ConCORDE Add-In Domain Tools.
- Own design modules for subsystems.

Main characteristics

- 6U CubeSat
- ~ 6.8 kg
- 2 deployable solar panels
- Continuous power generation of ~ 16.5 W BOL / ~ 16.3 W EOL
- RF ranging (S-Band)
- Available Δ*v* for the mission ~ 21 m/s

Concurrent Design Facility at IDR/UPM

Montegancedo Campus

Total Δ v

- The Δ v for maintaining a Lissajous orbit is very low 1.8 $ms^{-1}year^{-1}$·3 years·1.25 margin = 6.8 m/s
- Deployment can be performed with 0.2 ms^{-1} similar than PROBA-3
- Based also in PROBA-3, Δ v for FF maneuvers has been estimated in 14 ms^{-1}

~ 21 m/s

Mission

AOCS

- 2 Star trackers
- 6 Sun sensors
- 3-axis gyro
- RF ranging (S-Band)
- 3 Reaction wheels
- Cold gas thrusters (200 g butane)

Power

- The total power available comes from the solar panels: Area = 0.12 m^2; Cell eff = 28%
- Continuous power generation of 16W
- The battery has a total capacity of 80 Wh
- With the battery fully charged the CalSat is able to perform calibration (~35 W) during more than 2 hours

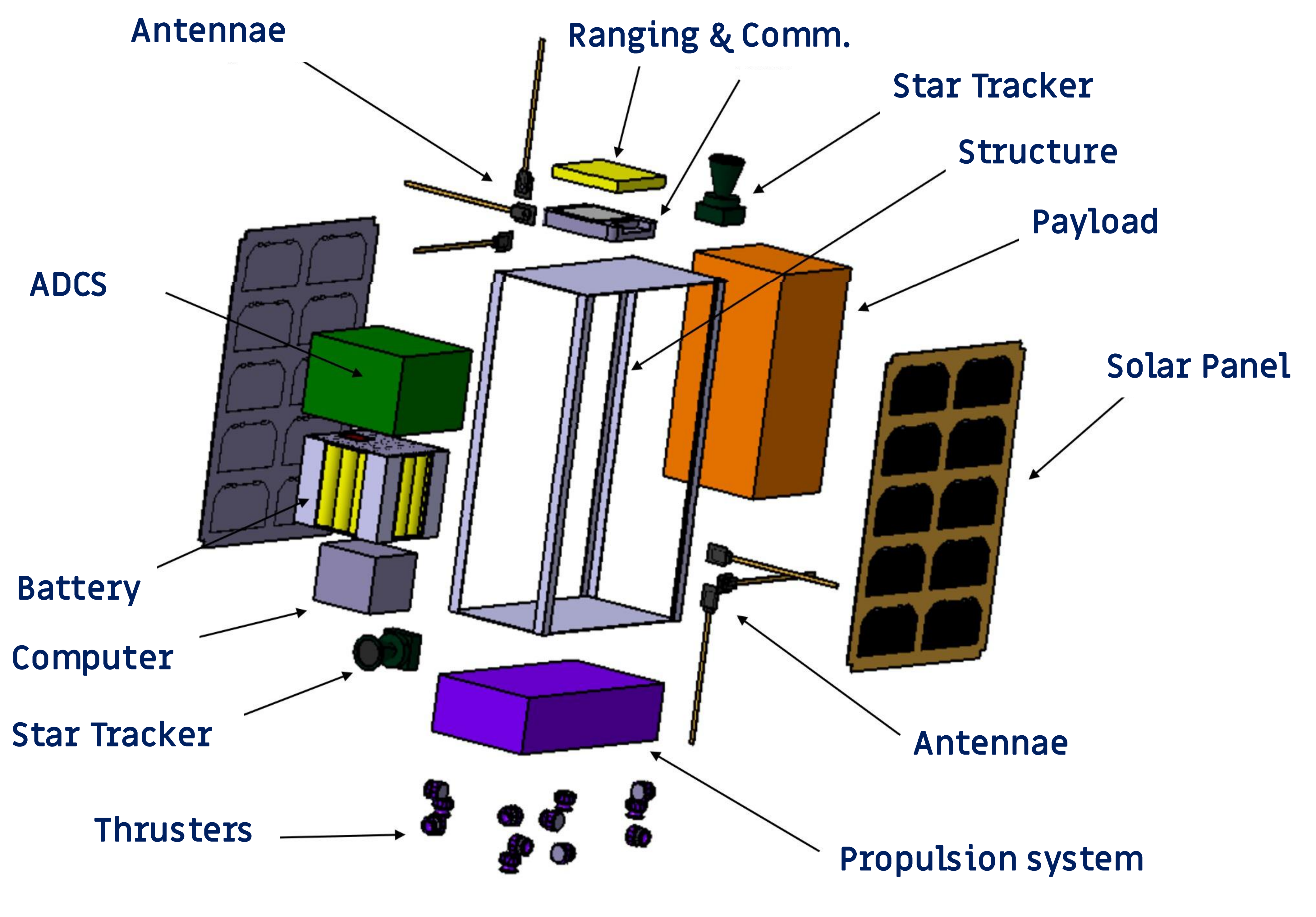
CalSat predesign

Dimensions

Subsystem	Height [mm]	Length [mm]	Width [mm]
Antenna	3	140	16
Radio	13	67	79
Structure	300	100	100
Propulsion (engine + tank)	50	98	198
Solar panel	280	202	1
Battery	76	90	90
Radiators	50	50	2
Sensors (ADCS)	55	30	30
Actuators	10	15	15
Payload	98	98	198

Mass and Power Budget

	Mass [kg]	Power [W]
S/C Dry mass	6.2	
ADCS	0.93	3.78
Communications	0.48	
Payload	1.28	30.3
Power	2.23	1.12
Propulsion	1.2	2
Structure	0.8	0
Thermal	0.15	-



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4 **Future Challenges and Conclusions**

Conclusions

- **Critical technologies for the mission have been tested and available as commercial products.**
- **The concept of the CalSat is feasible**
  - 6U CubeSat with all the instruments and subsystems.
  - Power production is enough.
  - Attitude and position determination can be performed with the desired precision.
  - Position control can be performed with the desired precision.
  - Needs of total Δv for the entire mission can be achieved with the proposed thrusters.
- **For the ranging method proposed, the CMB telescope needs to collaborate in position determination.**
  - A small and autonomous S-band transceiver is enough.

Future challenges

Minimize even more the impact of the calibration satellite on the telescope

- Optical camera for ranging?
- Operation without telemetry?

Fly with next CMB mission (e.g. LiteBIRD) as Science Enhancement Experiment

Apply the concept to future missions

- PICO, CMB-Bharat
- Other missions to Lagrange points

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[3] Tethers Unlimited, "SWIFTTM-RelNav" Available: http://www.tethers.com/SpecSheets/Brochure_SWIFT-RelNav.pdf.

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[6] Roth, N., Risi, B., Grant, C., and Zee, R., "Flight Results From The Canx-4 And Canx-5 Formation Flying Mission," Proceedings of Small Satellites Systems and Services-The 4S Symposium., 2016, pp. 1–15

[7] Llorente, J. S., Agenjo, A., Carrascosa, C., de Negueruela, C., Mestreau-Garreau, A., Cropp, A., & Santovincenzo, A. (2013). PROBA-3: precise formation flying demonstration mission. Acta Astronautica, 82(1), 38-46.

Muchas gracias

Thank you very much

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