FOSSIL

FTS fOr CMB Spectral diStortIon expLoration

A mission concept for the M-class ESA call

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1. Scientific goals

The Cosmic Microwave Background (CMB) provides us with an immense source of information about the physical properties of the Universe. In particular, measurements of the CMB temperature and polarisation anisotropies with ESA's *Planck* Surveyor have been incredibly successful, allowing us to cement the *cosmological concordance model*, with seven precisely-measured parameters. Ever increasing data volumes and more accurate measurements lie ahead, but to gain deeper insight into the cosmological model we ultimately have to access new independent observables.

With the *FTS fOr CMB Spectral diStortIon expLoration* (*FOSSIL*) surveying the sky from 30 to 2000 GHz, we have the unique opportunity to reveal a novel and fundamental tracer of the early Universe, particle physics and structure formation: the CMB *spectral distortions*. These tiny departures of the average CMB energy spectrum from that of a perfect blackbody provide us with a fundamental probe of the cosmic thermal history. More than thirty years after *COBE*, we have now come into the position to improve *COBE/FIRAS*'s seminal measurements by some three orders of magnitude. At this level of precision, the sky cannot have a blackbody spectrum and we are guaranteed to gain transformative insights into the physics of the Universe that can only be achieved with a dedicated space mission. The proposed concept builds on the heritage of *COBE/FIRAS* and previous space-mission proposals (i.e., *PIXIE* [1] and *PRISTINE* [2]). The ESA M7 call offers a unique opportunity to surpass the ambition of previously proposed CMB spectrometers and to target the rich science case envisioned in [3].

1.1 Primary science goals

Since the measurements with *COBE/FIRAS*, the CMB spectrum is known to be close to a perfect blackbody, with deviations limited to about one part in 20,000. However, it is well-understood that both standard and non-standard physics processes inevitably lead to spectral distortions. These signals come in two main types: the Compton y distortion from energy release at redshifts $z < 5\times10^4$, and chemical potential or μ distortion imprinted at $z > 5\times10^4$. The unprecedented leap forward in sensitivity and spectral coverage of *FOSSIL* will probe spectral distortions up to three orders of magnitude fainter than the *COBE/FIRAS* limits, allowing to either set the most stringent limits on their amplitude or to detect new signals beyond *COBE/FIRAS*' reach. *FOSSIL* will probe the thermal history of the Universe across time, providing guaranteed science results as well as a rich discovery potential for new physics.

Early-universe physics and inflation – In the standard cosmological model, cosmic structures grew from density perturbations generated during inflation. These perturbations dissipate their energy through Silk damping, inducing primordial spectral distortions that provide new insight into early-universe physics. Various inflation models may indeed be only distinguishable through effects at small scales, beyond those accessible via the CMB anisotropy and large-scale structure (LSS) measurements. *FOSSIL* will

$\rightarrow$ open a unique window to density perturbations at small scales, with wavenumbers $k \simeq 10^2 - 10^5\ \mathrm{Mpc}^{-1}$

$\rightarrow$ probe μ distortions $\simeq 650$ weaker than the *COBE/FIRAS* limit, tightly constraining or possibly detecting primordial perturbations at previously unexplored scales. A non-zero μ distortion at *FOSSIL*'s sensitivity would rule out the single-field, slow-roll inflation model, at the heart of *cosmological concordance model.*

Black hole formation scenarios – Recent LIGO-VIRGO measurements of gravitational waves (GWs) at $\simeq 10-10^3$ Hz opened a new observational window. This also provided evidence for a population of $\simeq 30-100$ solar-mass black holes (BHs) whose origin is still unknown. In addition, standard evolution models still lack an explanation for the origin of super-massive black holes (SMBHs) that reside at the centers of most galaxies. If the $\simeq 30-100$ solar-mass BHs form through the collapse of large-amplitude horizon-scale perturbations, this is expected to cause spectral distortions. Most importantly, since the relevant signals are imprinted at primordial times (i.e., $z \simeq 10^4 - 10^6$), confusion with signatures from stellar BHs is largely excluded. *FOSSIL* will thus

$\rightarrow$ complement astrophysical probes of BH formation, shedding new light on their origin and link to inflation

$\rightarrow$ constrain the populations of primordial intermediate-mass and stellar-mass BHs and complement third generation GW surveys which are expected to detect all massive BH mergers to $z \sim 20$.

Nature of dark matter – Although particle physics offers several attractive dark matter (DM) candidates, none have been observed directly. The long-favored WIMP scenario is increasingly challenged and attention is shifting to more exotic candidates, e.g., axions, sterile neutrinos and primordial BHs, that are being seriously considered in our quest for an understanding of the nature of DM. *FOSSIL* could detect spectral distortions due to processes related to DM decay, annihilation and scattering with standard model particles, should such processes take place. Dark matter physics can furthermore lead to distortion signals that go beyond the standard μ- and y- parametrisation, promising an invaluable probe for particle physics. *FOSSIL* will

$\rightarrow$ constrain the nature of DM by probing its interactions, and rule out many particle physics models.

Structure formation – After decoupling at $z \simeq 10^3$, density perturbations generated at inflation grew and evolved to form the first stars that eventually reionised the Universe. Galaxies assembled in clusters and filaments, creating the cosmic web. The details by which matter collapses to form galaxies are still not quite understood, nor is why the rate at which galaxies form stars peaked ten billion years ago and has since fallen by an order of magnitude. The inverse Compton scattering of CMB photons with the thermal electrons of the ionised gas during reionisation and inside the LSS (also known as thermal Sunyaev-Zel'dovich, tSZ, effect) generates a y-type distortion of order 2×10^{-6} that traces the hot gas content in the cosmic web. This is a guaranteed signal bearing very high scientific return and legacy value. *FOSSIL* will

$\rightarrow$ measure the tSZ monopole y distortion at $\simeq 300\sigma$, after foreground marginalisation, improving the limit set by *COBE/FIRAS* by three orders of magnitude. This will reveal the cosmic web's hot gas content providing a complete census of the thermal energy in the LSS, from structure formation and reionisation

$\rightarrow$ detect the relativistic corrections to the y distortion allowing us to measure the average temperature of hot gas down to $kT_{\rm eSZ} \simeq 1.3$ keV at $\sim 30\sigma$, after foreground marginalisation. This will put the most stringent constraints, at sub-percent level, on the total energy injected across time by the whole population of SMBHs hosted in galaxies.

Average CMB temperature – Even if often not explicitly listed, the average CMB temperature, T_0, is one of the most fundamental observable parameters of the Universe. It fixes the number density of photons, the overall energy scales relevant to Big Bang Nucleosythesis, the transition to matter-domination and the cosmological recombination era, all epochs that are crucial for the formation of the CMB anisotropies and structures. The value of T_0 is also required for the calibration of CMB experiments and sets the ambient light for the cosmological 21cm signal. *COBE/FIRAS* delivered the most precise determination of T_0. It is time to independently confirm and improve this long-standing observational milestone of cosmology. *FOSSIL* will

$\rightarrow$ determine T_0 to a few μK, reducing the uncertainty to cosmologically-irrelevant levels and testing the blackbody nature of the CMB monopole over a wider range of frequencies than ever before.

1.2 Additional science goals

After the immense success of ESA's *Planck* surveyor, *FOSSIL* will deliver a new independent legacy dataset enabling, for decades to come, extremely rich science explorations at high to intermediate redshifts as well as in the local Universe.

$\rightarrow$ *FOSSIL* represents a unique opportunity to obtain complementary information on the recombination era via the frequency-dependent signals imprinted by the interactions of CMB photons with hydrogen atoms. Rayleigh scattering from neutral hydrogen during and shortly after recombination will be detected for the first time, and with high significance on large-scales and over a wide range of frequencies. Resonant scattering of CMB photons in the hydrogen Hα line will be also detectable. These signals will allow us to directly probe recombination physics at last scattering.

$\rightarrow$ *FOSSIL* will explore the end of the reionisation epoch by providing low-resolution intensity maps of far-IR lines of CII and CO from galaxies at redshifts $5 < z < 9$. These lines provide an independent star formation history measurement and can be used to probe the distribution of matter at large scales and to characterize the gas content of galaxies, complementary to higher-angular resolution experiments. In addition, resonant scattering of CMB photons by the fine-structure lines of metals and heavy ions (i.e., OI, OIII, NII, NIII, CI, CII) produced by the first stars can be observed at the large angular scales probed by *FOSSIL*. This will shed new light on the history of the metal enrichment of the inter-galactic medium during the end of the dark ages and the reionisation epoch, constituting an alternative window to those cosmological times complementary to 21cm observations.

→ *FOSSIL* will measure the monopoles and dipoles of the CMB and diffuse foreground emissions with unprecedented accuracy. It thus offers the capability to derive the monopole of the Cosmic Infrared Background (CIB) at the percent level, while this is presently uncertain by a factor of two around its peak at $\simeq 150\,\mu$m and there are no direct measurements for the wavelengths > 1 mm probing the high-redshift dusty galaxies. *FOSSIL* will measure the absolute intensity and the dipole of the CIB, hence uniquely probing the dust-obscured star-formation history of the Universe for $z > 1$.

→ *FOSSIL* will allow breakthrough advances in our understanding of the diffuse Galactic components of the sky from the radio to the far infrared. Our current understanding of the thermal Galactic dust emission is based on the *COBE/FIRAS* and *Planck* data; given the sensitivity/systematics of the former and the limited frequency coverage and number of bands of the latter, models are hardly discriminated. By contrast, *FOSSIL* will allow significant improvements in our understanding of the dust properties. It will also provide crucial insights on the spatial variability of the CMB foreground SEDs, as well as on their SED distortions. *FOSSIL* will further constrain Galactic atomic and molecular spectral lines, which uniquely probe the physical conditions of the different phases of the interstellar medium.

FOSSIL's data, mapping the full sky at intermediate resolution, will provide a detailed description of the projected inhomogeneities of the different processes releasing energy to the CMB photon bath across time. By its launch, other probes of the late thermal history of the Universe tracing the LSS, such as CMB, 21cm, X-rays, optical, and IR, will be available. *FOSSIL* will hence be a goldmine for cross-correlation analyses that will permit us to follow the growth of the largest cosmic structures with redshift, probe the inhomogeneous sector of reionisation, and unveil the baryon content of the cosmic web.

→ The HI 21cm emission, measured with SKA, is expected to be spatially anti-correlated with ionised regions, where most thermal energy is released. The cross-correlation with *FOSSIL* data should provide crucial tests for theoretical models describing structure formation at reionisation.

→ High-resolution CMB maps, e.g., from CMB Stage4, will produce independent measurements of the y distortion from galaxy clusters and groups. By cross-correlating with *FOSSIL* maps, an independent probe of the released energy will be achieved, enabling isolation of the distortion produced during reionisation.

→ Deep far-IR surveys targeting redshifted line intensity mapping, such as CCAT-prime and *SphereX*, can be cross-correlated with *FOSSIL* maps to probe the first stages of structure formation.

1.3 Requirements

The definition and optimisation of *FOSSIL*'s requirements to reach the primary science goals rely on a baseline survey duration of 3-years and on state-of-the-art instrument- and sky-models. The former builds on the heritage of *COBE/FIRAS* and previous mission proposals (*PIXIE* and *PRISTINE*). The latter stems from the present knowledge of background astrophysical contributions from the cleanest 70% of sky seen by *Planck* (Fig. 2.1 grey thick line).

Frequency range: A wide frequency range, from low to high frequencies, is needed to optimize the constraints on μ and y distortions while monitoring foreground emissions. The trade off between low photon-noise, and accurate charaterisarion of Galactic dust and CIB emissions, implies measurements to 2 THz. The observation of the peaks of CMB emission together with μ and y distortions requires measurements down to 30 GHz. This ensures the monitoring of synchrotron and free-free emissions needed for the μ distortion measurement.

Spectral resolution: It depends on the maximum optical path difference modulation and can be optimized after launch by modifying the commanded mirror motion. The baseline resolution, 15 GHz, allows us to detect emission from spectral lines (e.g., CII, CI, NII, OI, CO) in distant galaxies or in the Milky Way.

Angular resolution: *FOSSIL*'s equivalent Gaussian beam-width of about 1.4° enables mapping of spatial variations in foreground properties and hence their separation from CMB spectral distortions.

Pointing: The modest angular resolution and continuous scan of *FOSSIL* impose easily-achieved requirements of 1° realtime control and few-arcmin post-flight pointing reconstruction.

Sky coverage: Full sky coverage, only possible from space, allows mapping the different contributions and identifying the cleanest regions to optimise the measurement of the CMB spectral distortions.

Monopole sensitivity: An improvement of three orders of magnitude w.r.t. *COBE/FIRAS* measurements necessitates a sensitivity of order 1.2 Jy/sr at 30 GHz and 2.8 Jy/sr at 200 GHz (Fig. 2.1 and NEPs in Table 2.1).

Calibration: Measurement of spectral distortions requires an on-board absolute reference target to compare to the sky. To reduce distortions arising within the calibrator, it must have power reflection coefficient of order -65 dB and be controlled to few-μK stability over the temperature range 2.5–2.9 K.

2. Mission configuration

To achieve the ambitious science goals outlined above while matching the requirements of the ESA M-mission call, a careful trade-off analysis among the technology options was performed, with most of the considered subsystems at TRL$\geq$ 6. Pathfinder ground-based and balloon-borne projects, e.g., BISOU [4], COSMO [5] and TMS [6], are planned to increase the maturity of some sub-systems. *FOSSIL*'s baseline design fulfills the science requirements with an instrument mapping the sky through a continuous scanning strategy, spinning around its axis while performing spectroscopic measurements at 30-2000 GHz with a Fourier Transform Spectrometer (FTS).

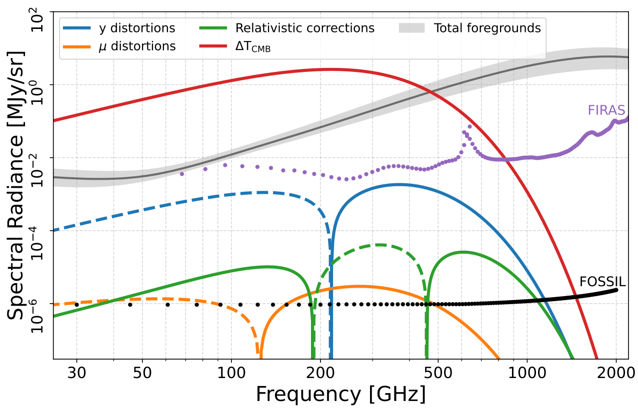


Figure 2.1: Expected CMB spectral distortion signals and total foreground emissions (grey) compared with noise levels from *COBE/FIRAS* and *FOSSIL*. Dashed curves represent negative values.

2.1 Instrument concept

The *FOSSIL* concept (Fig.2.2 right) is based on a 2-inputs - 2-outputs absolute FTS. Both sky inputs go independently through identical off-axis telescopes with a primary diameter of 60 cm, giving an equivalent Gaussian beamwidth of $\simeq 1.4°$. The optical inputs for the two arms of the FTS are two co-aligned telescopes in adjacent double-barrel baffles. A rotating wheel, with holes and mirrors directing either of the input beams towards a calibrator, permits three observing modes. In modes 1 and 2, only one input beam sees the sky, the other the calibrator, so that the difference between the sky and the reference blackbody is recorded. The FTS input beams are switched with the mirror, ensuring that these alternate measurements are limiting the telescope's optical systematic effects. The Fourier Transforms of the time domain interferograms of the detector outputs provide a set of modulated spectra, the combination of which will yield spectra of the desired source. The third mode, used only for optics calibration purpose, allows for both FTS input beams to be directed to the sky.

The two outputs are focused onto multimoded feedhorn-coupled detectors cooled down to sub-K temperature (typically 100 to 300 mK). To achieve the sensitivity required by the primary science goals, each FTS output is split into two bands, thus reducing the photon noise, notably for the low-frequency (LF) band. A dichroic at each FTS output divides the beam onto two focal plane units (FPUs): one low frequency (LF, 30 - 200 GHz) and one high frequency (HF, 200 - 2000 GHz). While the exact frequency split can be between 100 and 200 GHz, the baseline is 200 GHz.

In order to limit systematics in the measured spectral distortions, the whole instrument (telescopes, FTS mirrors, calibrator, FPUs) will be placed within an absorbing *Enclosure* maintained within 0.1 K of the CMB temperature (2.73 K). The calibrator temperature will be controlled over the temperature range 2.5–2.9 K, while the four FPUs (two bands for each of the two FTS outputs) will be cooled down to sub-K temperature.

2.1.1 Fourier Transform Spectrometer

The FTS (Fig. 2.2, right) is based on a scanning roof-top mirror which requires less demanding stroke and path sampling than that based on the *Herschel*/SPIRE FTS mechanism [7], given the comparably reduced spectral resolution (15 GHz) and maximum frequency (2 THz) required to achieve the science goals. Having to operate down to low frequencies, the optical components will be larger, leading to an FTS size of about 1.2 m.

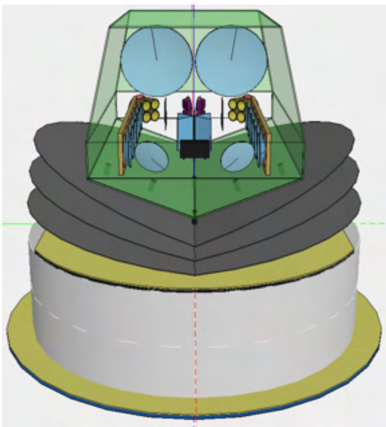
2.1.2 Detectors

Using multimoded feedhorns in order to maximise the sensitivity, implies large pixels, especially for the LF band. The estimated optical power (Sec. 1.3) and associated Noise Equivalent Power (NEP - Table 2.1) show that the required sensitivity can easily be reached with detectors at 100 to 300 mK. For the HF FPUs, several technologies could be used. On the one hand, KIDs technology [8] coupled to an FTS is already used for ground-based instruments CONCERTO and KISS (Institut Néel - Grenoble & Aix Marseille Univ.) and for the OLIMPO [9] balloon-borne instrument (Roma) for instance. R&D programmes have increased to TRL5 the maturity of KIDs from 80 to 600 GHz [10], and are aiming to bring this technology up to 2 THz to a TRL6 by 2028. On the other hand, semiconductor bolometers have been used in several missions (e.g., *Planck*/HFI, *Herschel*/SPIRE). Semiconductor bolometers could be used for the HF FPUs, but they are at present the only solution with high enough TRL for the LF FPUs. Substantial progress on bolometers at 100 mK has been achieved by NASA-GSFC for the *PIXIE* project, reaching at present TRL6 [11]. Either technology, KIDs or semiconductor bolometers will require a large absorber (typically 1 cm^2) in order to achieve the appropriate throughput with a large number of modes. Finally, sensitivity calculations (Sec. 1.3) were performed assuming one detector per FPU. During Phase A, a trade-off between mass, sensitivity and redundancy, will be performed in order to assess the possibility of increasing the number of detectors within the budgets.

2.1.3 Cooling chain

The instrument low temperature is maintained through a combination of passive cooling with the payload connected with struts through a 3-tier V-groove system and an active cooling chain. The inner V-groove is expected to reach a temperature of 80 to 50 K. In order to reach the necessary $\simeq 2.7$ K enclosure temperature, to have a warm launch configuration (cooling during travel to L2) and to allow the possibility of a mission extension, we chose a baseline cooling chain with mechanical coolers. It relies on a Pulse Tube Cooler to provide a 15 K stage followed by a combination of a 4 K ^{4}He Joule-Thomson and a ^{3}He J-T cooler which will also provide a thermal anchor for the sub-K cooler. Such an architecture is being developed for LiteBIRD [12], with heritage from Athena, both missions due to be launched at least five years before *FOSSIL*.

For the sub-K cooler, two options, providing 2-3 μW cooling power at the lowest 100 mK temperature, could be implemented in *FOSSIL*. On the one hand, recyclable ADR based systems developed by NASA already flew [13]. However, a continuous 100 mK system would be advantageous for *FOSSIL*. A continuous hybrid ADR system, presently at TRL5, is being developed for LiteBIRD and is due to reach TRL6 no later than 2026. On the other hand, a Closed Cycle Dilution Refrigerator is being developed with an Engineering model (TRL6) to be qualified by 2024. Both systems are subject to development programmes at CNES and CEA.



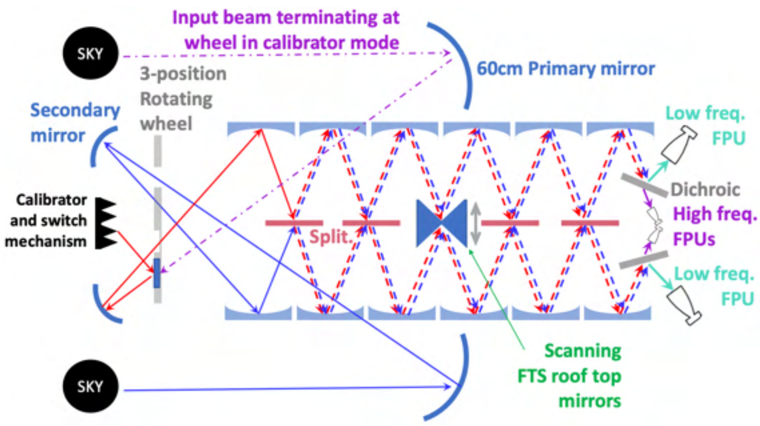


Figure 2.2: Left: View of the overall *FOSSIL* mission. Right: Sketch of the instrument concept.

2.1.4 Calibrator & Calibration

An internal blackbody calibrator provides an absolute reference for the sky brightness and a controlled source to evaluate systematic effects within the instrument optical path. Based on the ARCADE balloon [14] calibrator, it consists of a set of absorbing cones mounted on a thermally conductive plate and actively controlled over the temperature range 2.5–2.9 K. Thermometers within selected cones monitor temperatures with 15 μK single-read noise and a few μK absolute accuracy. The calibrator is surrounded by an absorbing enclosure so that reflections terminate within the instrument on a surface at nearly identical temperature. Providing further optimisation, the required -65dB will be at reach as shown by the ARCADE results [15, 16] within 3 to 118 GHz. Comparison of the interferograms taken with the calibrator at different temperatures or over different beams while observing the same sky pixel, allow calibration of the synthesized frequency spectra without prior knowledge of the sky signal [17].

A rotating wheel based on a high-heritage filter-wheel mechanism allows each beam to alternatively view either the sky or the calibrator (Fig. 2.2 right). Emission from the primary mirrors and baffles skyward of the calibrator can be identified and subtracted by varying their temperature, throughout the mission, thus correlating the sky-calibrator signal difference with component temperatures.

2.2 Scanning strategy

FOSSIL will be placed on a Lissajous orbit around the L2 point of the Earth-Sun system. The observational strategy combines a fast FTS scan with a slow spin velocity to minimise the smearing of the beam along the scan direction and to allow the reconstruction of the full interferogram from a single scan. The spacecraft will spin at ~ 1 revolution per hour around an axis offset by $\sim 87°$ from the telescope boresight. The spin axis will precede around the Sun direction with a full rotation every ~ 20 hrs and an angle of $\sim 5°$, which causes a small excursion of the spin axis from the anti-Sun direction, ensuring the observation of the whole sky with the entire focal plane (Fig. 2.3). This combination allows, following the Earth's revolution, full sky coverage in six months, and a thermally stable environment for the payload. The nominal mission duration of *FOSSIL* is three years, which enables six sky surveys. The adopted cooling chain allows for mission extensions, for which science objectives can be optimised depending on the results obtained during the baseline mission.

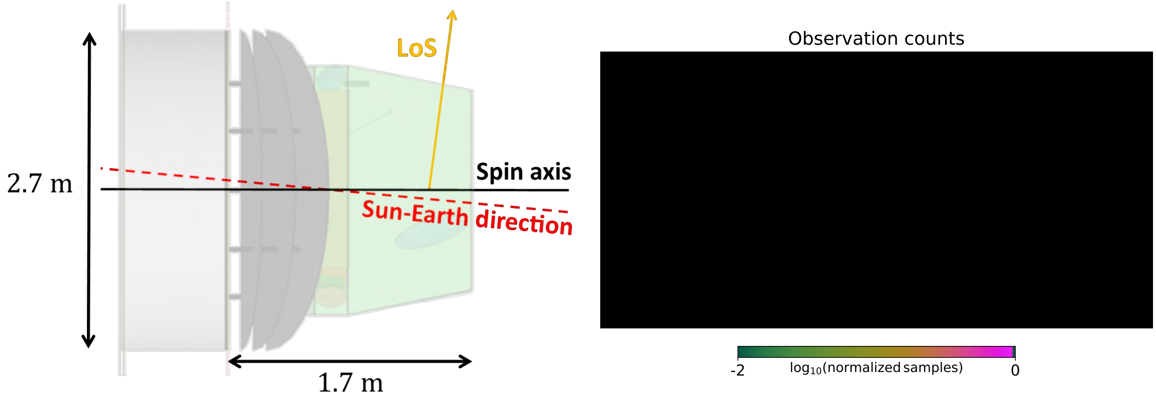


Figure 2.3: Left: Spacecraft ensemble view and scanning parameters. Right: Observation distribution in terms of normalized number of hits per pixel in Galactic coordinates for nominal 3-years duration.

2.3 Budgets

Adopting a concept allowing ARIEL type V-grooves as passive cooling, the overall payload module (PLM) fits within a diameter of 2.7 m and 1.7 m height (Figs. 2.2 & 2.3, left). **Mass:** The PLM and the service module (SVM) (based on ARIEL [18]) dry masses, including a 25% margin, add up to 1073 kg (Table 2.1). Building on a scanning strategy similar to *Planck*, an amount of 380 kg of propellant allows for all the necessary operations over the mission lifetime. **Power:** The payload power budget will be dominated by the cooling chain (estimated at 450 W for LiteBIRD). *FOSSIL* power needs for the overall payload, with one instrument to cool but two low-powered mechanisms, is estimated to be 550 W. With an SVM power-need of 450 W and an overall margin of 30%, a total of 1300 W is reached, equivalent to the *Planck* mission electrical power demand [19].

Table 2.1: TRL, budgets and NEPs: PLM and SVM sub-systems **and total** masses with SVM estimates from ARIEL [18]. NEPs for LF band (cyan) and HF band (purple) at the outputs of the FTS

	Optics +Mec.	FTS	Calibrator + Rot Mec.	FPUs + Readout	Enclosure + Mec.st.	Mech. Coolers	Sub-K Cooler	Th. Shields (V-Gr.+Struts)	Elect.
TRL	>7	>7	Cal.>5, Mec>7	>5	>7	6	>7 to 4	>7	>7
Mass	40 kg	25 kg	8 kg	5 kg	35 kg	10&60 kg	10 kg	130 kg	15 kg
Dry Mass	PLM (Payload + part. of coolers) +Thermal Shields = 263 kg			SVM alone = 520kg SVM+part of coolers = 595 kg			Total dry: 858 kg **Total with 25% margin: 1073 kg**		
Data rate		few detectors sampled at 200 Hz + housekeepings, with 50%margin: $\simeq$**50 kbps**							
			$NEP_{photon}(W.Hz^{-1/2})$		$NEP_{detector}(W.Hz^{-1/2})$			$NEP_{total}(W.Hz^{-1/2})$	
30-200 GHz FPU			$\simeq 2 \times 10^{-16}$		$\simeq 5 \times 10^{-17}$			$\simeq 2.1 \times 10^{-16}$	
200-2000 GHz FPU			$\simeq 1.3 \times 10^{-15}$		$\simeq 10^{-16}$			$\simeq 1.3 \times 10^{-15}$	

3. Managment

3.1 Payload elements

For *FOSSIL*'s complex payload, the elements together with the Scientific Ground Segment (SGS) will be provided by a consortium of scientific institutions under the responsibility and with funding from the Member States, and NASA as an international partner. The payload will be managed by ESA who will also be responsible for the system engineering and the system AIV. ESA could also be responsible for subsystems such as the telescopes, the 3-K enclosure and/or the cryogenic chain down to the 3-K level.

Given the necessary control of the systematic effects to reach the scientific goals, the *FOSSIL* consortium will procure the elements of the payload directly related to the measurement, namely the FTS, the sub-K cooling system, the internal calibrator and the detectors. In addition to potential ESA contributions, *FOSSIL*'s present consortium will design and procure elements and sub-systems listed below with potential providers. The long-standing experience in space science missions (*COBE*, *Planck*, Herschel, JWST, Euclid, Ariel, Athena, *LiteBIRD*) of the institutions in *FOSSIL* ensures that the necessary expertise is available within the consortium as shown below:

- Mechanisms for FTS and calibrator – Canada (University of Lethbridge); France (LAM); USA (NASA GSFC); Italy (Roma); Switzerland (Geneva University)
- Filters and beam-splitters – UK (Cardiff University); USA (NASA GSFC)
- Thermo-mechanical design (3-K & sub-K) – France (IAS, IRAP); Spain (IAC); UK (UCL, UCL-MSSL, Oxford University)
- Mechanical structures – Norway (Oslo University); UK (UCL, UCL-MSSL, Manchester University, Oxford University)
- Optical design – Ireland (NUI-Maynooth)
- Tests of optical systems – France (IAS); Italy (INFN, Pisa, INAF OAS Bologna, Roma, Ferrara University, Milano)
- Warm electronics – Poland (Center for Cosmic Research); Spain (IAC)
- Blackbody calibrator – France (IAS); Italy (INFN Pisa, University of Milano-Bicocca, Roma, INAF OAS Bologna); USA (NASA GSFC)
- Housekeeping & Thermometry – France (LNE-IAS); Italy (Roma); Spain (IAC)
- Sub-K cooler – USA (NASA); France (IAS, CEA)
- Detectors and readout electronics – France (Institut Néel, LPSC); USA (NASA-GSFC, JPL)
- Integration/calibration – France (IAS, CEA)

Payload elements and subsystems listed above can be provided by several institutes. The details of the procurement will be discussed after the Phase-1 selection.

3.2 Funding agencies

From a sub-system bottom-up approach, the Rough Order of Magnitude cost of *FOSSIL* payload is estimated to be about 100 Meuros. In addition to ESA, the expected main funding agencies are CNES, UK Space Agency, ASI, NASA, Spanish Ministry of Science, and Ireland, Norway, Poland, Portugal and Switzerland. The details of the possible funding schemes by Member States will be discussed after the Phase-1 selection. The details and nature of proposed USA contributions will be subject to a formal agreement with ESA.

3.3 Management structure

The *FOSSIL* consortium includes highly experienced and recognised leaders in CMB, spectral distortions, foregrounds, and large scale structures, and in data analysis. It also includes an extensive expertise in instrument design and development (FTSs, cryogenics, optics, detectors, calibrators) for space, sub-orbital and ground-based experiments including *COBE*, BOOMERanG, ARCHEOPS, *WMAP*, *Planck*, Herschel/SPIRE, TRIS, ARCADE, PIPER, OLIMPO, QUIJOTE, KISS, COSMO, CONCERTO, PILOT, TMS, BISOU.

The *FOSSIL* consortium will perform all necessary activities for the instrument and SGS development, instrument calibration, data analysis, and dissemination of scientific results, including communication and outreach. These activities will be tightly coordinated through a consortium management structure in order to ensure that the science goals of the mission are achieved. This structure will be finalised after the Phase-1 selection. We foresee that it will include a top-level management team; an instrument team; a scientific team; a Science Ground Segment (SGS) team; and a Consortium Board.

→ The management team will be in charge of coordinating all activities, ensuring timely execution of the project, and fulfilling the science performance goals.
→ The scientific team, organised in Working Groups (WG) focusing on the scientific goals, will prepare and coordinate the analysis of the *FOSSIL* data relevant to the scientific objectives.
→ The SGS team will be in charge of preparing and executing *FOSSIL* data calibration and processing.
→ The instrument team will be organised in Work Packages (WPs) for the different payload elements and subsystems that are under the responsibility of the consortium, in agreement with the procurement scheme of these elements/sub-systems.
→ The Consortium Board gathers co-investigators and representatives of the science and instrument teams. It will ensure the coordination with the national agencies together with the adequacy between resources and responsibilities in the procurement of hardware/software contributions.

3.4 Data Reduction, Scientific Analysis and Archival plans

The mission operations (MOC) and the science operations (SOC) will be carried out by ESA. The *FOSSIL* consortium will participate in the operations and post-operations phases. The analysis of the data (for data rate see Table 2.1) relevant to the scientific objectives (CMB spectral distortions, additional science) will be performed by members of the WGs who will take part in all the SGS activities relevant to the science goals. These activities cover calibration, data processing, analysis of the science ready data, and combination with external datasets. The *FOSSIL* consortium will be responsible for data processing and hence the development and maintenance of the SGS pipeline to produce level 2 and 3 data. The *FOSSIL* consortium will be in charge of delivering the data to the ESA archive that will provide them to the community. We foresee a proprietary period, to ensure the optimal analysis of the data closely related with the instrument systematic effects, that will be agreed upon with ESA, within the Science Management Plan (SMP). We also foresee an early release of the *FOSSIL* data followed by one or several releases. The SMP and the Interface Control Document will specify the content, timescales and formats compliant with the ESA scientific data policy. The *FOSSIL* consortium in collaboration with ESA and national space agencies will develop a strategy for the outreach activities to be performed during the whole project from development to science exploitation phase.

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