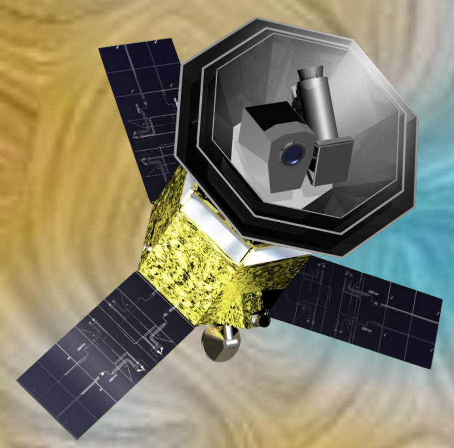
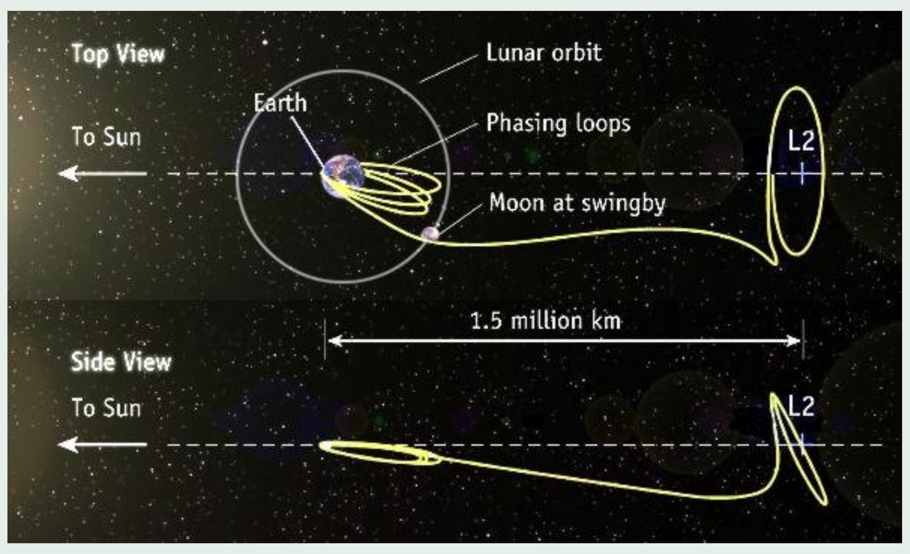


SPAIN

Feasibility Study for a Calibration Satellite

To expand beyond LiteBIRD full success scientific goals

Mission



LCS Mission

Lissajous orbit like Planck and Herschel.

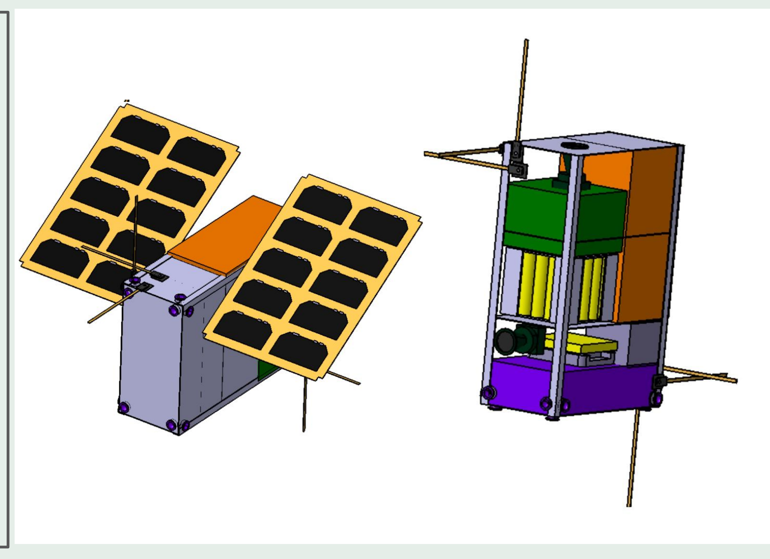
Formation flying of LCS and LB for periodic calibration.

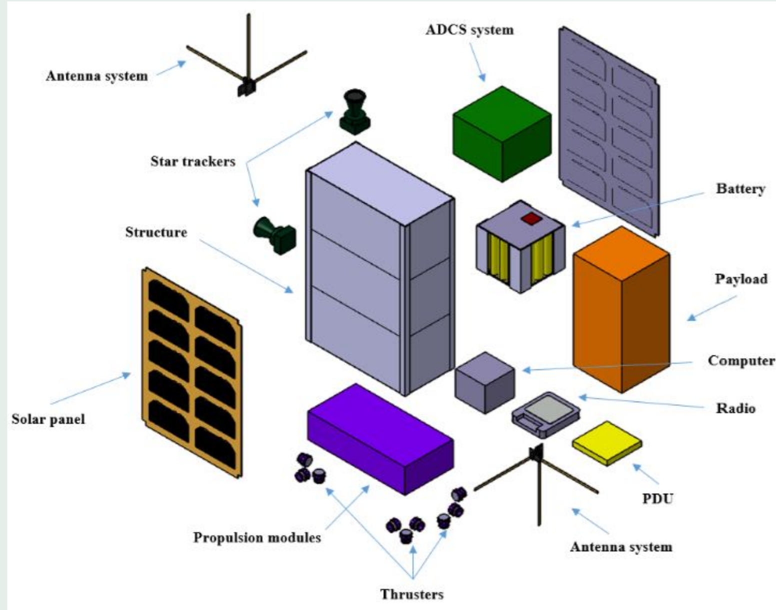
Orbit maintenance:

- Manoeuvres required periodically.
- L2 presents low force gradients.
- **Very low ΔV (~1 m/s per year).**

Control strategy, formation, orbit and tolerance define a calibration: **ΔV of 9 m/s for the entire mission.**

Concurrent Design Analysis





Exterior view and exploded view of LCS.

LCS has been pre-designed in IDR-UPM's Concurrent Design Facility (CDF)

It has been designed as a piggy-back of the LB minimizing the impact on its architecture. The concept of LCS can be extended to a microsatellite capable of reaching L2 autonomously by modifying mainly the propulsion and communication subsystems.

Main Specifications:

- 3 years mission
- Size: 6U Cubesat.
- Minimum distance between LCS and LB of 240 m;
- Calibration distance = 270 ± 3 m;
- Distance error determination < 13.5 cm;
- LB direction location error < 10'; LB orientation detection error < 1';
- LCS pointing error < 3';
- Power enough for 1 calibration per month;
- Minimum impact on LB (CubeSat deployer and 3 patch antennas).

Critical Technologies:

- Attitude control and determination: Sun sensors (Fine Sun Sensor) and star trackers (CubeSpace CubeStar).
- Metrology (relative position determination) and communications: RF ranging e.g. "Swift RelNav" by Tethers Unlimited.
- Propulsion: Cold gas thrusters (small and precise impulses with low consumption) e.g. GOMSPACE NanoProp.

Thermal Control:

- A preliminary LCS design implemented in the ESATAN® software shows a maximum temperature of 39 ºC in the solar panels.
- In the covered bandwidth by the telescope, this corresponds to a noise signal of 70 fW/pixel that is ten times below the LCS calibration signal at those frequencies.

Overall features:

- Total mass: 7.07 kg (dry mass) + 0.08 kg (propellant).
- Power: 2 orientable arrays of 6U-cubesat solar panels with a triple-junction technology by SpectroLabs.
- Total power generation: 57.2 W.

Calibration

Calibration strategy analysis

LCS must be inside LB's FoV during calibration and move away at finishing.

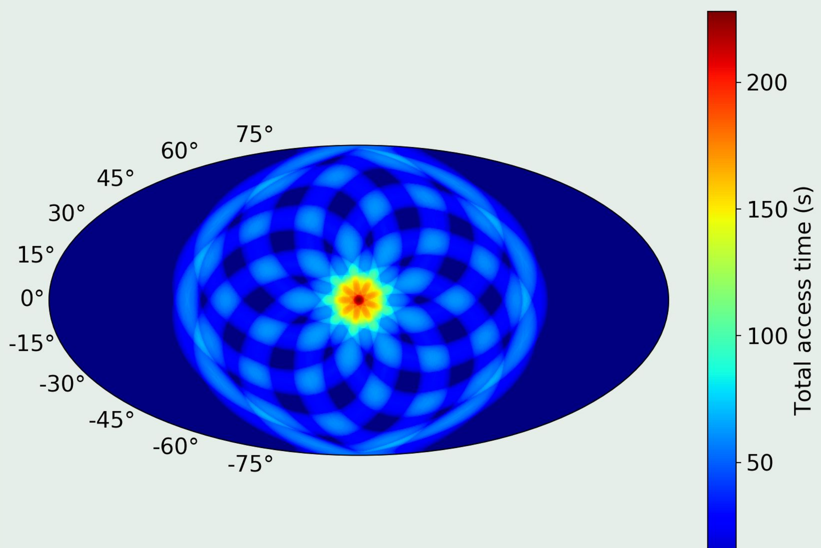
- 4 impulses for each calibration manoeuvre.

LiteBird scanning law and LCS relative position define:

- Total access time.
- Number of viewed LB instrument sensors.

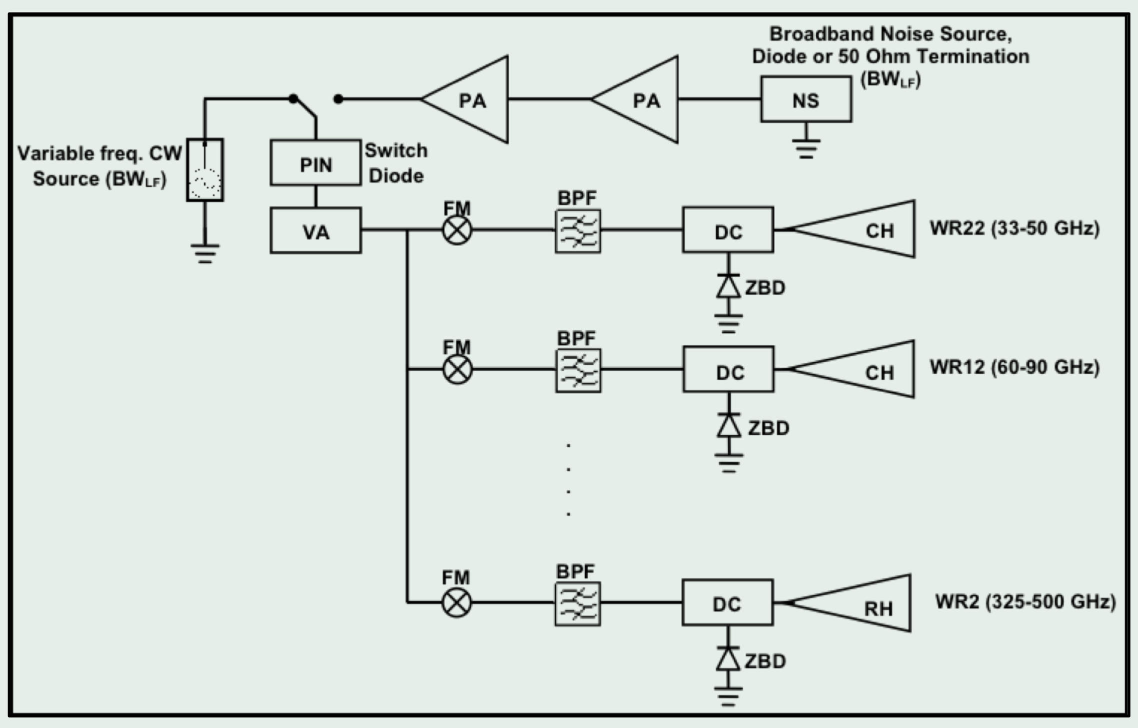
The best option to place the LCS is close to the **anti-Sun axis**.

- The percentage of viewed sensors is around 14% but it reaches the 70% in that region for one day even when the LCS is at the same position.
- Average access time is uniform and around 30 s, regardless of the LCS position.



Total access time according to the position of LCS relative to LB throughout 90 minutes.

Payload: Calibration Source

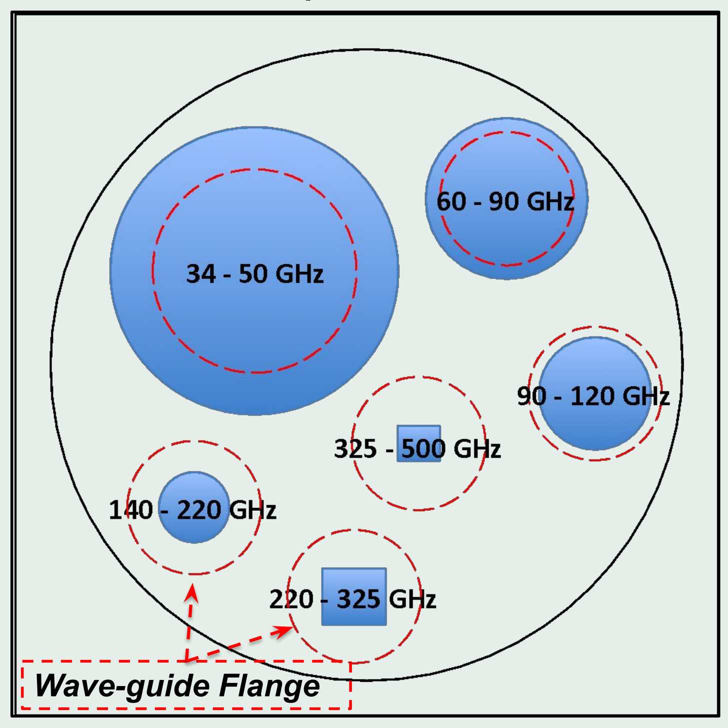


Cal. source diagram

- Multi-frequency (**6-bands**) variable source covering **34 - 450 GHz**
- Signal **frequency and power** should be **variable** for systematics characterization
- CW amplitude- and frequency-variable signals and also broadband signals
- **Common low-frequency sources** to feed the different bands: CW frequency-variable (bandwidth BW_{LF}) and broadband noise source (NS)
- A variable attenuator (VA) change the power level in linearity calibrations. VA applied directly to the common low- frequency signals to reduce the cost and complexity.
- **Bandwidth coverage** achieved by means of power splitters and **Frequency Multipliers (FM)**
- Band-Pass Filter (BPF) rejects undesired harmonics and Directional Coupler (DC) measure power levels with a Zero-Bias-Detector (ZBD).
- Feed-horns: **circular at lowest frequencies** (lower gain and size) and **rectangular at highest** freq. (higher gain required)
- **Cross-polarization of -60 dB: Wire-Grid Polariser** in front of the horns (precise alignment with the polarization axis)
- **Alternative** source **designs and technologies** (thermal source, microwave photonic source…) are being **also considered**

Estimated Characteristics:

- **Volume: 10 cm x 10 cm x 20 cm**
- **Weight: 1.3 kg**
- **Power consumption: 50 W**



Frontal view sketch

Contribution to Calibration, Systematics and Foregrounds JSGs

- Polarization angle requirements on each frequency induced by the component separation process:

$$s(p)=\sum_{\nu=1}^{15}\omega_\nu d_\nu(p)$$

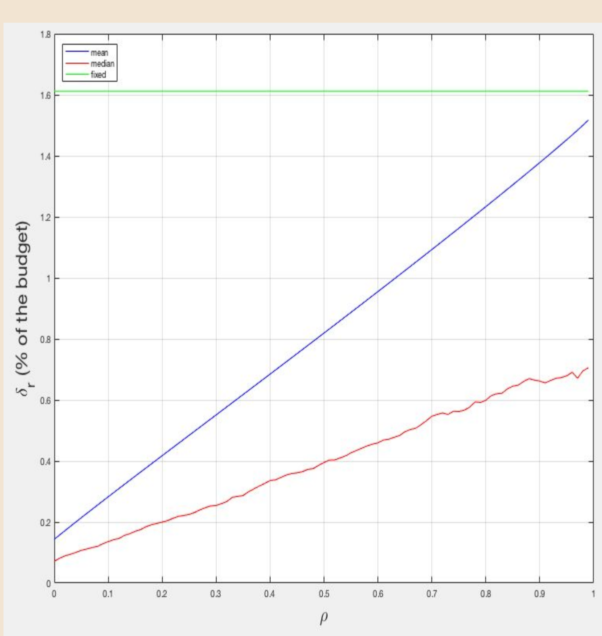
Estimated CMB (both, Q and U Stoke's parameters) at position *p*

Weight given at each frequency ν (pixel independent)

Data at **frequency** ν and position *p*

error in δ(r) as a function of the correlation degree

ν(GHz)	α [arcmin] 2 parameter (from Yuto)
40	59.2750
50	17.6430
60	8.1520
68	3.4500
78	2.1610
89	1.5396
100	1.2960
119	1.0160
140	1.2010
166	1.8050
195	2.6320
235	6.0550
280	11.9040
337	53.3570
402	360.1110
δ_r (% sys.)	1.612



- In order to **assure a 1% of** the budget assigned to **systematics**, the **requirements are not far from the expected errors coming from EB = 0** at the spectra level.
- **If correlations** among frequencies **are below 60%,** even the most damaging case (in the sense of polarization angle error) is **below the budget**.

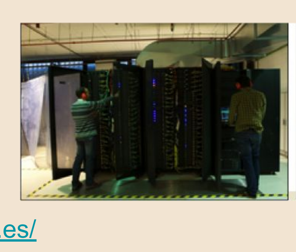
- Expected contribution to the component separation process using Internal Template Fitting and Neural Networks

Interest in Data Management

Expertise

- **IFCA** was the **Spanish DPC node for Planck-LFI**
- The IFCA ***Advanced Computing and e-Science group*** will support the DPC management:
  - **Foster** the **usage**, **maintain** and **improve** the existing computing and storage infrastructures
  - Expertise in building **software quality assurance systems**
  - Implement **industry-standard best practices**
  - Continuous **build**, **integration** and **deployment** of scientific **software**
  - **Containerization** (Docker) of software components **to ease sharing**, deployment and distribution

Hardware resources at IFCA



- **Altamira** supercomputer (RES)
  - 158 nodes 32 cores, 64GB RAM, Infiniband connection + 4 GPU nodes
  - **7.4M CPU hours since May 2018**
- **Grid** resources
  - 4M (56M normalized) CPU hours in 2018
- **OpenStack Cloud**: http://portal.cloud.ifca.es/
  - Up to 7700 cores available
    - Largest node: 48 cores, ~1TB RAM
    - GPU nodes: 1 NVIDIA TitanX (donated by NVIDIA grant), 1 NVIDIA 1080ti, 10 NVIDIA 1080ti
    - 90 nodes with In niband connection
    - 1st overall resource provider (size) in EGI.eu Federated Cloud
  - **1st overall contributor** (CPU-hours) in EGI.eu Federated Cloud
    - 6M CPU hours during 2018
- Renewed **storage** system (2018)
  - Cloud: Up to 300TB (Ceph) via object storage (S3-like) or block storage
  - GPFS: 1PB GPFS storage + 1PB tape

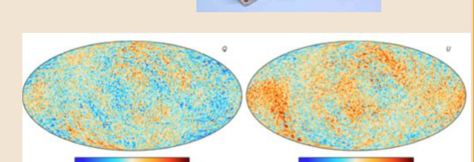
Interest in DPC activities

The **funding expected** from the **National Research Program for Space** and **IFCA**, in relation to the **DPC**, can be used for:

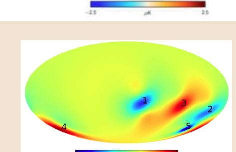
- Computing (~ 500 cores)
- Storage (0.5 PB)
- 2 FTE

Expertise and other potential contributions

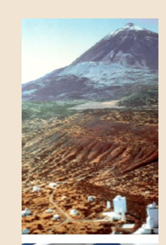
- Design, development and characterization for CMB Instrumentation:
  - Planck-LFI for 30GHz and 44GHz
  - QUJOTE TFI and FGI
  - Optical Interferometric prototype for microwave signals
  - Calibration sources for CMB polarization

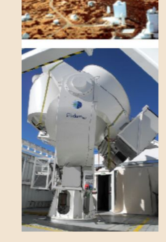


- Computation
  - high-performance, grid and cloud computing
  - Development of support chains for data management
- Component separation
  - Diffuse component extraction
  - Compact source detection and estimation



- Optimal power spectra estimation
- CMB cross-correlations: secondary anisotropies science
- Isotropy and Statistics on the universe: inflation paradigm, non-Gaussianity, anomalies, topological defects

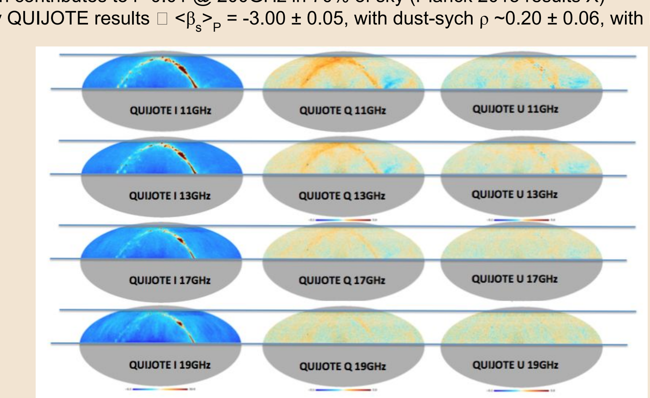




- Development, fabrication, integration and operation of CMB experiments over more than 30 years (some of them in-house, others in collaboration with other institutes)
  - Most recent ones: COSMOSOMAS (10-17 GHz, 1998-2008), VSA (33 GHz, 1999-2008), and QUIJOTE (10-40 GHz, 2012-)
  - Future experiments: GroundBIRD (150-220 GHz), LSPE- STRIP (43, 90 GHz), TMS (10-20 GHz)
- Programming and planning observational programs
- Basic data processing and data reduction (calibration, characterization of noise properties, characterization of systematics, data flagging).
- Characterization of foregrounds (mainly at low frequencies, synchrotron and AME) both in intensity and in polarisation, and component separation
- Extraction of power spectra and cosmological-parameter estimation
- Statistical tools and techniques: MCMC, cross-correlations.

Current and future QUIJOTE maps will be essential to clean higher-frequency maps (including LiteBIRD) from synchrotron emission:

- Synchrotron contributes to r=0.01 @ 200GHz in 70% of sky (Planck 2015 results X)
- Preliminary QUIJOTE results $\langle\beta_s\rangle_P$ = -3.00 ± 0.05, with dust-sych ρ ~0.20 ± 0.06, with high variability in the sky



Planned extension to the Southern hemisphere to cover the full sky

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