LEO-CalSat for the Calibration of W-band Ground-Based CMB Polarization Experiments

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IFCA[1] and UPM-IDR[2]

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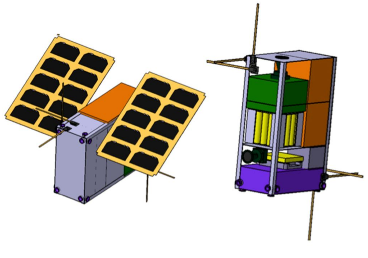
Motivation

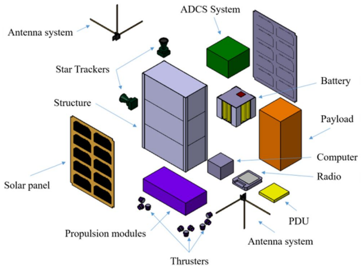
- The **high sensitivity** that the new generation of ground-based and space-based **CMB telescopes** must achieve to detect the **primordial B-mode** signal requires **very precise calibration** processes.

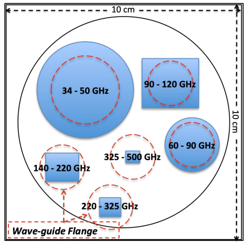
- **Celestial** polarised **sources** (like Crab) are **not** characterised with the **required accuracy.** Non-polarised sources (like Jupiter) hardly reach the required noise-floor for the characterization of the intensity beam.

- Proposals of l**ow-cost calibration satellites**: During calibration, the sources on-board CalSat emit purely polarized microwave radiation f**rom the far field** towards the CMB telescopes.

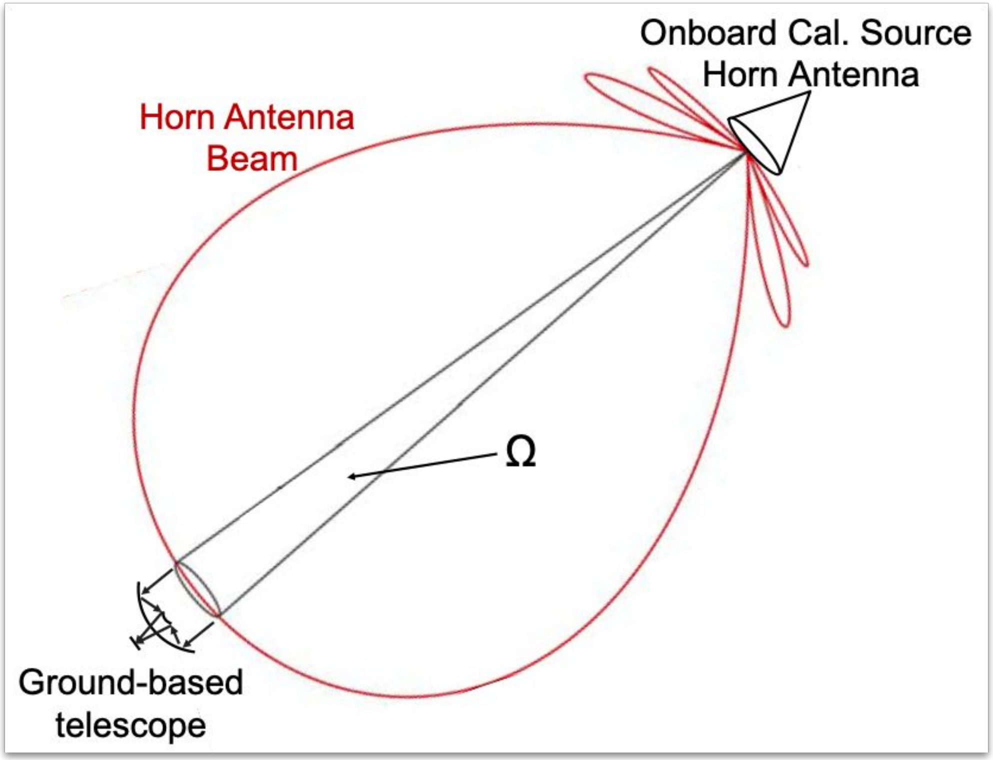
- During the previous years a CalSat for a space misión at L2 (L2-CalSat) was proposed and some preliminary studies were done (*Casas, F.J. et al., Sensors, 2021, 21, 3361; Bermejo-Ballesteros, et al., J Astronaut Sci, 2022*)







Motivation



* Work based on
B. R. Johnson's
DOI: 10.1142/S2251171715500075

experiments*. The interest is twofold: well calibrated ground-based experiments can help the calibration of **L2** missions, while **increasing the TRL** for L2.

LEO-CalSat Schedule

- We had an **opportunity to use a new rocket** (Spectrum from ISAR) to launch a microSAT (UPMSat-3) with a calibration source as part of the payload.

- The satellite is expected to be in a **sun-synchronous LEO** orbit at about 400 Km altitude.

- The **development** of the calibration signal **source** could **not** be well **synchronized** with the **satellite's** development **program** and launching expected date (initially expected launch date between Q4-2023 / Q1-2024).

- **New opportunities:** UPMSat-4 is one of the shortlisted for the Spark-program of PLD's Miura-5 rocket. On November 30th we should know if we are selected.

- We are **currently** working with the **MIURA** option, **launch date of Q1 2026,** for a LEO-CalSat for ground experiments operating in the **W-band (75-110 GHz)**.

- **Planned application** for the **Atacama and Tenerife** sites due to the **limitations** offered by the heliosynchronous **LEO** orbit for observations from **South Pole**.

Sun-Synchronous Orbit

- **SSOs** are those whose orbital plane makes a **constant** angle α with the **radial from the sun.** This can be achieved when the precession rate **Ω equals** to the **mean motion** of the **Earth** around the Sun.
- The equation which describe the average rate of change of the Ω angle is:

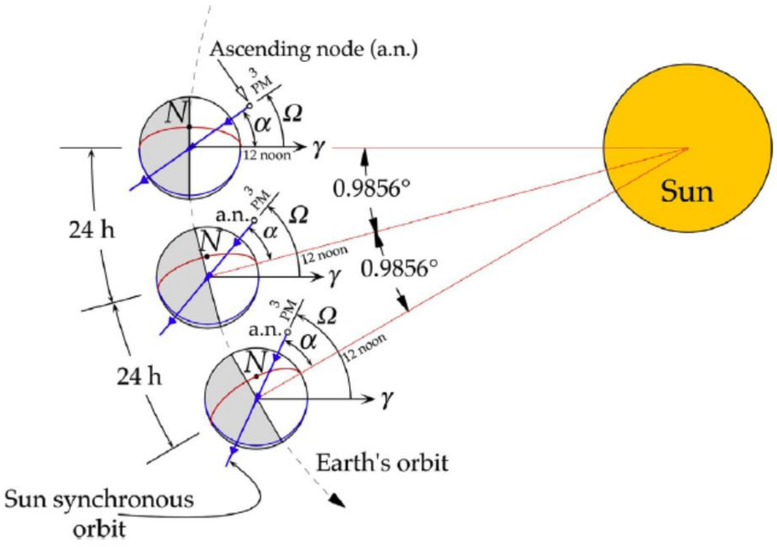


Figure 12: *Visualization of a sun-synchronous orbit. The angle α remains constant and the RAAN (Ω) of the orbit should change 360° per year, thus rotating the orbital plane 0.9856° per day. From Curtis, 2020.* **https://doi.org/10.1016/C2020-0-01873-6**

$$\dot{\Omega} = -\left[\frac{3\sqrt{\mu}J_2R^2}{2(1-e^2)^2a^{7/2}}\right]\cos i,$$

- R is radius of the planet, μ is the gravitational parameter;
- a and e are the semi-major axis and eccentricity of the orbit, respectively;
- i is the orbit's inclination
- J_2 is the coefficient for the second zonal term related to the oblateness of the planet

Sun-Synchronous Orbit

- For SSOs, due to **power generation needs**, the **inclination and altitude are linked**. For LEO **altitudes** the inclination is usually between **96º-98º**. As a consequence the **visibility at the poles is limited** (passes close to the horizon) especially if the orbit is low, which is likely in an experimental launch.

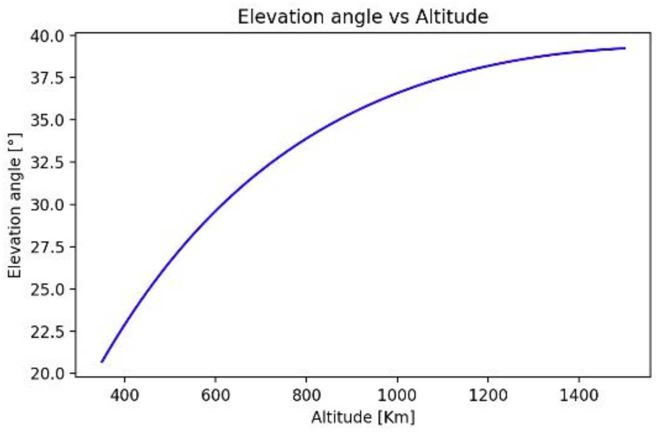


Figure 14: *Elevation angle of a satellite measured by an observer in a pole as a function of the orbit altitude.*

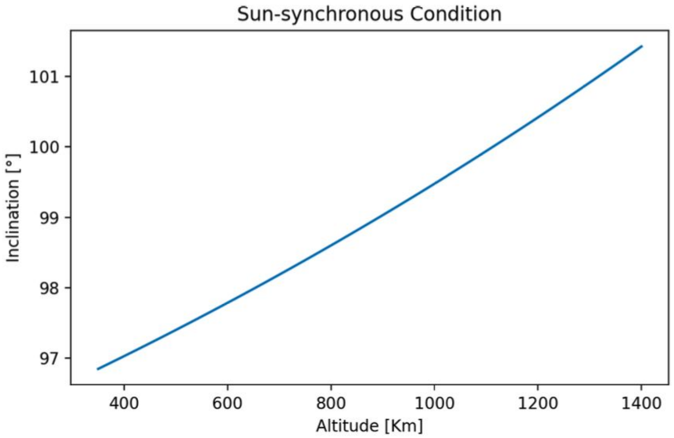
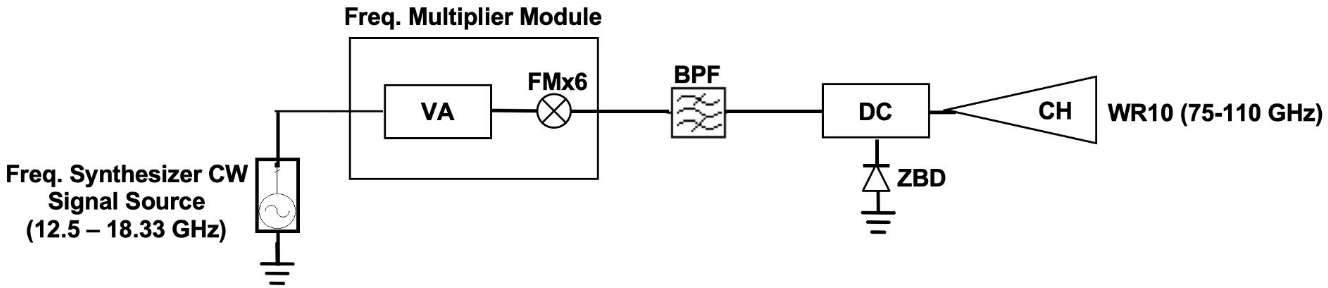


Figure 15: *Sun-synchronous condition: inclination vs altitude, where we have considered the radius of Earth as 6378 km, the eccentricity as 0, and the constant values described in the text.*

Payload

- Calibration **source** composed of a **freq. synthesizer**, a x6 freq. **multiplier** with signal attenuation and modulation capabilities, a **band-pass filter**, a directional **coupler**, a zero-bias **detector** to monitor the emitted power, a **horn antenna** and a wire grid **polarizer** (not included in the scheme).

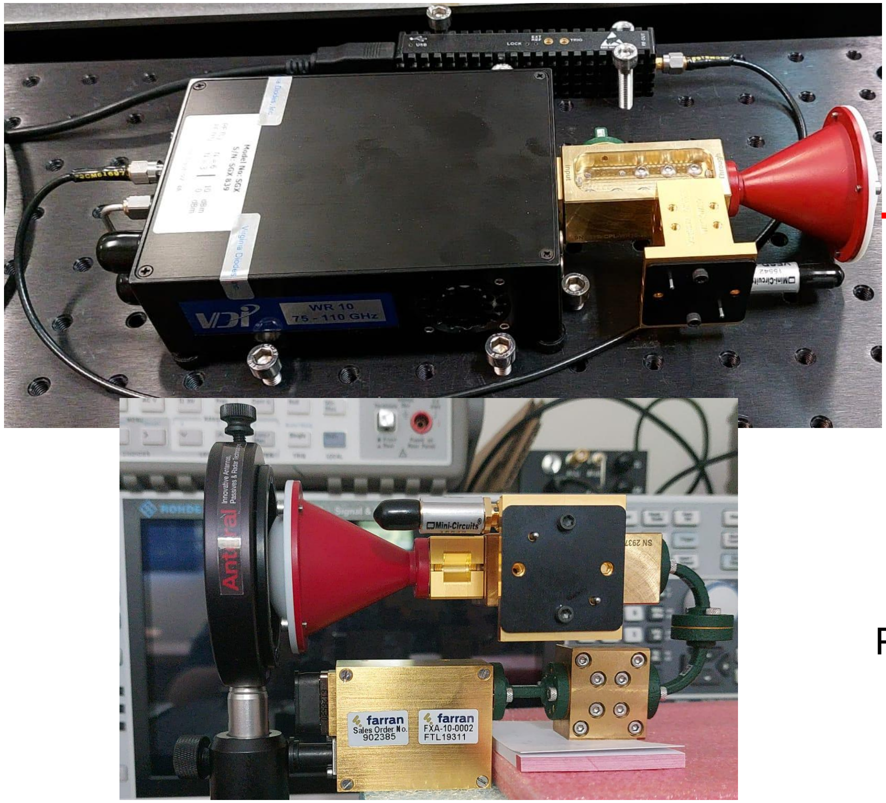


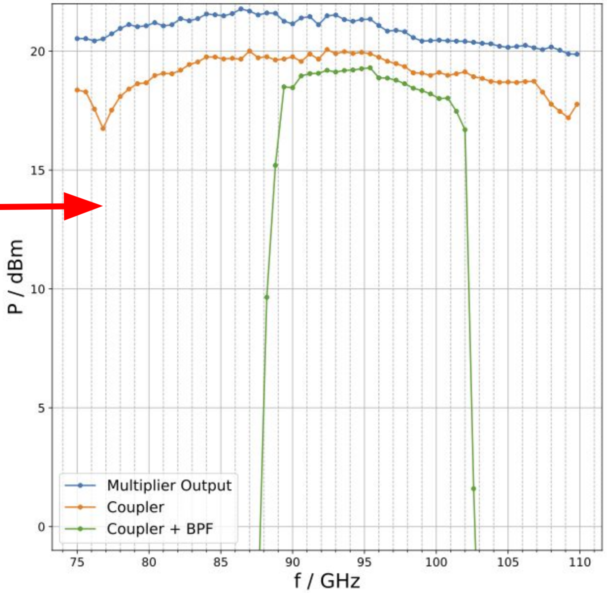
- Depending on the experiment sensitivity, it is expected that **SNR** values around **30 dB** will be available.

- **Two** source **versions**: The first, able to emit around **20 dBm** (100 mW) of power within the WR10 standard bandwidth (75-110 GHz), but **difficult** to mechanically **fit** with the available space onboard (2U). The **second**, **optimised** in size, volume and power consumption but less emitted power (6 dBm, 4 mW). Based on a frequency multiplier with integrated VCO, avoiding frequency synthesizer.

Payload

- The **first** source version has been **characterised in laboratory** conditions and used in preliminary studies. The two versions use commercial components.





Power measured at W-band (1st version) with and without coupler, and with a bpf to improve harmonic rejection.

A **possible configuration of the 2nd** version of the source

Payload

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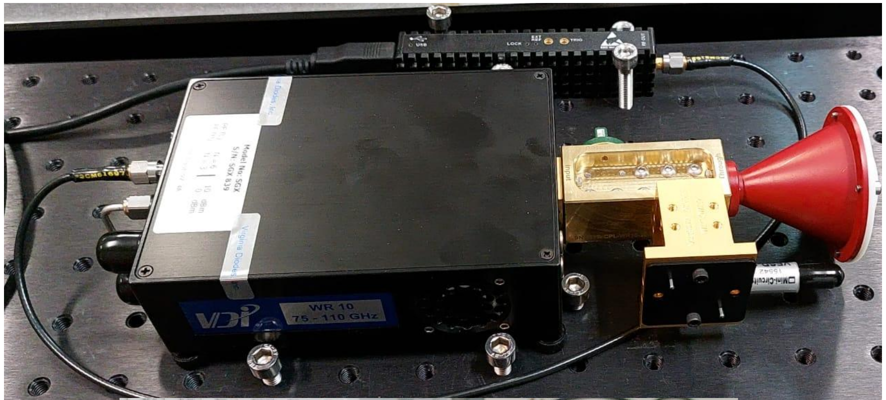
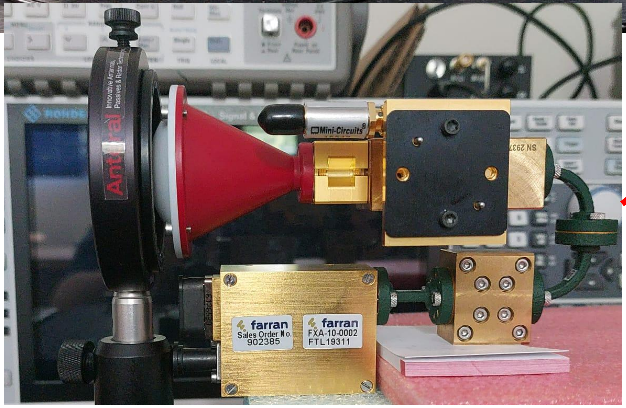




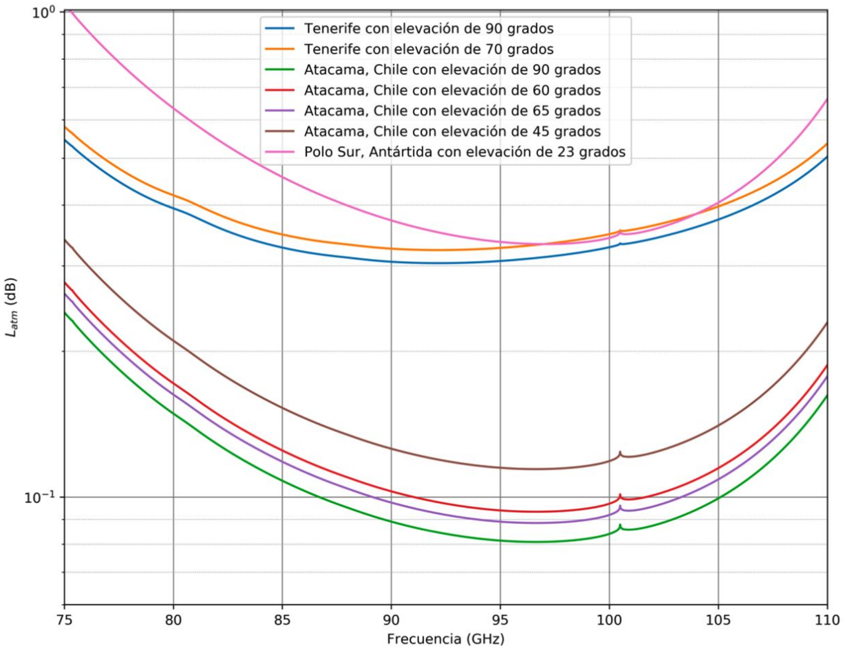
A **possible configuration of the 2nd** version of the source

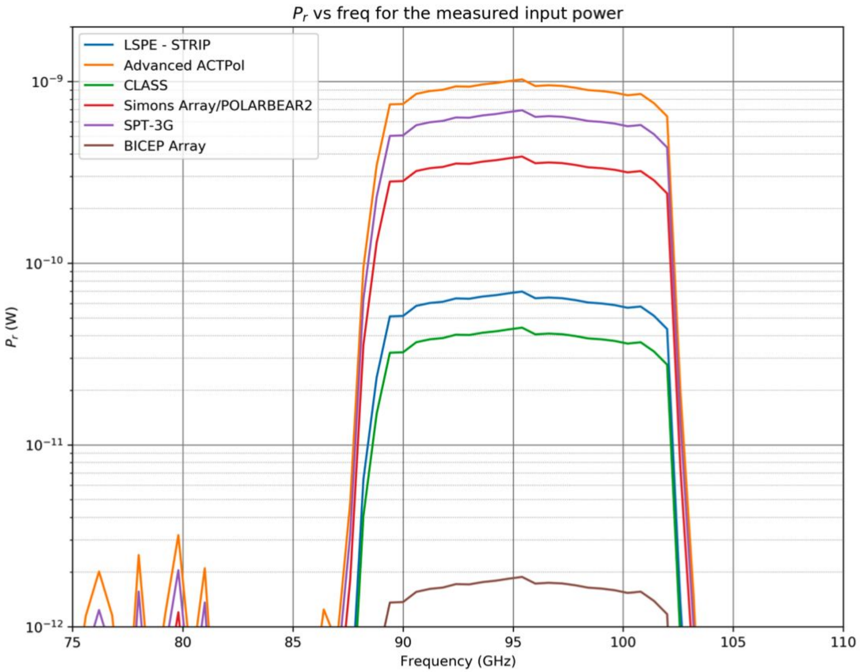
Mass	1 Kg
Volume	2U (10x10x20 cm^3)
Power Cons.	9 W (max)

Performance under test at this moment

Received Power Study

- Studies on **atmospheric attenuation** and **power received** by detectors have been carried out **considering the bpf**.
- Considering **around 70 mW** of emitted power, and the atmosphere of different sites and sensitivity values from the bibliography of the experiments, some preliminary results have been achieved.





Saturation and expected SNR

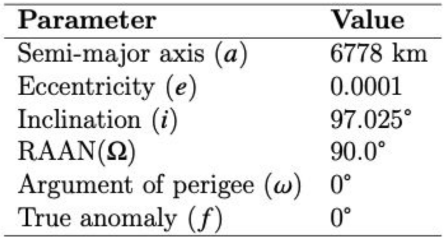
- At the **power** level of the **1st** version of the source, about **20 dB of signal attenuation** is **needed** to avoid saturation in most telescopes. The **2nd version** of the source **improves** this problem (signal about 14dB lower).

- SNR without attenuating the emitted signal. Considering 20 dB att. **SNR values between 10 and 50 dB** are expected. Most of them around 30 dB.

	Ubicación	A (m)	α	$\Delta\nu$ (GHz)	NEP ($\mathrm{W}/\sqrt{\mathrm{Hz}}$)	P_{ruido} (W)	SNR (dB)
LSPE - STRIP	Tenerife	1.5	70°	7.6	$3{,}39 \cdot 10^{-16}$	$9{,}36 \cdot 10^{-16}$	49
ELFS - North	Tenerife	6	90°	25	$6{,}16 \cdot 10^{-16}$	$3{,}08 \cdot 10^{-15}$	56
ELFS - South	Atacama	6	90°	25	$5{,}83 \cdot 10^{-16}$	$2{,}91 \cdot 10^{-15}$	56
AdvACT	Atacama	6	60°	20	$5{,}21 \cdot 10^{-16}$	$2{,}33 \cdot 10^{-15}$	56
CLASS	Atacama	1.5	45°	31	$6{,}49 \cdot 10^{-16}$	$3{,}61 \cdot 10^{-15}$	41
Simons Arr./PB2	Atacama	3.5	65,5°	28.998	$6{,}28 \cdot 10^{-16}$	$3{,}38 \cdot 10^{-15}$	50
SO - LAT	Atacama	6	90°	25	$5{,}83 \cdot 10^{-16}$	$2{,}91 \cdot 10^{-15}$	56
SO - SATs	Atacama	0.42	90°	25	$5{,}83 \cdot 10^{-16}$	$2{,}91 \cdot 10^{-15}$	33
CMB-HD	Atacama	30	90°	25	$5{,}83 \cdot 10^{-16}$	$2{,}91 \cdot 10^{-15}$	71
CMB-S4 - CD	Atacama	6	90°	25	$5{,}83 \cdot 10^{-16}$	$2{,}91 \cdot 10^{-15}$	56
CMB-S4 - TMA	Polo Sur	5	23°	25	$4{,}89 \cdot 10^{-16}$	$2{,}44 \cdot 10^{-15}$	48
CMB-S4 - SATs	Polo Sur	0.55	23°	25	$4{,}89 \cdot 10^{-16}$	$2{,}44 \cdot 10^{-15}$	29
SPT-3G	Polo Sur	10	23°	26.4	$5{,}02 \cdot 10^{-16}$	$2{,}58 \cdot 10^{-15}$	54
BICEP Array	Polo Sur	0.52	23°	23.75	$4{,}77 \cdot 10^{-16}$	$2{,}32 \cdot 10^{-15}$	29

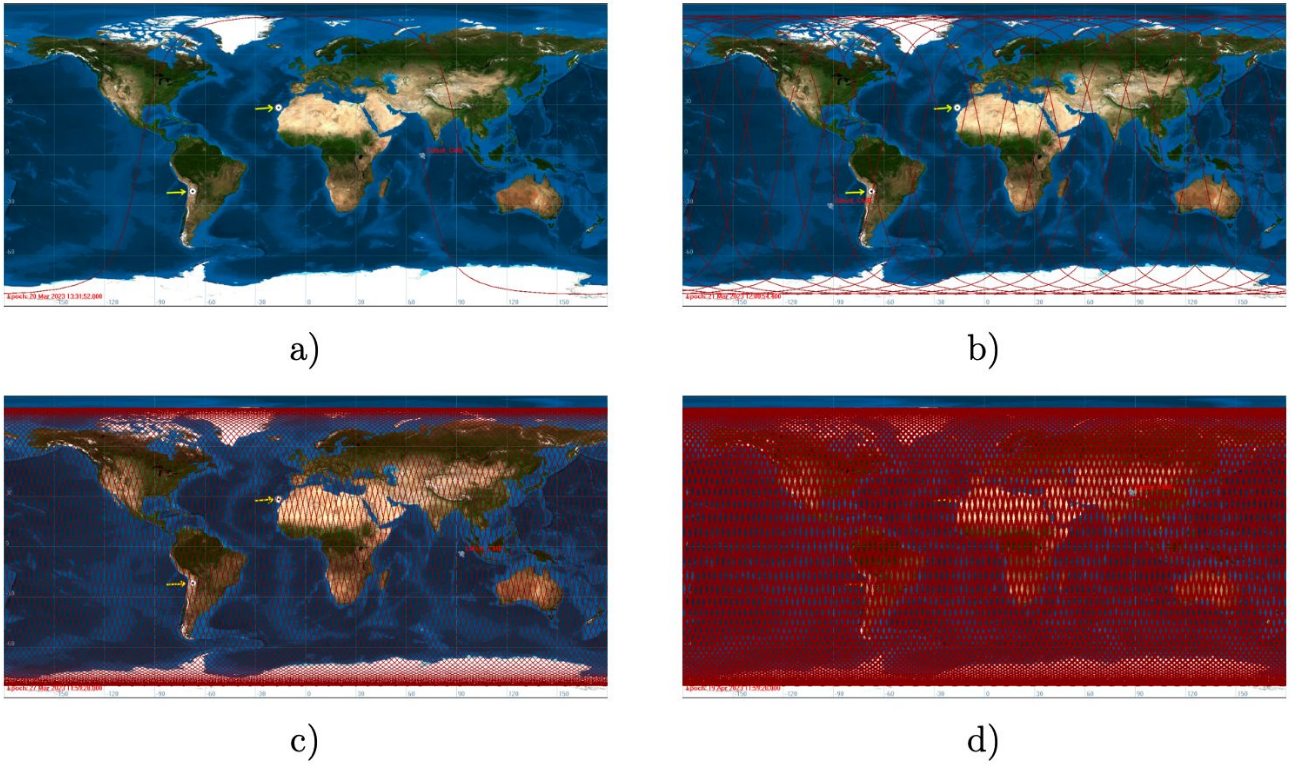
Visibility

- CalSat **SSOs** projected on the Earth surface (GMAT **simulations**):



Parameter	Value
Semi-major axis (a)	6778 km
Eccentricity (e)	0.0001
Inclination (i)	97.025°
RAAN(Ω)	90.0°
Argument of perigee (ω)	0°
True anomaly (f)	0°

Orbital Parameters of a dawn-dusk SSO at 20th of March 2023.

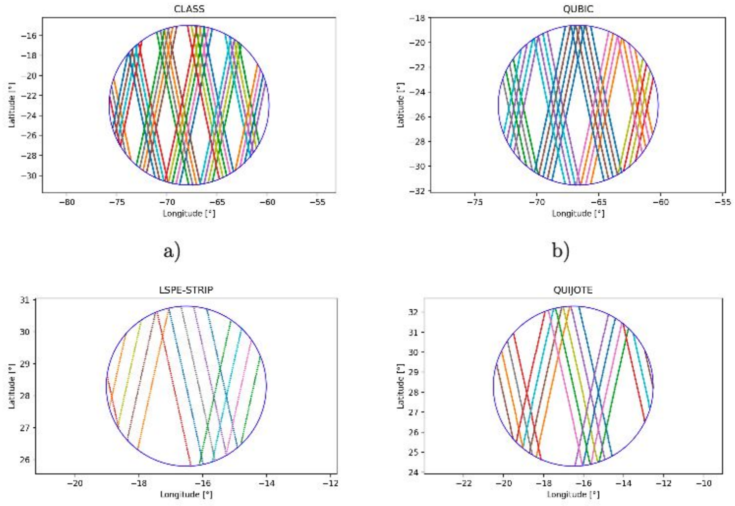


a) b) c) d)

Figure 16: CalSat orbits projected on Earth (in red lines) for a) 1.54 hr, b) one day, c) 7 days, and d) 30 days. The experiments of our interest are marked with a black point surrounded by a circle.

Visibility

- Orbit **trajectories** in the field of view of the different experiments for **one month**:

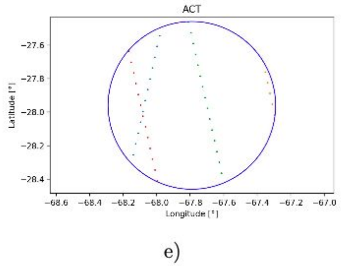


a)

b)

d)

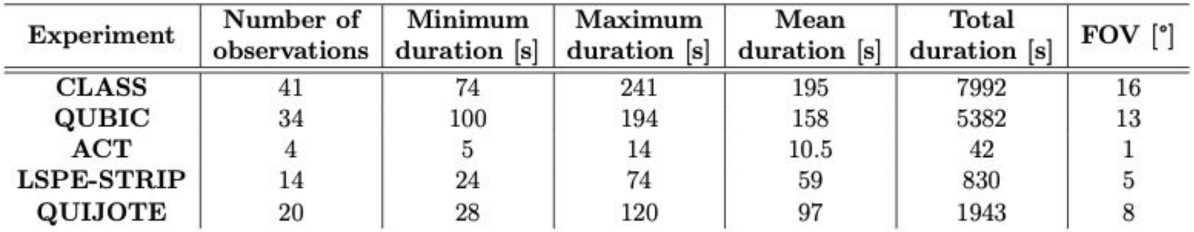
c)



e)

Figure 17: *CalSat trajectories for each experiment, where we have considered the observation time as one month, and the respective FOV for the experiments. The lines constructed by the points represent the trajectories of the CalSat and the 'lines' with same colour represent the same observing day.*

- **Circular FOVs** and telescopes observing to the zenith have been considered.
- **Not optimal** strategy for big telescopes like **ACT**.
- Smaller telescopes have the possibility to **track the satellite** to increase the calibration time.
- Number of observations slightly dependent on the initialisation time of the simulation.

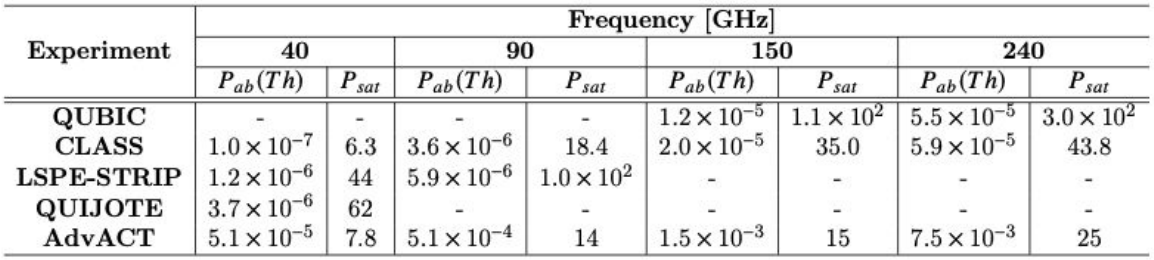


Experiment	Number of observations	Minimum duration [s]	Maximum duration [s]	Mean duration [s]	Total duration [s]	FOV [°]
CLASS	41	74	241	195	7992	16
QUBIC	34	100	194	158	5382	13
ACT	4	5	14	10.5	42	1
LSPE-STRIP	14	24	74	59	830	5
QUIJOTE	20	28	120	97	1943	8

Table 9: *Number of observations in one month and information about the observation time for each experiment.*

Thermal Control

- Thermal signal from spacecraft (solar panels at 39ºC and with an area similar to the one of the UPMSat-2 walls has been considered):



Experiment	Frequency [GHz] 40 $P_{ab}(Th)$	40 P_{sat}	90 $P_{ab}(Th)$	90 P_{sat}	150 $P_{ab}(Th)$	150 P_{sat}	240 $P_{ab}(Th)$	240 P_{sat}
QUBIC	-	-	-	-	1.2×10^{-5}	1.1×10^{2}	5.5×10^{-5}	3.0×10^{2}
CLASS	1.0×10^{-7}	6.3	3.6×10^{-6}	18.4	2.0×10^{-5}	35.0	5.9×10^{-5}	43.8
LSPE-STRIP	1.2×10^{-6}	44	5.9×10^{-6}	1.0×10^{2}	-	-	-	-
QUIJOTE	3.7×10^{-6}	62	-	-	-	-	-	-
AdvACT	5.1×10^{-5}	7.8	5.1×10^{-4}	14	1.5×10^{-3}	15	7.5×10^{-3}	25

Table 10: *Absorbed power and saturation power by the detectors, for the different experiments and frequencies. All the power values are in pW.*

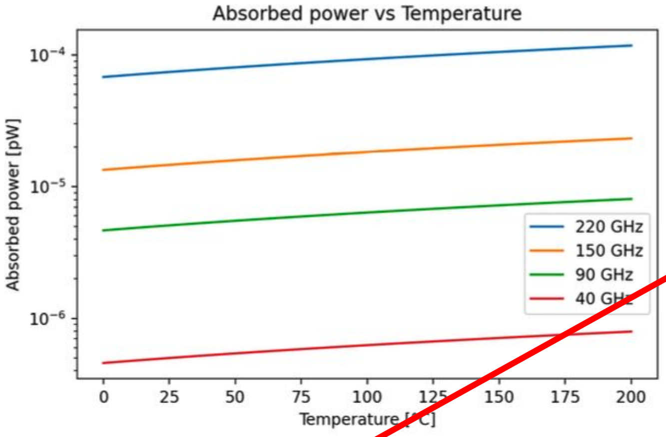


Figure 18: *Absorbed power by the ACT experiment from the thermal emission of the horn antennas as a function of the temperature. It has been considered each frequency band at which ACT detects.*

Impact of antenna temperature:

Worst case due to the telescope size.

Most pessimistic estimation is shown.

Conclusions

- The use of a **low-cost satellite** with a **90 GHz** reference signal source payload is proposed, for the **calibration of ground-based CMB polarisation** experiments.
- Additional objective: **TRL increase** for the development of a CalSat for space missions at L2.
- CubeSat or microSat in a **~400 km altitude** SS-LEO to save costs.
- Until now **two source versions** covering the W frequency band (75-110 GHz). The band can be l**imited to 90-100 GHz with a BPF** to reduce the **harmonic distortion** level.
- **SNR values around 30 dB** (1000) can be achieved while **preventing saturation** of detectors.
- The **visibility** of the satellite is **well suited** for CMB experiments at Tenerife and Atacama and for **telescopes size < ~3 m**.
- **Spurious thermal emission** is **orders of magnitude lower** than the saturation power of the detectors.