Concept Design for an Experiment to Measure the CMB Spectrum at Low Frequency from the Moon

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Introduction

This report describes the option for a small payload to observe the CMB spectrum at low frequency from the Moon. The original design, described in the Final Report of the contract *Italian Vision for Moon Exploration Studio Osservazione dell'Universo dalla Luna*, was based on the design with basically not mass, volume and power constraints. This is true under the assumption that a permanent base on the Moon is already operating.
The scientific requirements for this experiment are fully discussed in Burigana and Salvaterra (see bibliography). We report here the concept design for this experiment, along with some options.

Requirements

The request to reduce the mass and the volume for first-generation experiments on the Moon led to new requirements for a smaller payload. We started from the possible options given in the scientific definition and set some technical requirements for the concept design.

Mass: The overall payload shall have a mass smaller than 300 Kg. This is a reasonable trade-off between the complexity of the original design, the load of a possible lander vehicle, the minimum number of observing channels from the scientific requirements.
Simplified cooling system: In the original design, all the optics are kept at a temperature of about 4K. A cooler with a large heat-lift is therefore required to keep all the feed-horns at that temperature. In this new concept, the optics are passively cooled at a temperature of about 100K. Detectors and calibrators (internal and absolute ones) are actively cooled. This led to a significant reduction in the required power.
Location at the pole: In principle an observer on the Moon equator is able to explore the whole sky. However, the observation of a smaller fraction of the celestial sphere is sufficient to reach the main goal of this experiment, the investigation of distortions in the CMB spectrum. Moreover, it seems that the Moon poles will be a preferred site for the first generation landing mission. It is also possible to select peculiar sites where the sun never set. This will ensure continuous solar power to the experiment. A further consideration is linked to the passive cooling system. The needed radiation shield size for an experiment at the Pole is smaller than that required for a similar experiment at the equator. It is also possible to design them in such a way that *daytime* observations are always possible, keeping the inner part of the payload always passively cooled.
Simplified pointing system: The original design was much more similar to a classical telescope, with altitude-azimuth pointing and tracking system. That design allows maximum flexibility in the observing direction, the payoff being big volume, large mass and complexity. A smaller experiment should use a different observing strategy, taking advantage of the location at the Poles that makes it possible to observe continuously in drift-scan mode.
Autonomous, unmanned operations: it is reasonable to assume that the first generation of experiments on the Moon shall not rely on the presence of a permanent, manned station. The original experiment concept is so ambitious that the presence of trained astronauts is probably required for assembly and maintenance. The new concept shall be completely autonomous and shall not require any human help for deployment and operation.

Simplify deployment: the optimal location for a cryogenic experiment is a permanently shaded area, where the system can be efficiently cooled and the heat produced can be radiated towards the outer space. However, this location makes it difficult the deployment for many reasons: it is not reasonable to land on the shaded part of a crater, data communication with the payloads are not easy, solar panels must be located far from the payload, manned operations are probably required. Moreover the possibility of a deployment using a rover to move from the landing site to the final location obviously reduce the allowed mass and volume for the payload itself.

From requirements to concept design

The concept for this new, smaller payload is derived from the above listed requirements and it is obtained following the guidelines listed below.

Reduction of the number of channels and selection of the highest frequency bands.
Although the optimal determination of the CMB spectrum is obtained with the complete frequency coverage, it is possible to obtain significant results on some of the scientific topics with less channels. A trade-off must be found between the complexity of the payload design, the overall mass and dimension, and the number channels and their central frequency. Among the possible choices, the one with the highest frequency is selected for this concept design. It is therefore possible to reduce the overall dimension of the feed-horns and calibrator, since they are inversely proportional on the frequency. The reduction of the number of channels and, in particular, the choice of the longest wavelength channel at λ not exceeding ~ 5 cm requires a smaller cooler, reducing both mass, volume and power requirements, along with overall payload dimensions. Three frequency channels (at ~ 40, 16, and 6 GHz) are enough for a significant scientific improvement, as previously discussed, although using few additional channels (for example two channels at ~ 63 and 25 GHz) for a better foreground monitoring do not represent a serious problem in terms of mass and size.

Enlarging the Field-of-view (FOV)
The smaller the FOV is the larger the feed-horn is. Therefore, while a FOV around 7° is an optimal choice in order to directly compare with previous experiments at higher frequency, a trade-off between the overall dimension and the FOV can be found. The actual experiment is based on a 14° FOV, a good compromise that preserves the primary scientific goal while significantly contribute to the reduction of feed-horn dimension.

Passive cooling for the optics
The reduction of the cooling power has an important role in limiting the mass and power budget. We have implemented a new concept for the calibrator, which is observed by rotating a movable mirror. It is therefore possible to avoid the active cooling of the feed-horns, provided that the passive cooling is able to keep the temperature stable.

Steer-able mirrors
One of the main requirements for an absolute measurement of the CMB temperature is that the sky and the calibrator are observed with the same optical system. The design for the large experiment is based on a large calibrator that is moved on the feed-horns. In order to simplify the system, we introduced a steer-able mirror in front of each of the feed-horns. The mirror can be rotated to observe the calibrator and then back to observe the sky.

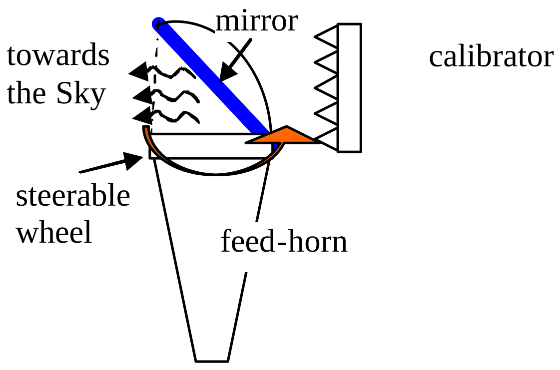

Figure 1: Sketch of the design for the steer-able mirrors. The mirror can rotate completely to observe the absolute calibrator.

The mirror can also be oriented at different angles between approximately +-45° from the zenith. By combining this pointing with the rotation of the Moon, it is possible to scan ≅ 1/6 of the sky without an altitude-azimuth system. This solution further reduce the overall mass and volume.

Location

We studied the effect of locating the experiment close to the Moon's poles. It is possible to reduce the global dimension of the passive cooling shields. The observable sky is reduced, but this is still acceptable in terms of the main scientific objective.

If we further relax the requirement of a location in a permanently shaded crater, we obtain some further simplifications:

- Deployment is simplified, because the payload can be located on the lander itself, without the need of a deployment system and, possibly, a rover to be moved inside the crater.
- Power generation is possible using solar panels mounted on the payload. In fact, in a shaded crater it is needed to link the experiment (always in a shaded area) with the power supply unit (exposed to the sun most of the time).
- If the location is very close to the Moon's pole, the experiment is always illuminated by the Sun on one of the sides. This allow to design a system that can generate power with solar panels on one side and radiate power from the cooler on the opposite side.

The choice of high frequency bands, far from man-made radio interference, allows a location on the near-side of the Moon.

Payload concept

The radiometric chain consists of steering mirror that allow to aim alternatively to the sky and to the absolute reference. It is needed to ensure that the mirror does not change the optical configuration due to its motion in order to avoid systematic errors. The absolute reference is made of an absorber material, like Eccosorb CR-series, that can be used successfully at low temperature and especially that allows to reach a signal attenuation of about 50dB in this frequency range (Cuttaia 2004). In order to have a better stability and control of the temperature, it is preferred to have 3 distinct calibrators one for each frequency channel

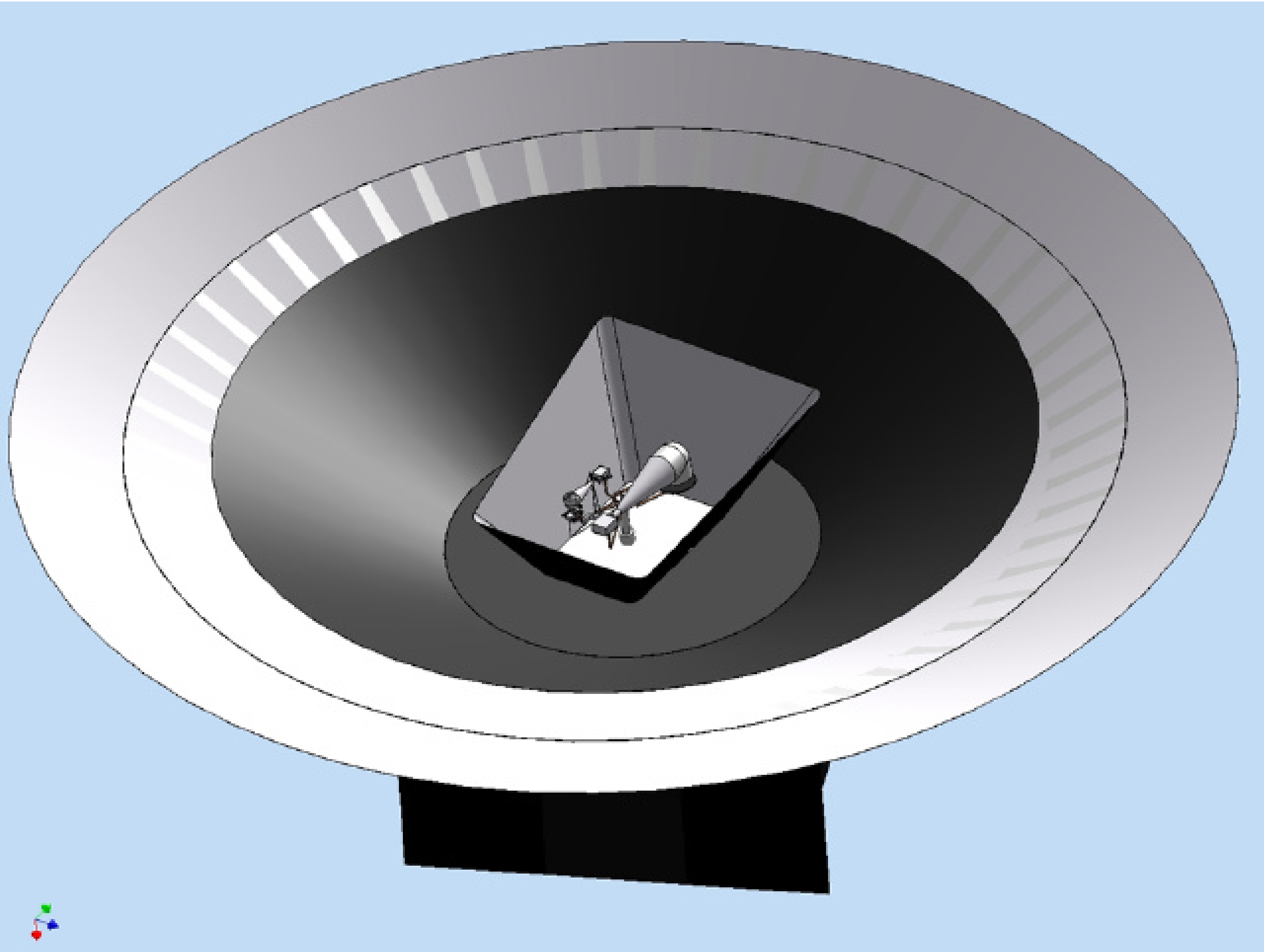

Figure 2: Overall view of the proposed payload. The large V-grooves, deployed, are shown. Outer diameter is approximately 6 meters. Internal shield, around detectors, is also displayed.

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The horn has to be corrugated so as to have the best performance in terms of attenuation, return loss, side lobes, and cross-polar pattern. For a first dimensioning the following geometrical ratios can be assumed:

Horn aperture	5 ?
Cone half opening	10°
Horn length	14 ?

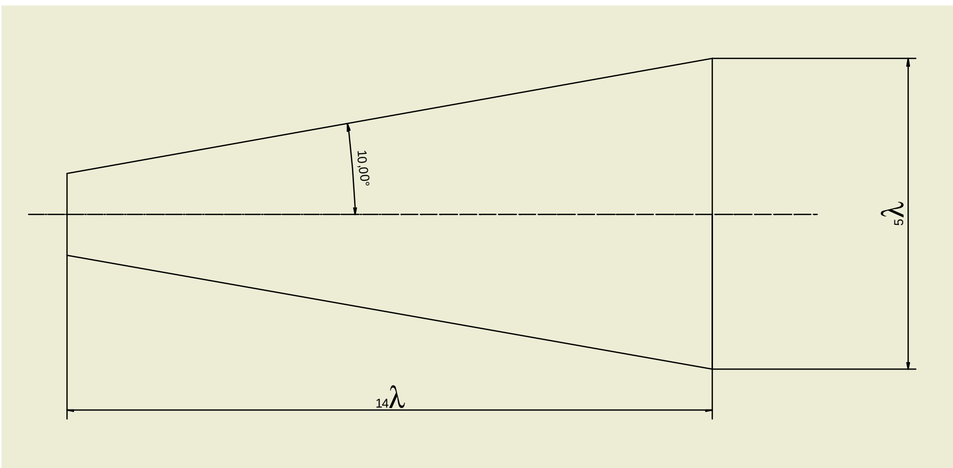

Figure 3: Design parameters used to obtain feed-horn dimension.

At the aperture of the horn, an offset shaped mirror is foreseen to tilt the beam at 90 degrees and modify the horn pattern to optimize the horn / reference electromagnetic coupling. The mirror can be rotated along horn axis to alternatively see the reference target and the sky as previously mentioned.

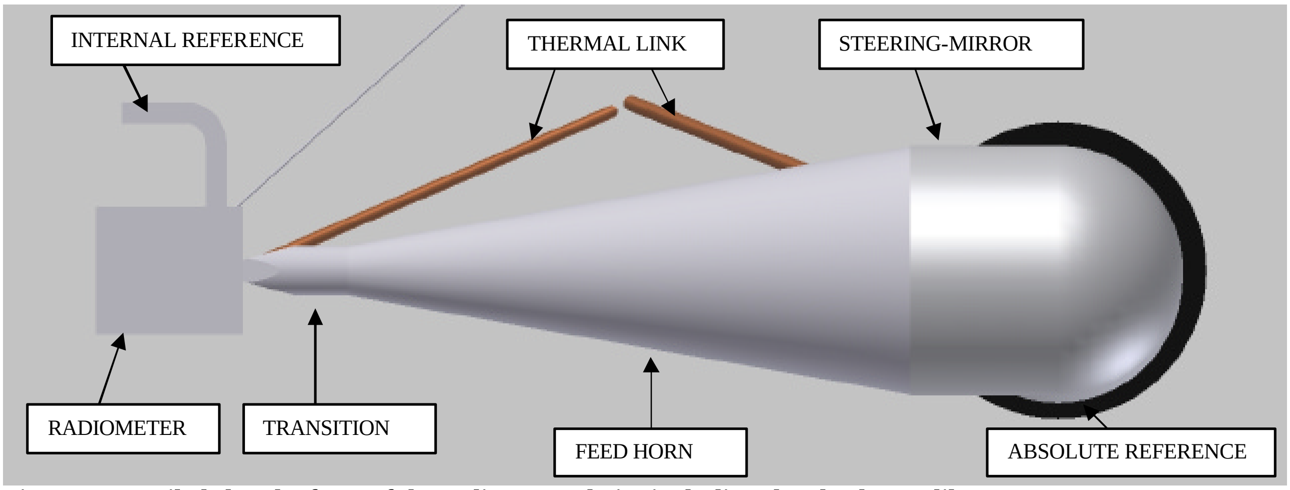

Figure 4: Detailed sketch of one of the radiometer chain, including the absolute calibrator.

In order to obtain the required sensitivity it is needed to have the absolute reference and the detector at 4K.
To achieve the operating temperatures, the combination of passive and active cooling can be used. Exploiting the unique environment of the Moon, it is possible to design radiators that can passively cool the thermal stages of the system at intermediate temperatures. At the same time, radiators can provide heat sinks for precooling and parasitics interception, simplifying the overall cryogenic active system and reducing power consumption.

Passive cooling is achieved by using thermal shields and V-Groove radiators. Their configuration and dimensions strongly depend on the position on the Moon. From a radiator efficiency point of view, polar regions clearly result more attractive given the small incident angle of Sun and Earth light. For this reason, a polar site is required for the proposed payload design.

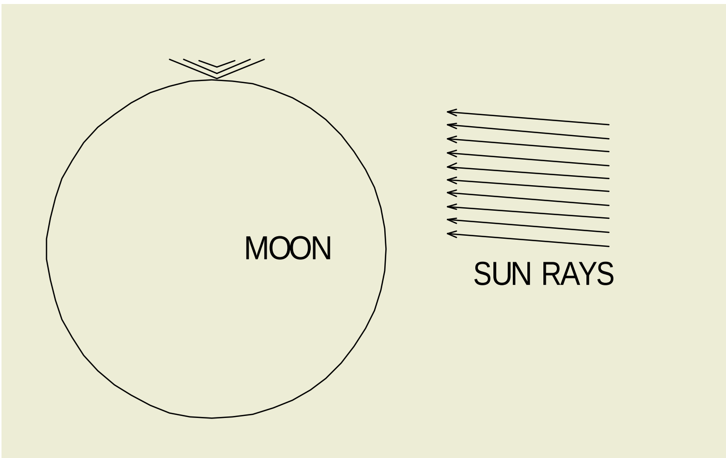

Figure 5: Sketch illustrating how the V-grooves are designed if the experiment is located at the Pole.

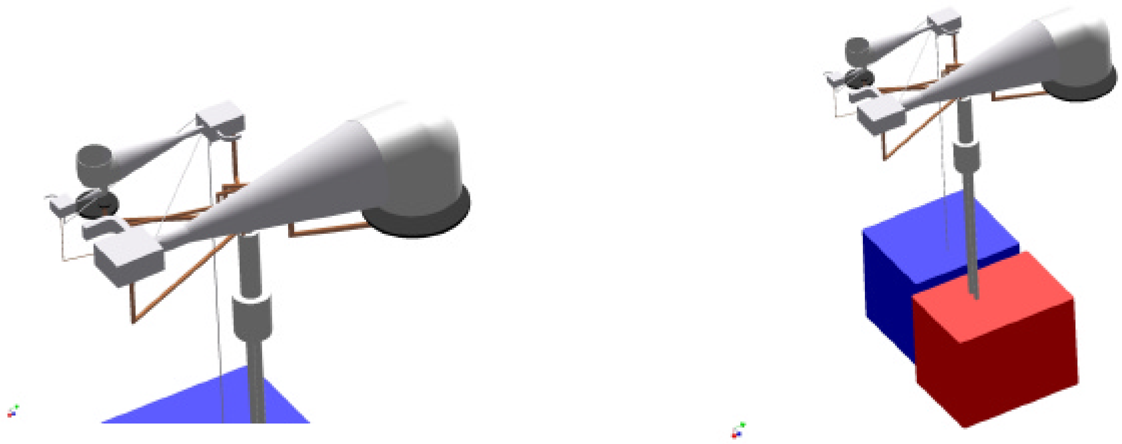

Figure 6: Detailed view of the radiometer assembly. 3 channels are shown.

Generally radiometers performance is not influenced by mechanical vibrations. For this reason, mechanical refrigerators such as Pulse tubes or Stierling can represent suitable solutions. Calibrators and radiometers are thermally connected to the cold head by high-conductance links in order to minimize temperature gradients. Active and passive control systems are used to stabilize their temperature. The heat produced by the cooler can be rejected by radiators. A radiator with a few square meters surface, 0.8 emissivity at 300K should be able to dissipate the produced heat. Due to Moon rotation and polar location, the radiating surface extends all round the structure. A heat pipes and thermal control system ensure the required temperature stability for an efficient heat rejection.
The required electric power is supplied by solar panels arranged around the structure. In order to maximize solar energy transformation, the solar panels must be adjustable at least along one axis to expose to the Sun, at any time, the required surface.

A first mass estimation is reported in the table below:

Horn, radiometer, reference[kg]	10
Cryo cool end [kg]	5
Cryo compressor [kg]	15
Thermal shield [kg]	20
Battery [kg]	30
Solar panel [kg]	50
Structure [kg]	50
Electronics [kg]	10
Total [kg]	190

Options

We have presented in the above section our proposal for the experiment baseline. We introduce here few options aimed from on side at improving the science capability of the experiment with a minimal impact and from the other side at providing an alternative scenario with respect to the Moon ground based approach.

A) Better frequency coverage - As an improvement with respect to the baseline frequency coverage (~ 40, 16, and 6 GHz), we propose to extend the frequency coverage to ~ 63 GHz for a better overlap with the best accuracy frequency region of the COBE/FIRAS measures. In addition, we could also add a channel at 25 GHz, for a better foreground monitoring. These options, and in particular the first one, do not increase appreciably the experiment mass and size. Adding a ~ 10

GHz channel would further improve our capability to subtract foreground, but this option should be considered very carefully because of its heavier implication in terms of mass and size.

B) Experiment during transfer phase – Given a receiver intrinsic sensitivity of ~ 1 mK sec$^{-1/2}$, such that adopted, it is immediate to derive a sensitivity of ~ 0.1 mK with an integration time of ~ 100 sec. An all-sky observation with an rms sensitivity of ~ 0.1 mK for each resolution element of ~ 1/2 deg (1/4 deg) side can be then achieved in about half an year (two years) of integration. Clearly, one or two months of operations are typically necessary for an accurate experiment calibration in flight. We note that such a good sensitivity (close to the final sensitivity on the CMB spectrum) on the considered angular scales is necessary for a precise separation of the CMB signal from the foreground components, possibly spatially localized. Such sensitivities per resolution element are certainly enough to achieve the requirement of ~ 0.1 mK sensitivity in the knowledge of the CMB spectrum (monopole term) considered in the previous sections, the final uncertainty being then determined by the accuracy of component separation process and no longer by sensitivity limitation. Many of the orbital transfer phases currently foreseen for the considered launchers require time scales comparable or longer than ~ one year. Alternatively, this experiment could be also performed from an orbit around the Moon. Therefore, the experiment described in this WP can be carried out also as a free-flyer taking advantage from various launches aimed at the Moon exploration or at Moon based activities. The advantage of such a scenario mainly relies on the evident possibility to observe the whole sky, thus overcoming the limitation introduced by a Moon ground-based experiment. Obviously, in these cases the observational strategy should be studied according to the details of the adopted orbital transfer.

Summarizing, about 220 days of in-flight observation allow to achieve an all-sky survey with the required sensitivity (0.1 mK on 0.5 deg resolution element) while a longer mission of about 800 days (compatible with some transfer phase scenarios) would improve by a factor of two the ultimate experiment sensitivity.

In this option, the design of the payload will be modified according to the different operating conditions, similar to a free-flyer spacecraft. In particular, V-grooves design, shield design, solar panels will be affected.

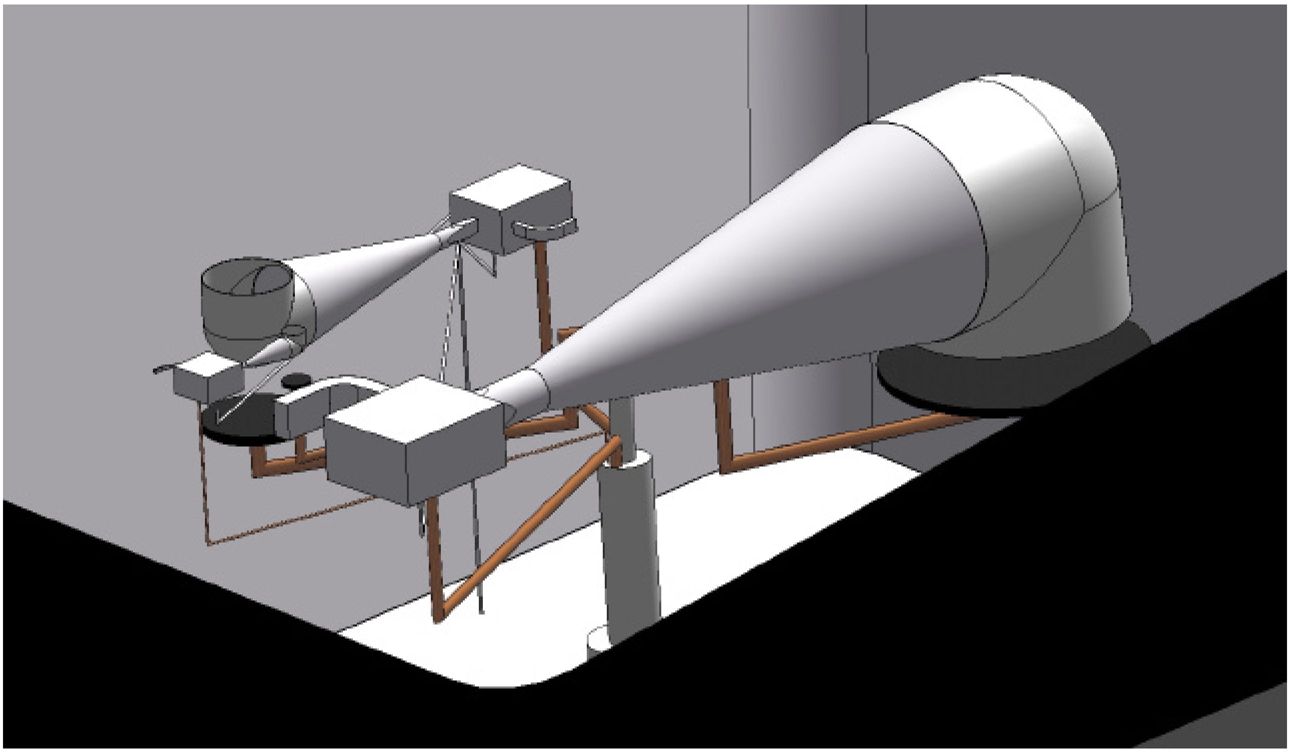

Figure 7:Enlarged view of the internal part of the payload.

Summary of instrumental characteristics

We report here a summary of the technical requirements for the Moon-based experiment. We describe the baseline design and some options for the payload, which will significantly improve the scientific return.

In the last section we report the expected performance of the payload if mounted on the Orbital Transfer Module (MTO) and operated during the cruise to the Moon.

Payload baseline design

1. Number of channels: 3, centered at 6, 15 and ~40 GHz. Bandwidth: 10%
2. Optics: Corrugated feed-horns, Field-of-view (FOV) 14°, passively cooled
3. Scanning angle for the steer-able mirror: from -45° to +45° from the zenith
4. Detector technology: HEMT differential radiometers, cooled at T<= 20K, sensitivity: 1mK $sec^{-1/2}$
5. Internal calibrator for the differential radiometers: reflectivity < -40dB, temperature: ~4K, thermal stability
6. Absolute calibrators: reflectivity < -60dB, temperature: <4K, thermal stability: better than 1mK (temperature monitoring with sensitivity and accuracy better than 10 μK.
7. Inter-calibration between the channels: better than 30 μK
8. Estimated cooling power: 1 W @ 4K
9. Expected data rate: <10kbit/sec
10. Require minimum lifetime: 4 months of observations (operating)

Payload options

This option include all the requirements in the baseline design plus additional frequency channels. These options, in increasing complexity, will impact in a limited way the overall mass, power and data rate budget.

- 4 channels option: 6, 16, 40, **63** GHz, other characteristics unchanged
- 5 channels option: 6, 16, **25**, 40, **63** GHz, other characteristics unchanged
- 6 channels option: 6, **10**, 16, **25**, 40, **63** GHz, other characteristics unchanged

Transfer phase option

If the payload is mounted on the MTO, taking advantage of a long transfer phase to the Moon, it is possible to observe the whole sky and to reach higher sensitivity. This will dramatically improve the scientific return.

- Assumed detector sensitivity: 1 mK $sec^{-1/2}$
- Required sensitivity per resolution element: 0.1 mK
- Observed sky fraction: 100%
- Resolution element: 0.5 deg
- Required minimum observing time: 200 days

If the transfer phase was longer, it is possible to obtain the same sensitivity on a resolution element of 0.25 deg, further improving the science return, in approximately 800 days.

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