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The first flight of the OLIMPO experiment: instrument performance

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Abstract. OLIMPO is a balloon-borne experiment aiming at spectroscopic measurements of the Sunyaev-Zel'dovich effect in clusters of galaxies. The instrument operates from the stratosphere, so that it can cover a wide frequency range (from ~ 130 to ~ 520 GHz in 4 bands), including frequencies which are not observable with ground-based instruments. OLIMPO is composed of a 2.6-m aperture telescope, a differential Fourier transform spectrometer and four arrays of lumped element kinetic inductance detectors operating at the temperature of 0.3 K. The payload was launched from the Longyearbyen airport (Svalbard Islands) on July 14th, 2018, and operated for 5 days, at an altitude of 38 km around the North Pole. We report the in-flight performance of the first lumped element kinetic inductance detector arrays ever flown onboard a stratospheric balloon.

1. Introduction

Since recombination, CMB photons have been travelling through the universe with very limited interactions with matter. They were diluted and redshifted due to the expansion of the universe and they form a black body spectrum with a temperature of 2.725 K [1, 2]. When crossing the plasma of galaxy clusters, about 1% of CMB photons increase their energy (frequency) resulting in a characteristic spectral distortion [3]. This is the Sunyaev-Zel'dovich (SZ) effect [4], which is observable in the direction of the galaxy clusters. The effect is redshift-independent and can be used to study the physics of galaxy clusters; moreover, distant clusters can be used as probes of the standard cosmological model e.g. through the estimate of the Hubble constant H_0 , the age of the universe, and the baryonic fraction [5].

Recent photometric surveys of the SZ effect have been performed from the ground by



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large telescopes as SPT (South Pole Telescope) [6], ACT (Atacama Cosmology Telescope) [7], APEX (Atacama Pathfinder EXperiment) [8] and IRAM (Institute for Radio Astronomy in the Millimeter Range) [9], with a spectral coverage limited to frequencies lower than 250 GHz because of atmosphere transparency and noise [10]. Multiband photometric measurements have been obtained by the *Planck* satellite, mainly from the 6 channels of the high frequency instrument, operating from 100 to 857 GHz [11].

Here we focus on an original effort to measure the SZ spectroscopically, with a large-aperture telescope working from the stratosphere. Such an experimental approach can vastly improve the accuracy, allowing an efficient component separation of the Galactic foregrounds [12] and of the different SZ components along the same line of sight.

The advantage of spectral measurements is evident considering that the crudest model for microwave emission of galaxy clusters involves, at least, 8 independent parameters: the Comptonization parameter, the electron optical depth, the peculiar velocity of the cluster along the line-of-sight, the minimum momentum of electrons in the non-thermal component, the amplitude of the non-thermal component, the CMB anisotropy, the optical depth of interstellar dust and the dust temperature. This means that at least 8 independent photometric channels are required. This is difficult to achieve with ground-based measurements, limited to a few atmospheric windows even in the best sites on Earth. However, an effort to build a ground-based observatory able to provide a broad frequency coverage is represented by Prime-CAM/CCAT-prime [13, 14].

OLIMPO is the first instrument dedicated to a measurement of the SZ spectrum from a stratospheric balloon. It is designed to measure the SZ effect spectrum in a sample of ~ 40 galaxy clusters. Using a differential Fourier Transform Spectrometer, and continuously comparing two fields of view separated by $\sim 0.5^\circ$, OLIMPO rejects the common mode signals from the instrument, the atmosphere and the CMB, and it can produce 30 independent spectral measurements (with a resolution 6 GHz) of the SZ in the range 130 - 520 GHz [15].

An important issue which can affect measurements with detectors operating in the stratosphere, as well as onboard satellites, is the interactions with primary cosmic rays, which would produce glitches in the signal timestreams, potentially causing a significant loss of data. In OLIMPO we overcome this problem using very fast detectors, so that masking cosmic-ray events results in a very limited data loss.

In this paper, we focus on the technological aspects of the OLIMPO experiment. The structure is as follows. In Sec. 2 we provide a short description of the OLIMPO instrument and detector arrays. In Sec. 3 we give an overview of the pre-flight calibration and in-flight performance of the OLIMPO detector arrays, with a special attention to the study of cosmic glitches. We provide our final remarks in Sec. 4.

2. The OLIMPO mission

2.1. The instrument

OLIMPO is the acronym for Osservatorio nel Lontano Infrarosso e le Microonde su Pallone Orientabile, literally “observatory in the far-infrared and the microwave (bands) on a steerable balloon gondola” [16]. OLIMPO features a Ritchey-Chretien telescope [17] with a primary mirror aperture of 2.6 m, feeding four low-temperature lumped element kinetic inductance detector (LEKID) arrays [18, 19], cooled to ~ 300 mK through a wet LN₂ plus L⁴He cryostat and a ³He refrigerator. A room-temperature, plug-in, differential Fourier transform spectrometer (DFTS) [20] can be inserted between the telescope and the cryostat, which allows us to switch between photometric and spectroscopic configurations. The attitude control system is composed of an azimuth pivot, an elevation motor, three gyroscopes, a star camera, and two sun sensors, all controlled by two computers. Furthermore, it features a boresight precision of the order of

one arcminute. The payload is sketched in Fig. 1. It was designed for a polar summer, long-duration stratospheric flight. It is powered by four arrays of solar panels ($\sim 8\text{ m}^2$) that charge two sets of pressurized gel lead-acid batteries. OLIMPO has been launched from Longyearbyen airport on July 14th, 2018. The flight duration was 5 days, at a float altitude of 37.8 km.

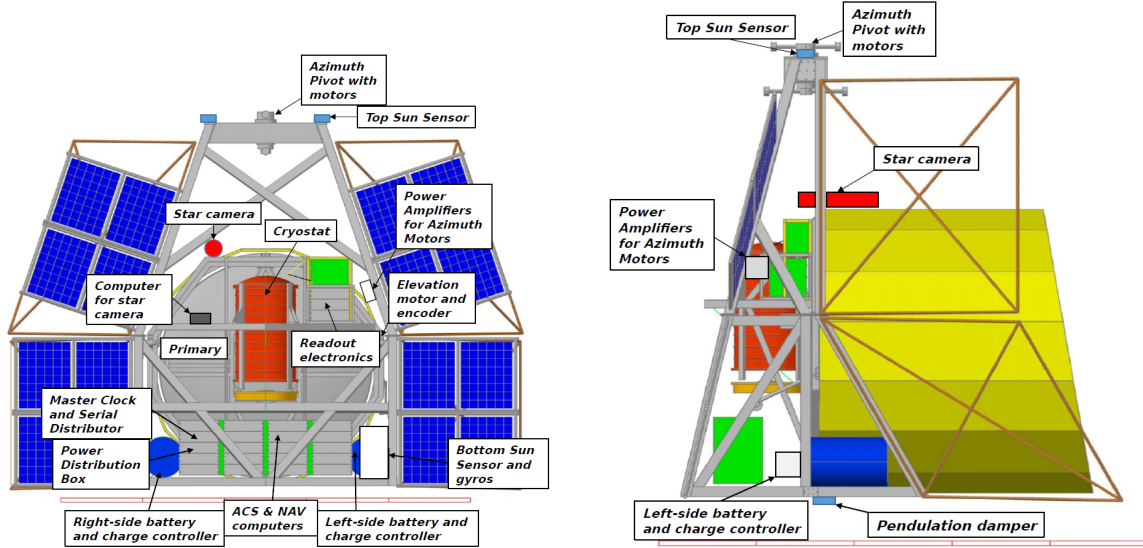


Figure 1. Sketch of the OLIMPO experiment, with a labelling of the main components. The rear view and the side view are shown in the left and in the right panels, respectively.

2.2. The OLIMPO Detector Arrays

Precision measurements of CMB temperature anisotropy, polarization and spectrum require very sensitive arrays of detectors operating at cryogenic temperatures. The LEKID detector arrays [21–23] consist of planar, high-quality factor superconducting LC resonator pixels, where the inductor also absorbs the incoming radiation [24, 25]. Each absorbed photon with energy larger than the superconductor energy gap breaks a Cooper pair, generating two quasiparticles [26]. The resulting increment of the quasiparticle density induces a change of the kinetic inductance as well as the resonant frequency. These variations are measured monitoring the amplitude and the phase of a microwave bias signal, transmitted through a feedline coupled to the resonator, i.e. measuring the scattering parameter S_{21} of the resonator. The *lumped element condition* for the resonator is obtained if the dimensions of the components are smaller than the wavelength of the bias signal: in this way the current density in the inductor and the absorption efficiency are uniform. The geometry chosen for our inductor is a IV order Hilbert [23]. When used to uniformly fill a given surface, this geometry results in an efficient absorption of both polarizations of the incoming radiation. LEKIDs are easily replicable in large arrays of thousands of pixels, and they are intrinsically multiplexable. These features, together with the simplicity in microfabrication, and the short response time (0.1 ms), make KIDs more appealing than other detector technologies (e.g. transition edge sensors) for our application [27]. In OLIMPO, the resonators are made in Aluminum film, with a critical temperature $T_c \sim 1.31\text{ K}$ (thus responding to frequencies larger than $\sim 120\text{ GHz}$) deposited on a Silicon dielectric substrate. The four OLIMPO arrays have been optimized to operate at 150, 250, 350 and 460 GHz, with angular resolutions of 5, 3.5, 2 and 2 arcmin respectively.

3. Results

In this Section, we show our results on detector calibration and in-flight performance issues.

3.1. Pre-Flight Calibration

The OLIMPO LEKID arrays have been characterized for their electrical performance in a dilution refrigerator. We optimized the bias power at the operating temperature first. Then, the forward transmission S_{21} scattering parameter was measured, to estimate the quality factor [25]. Finally, the variation of the response with temperature was measured, to evaluate the electrical noise equivalent power (NEP) (see [18] for details).

After the dark tests, the optical measurements were performed in the OLIMPO cryostat. We have reproduced the expected radiative background at ~ 40 km altitude. The reduced radiative load was mimicked inserting a 1% transmittance cold (2K) neutral density filter (NDF). In this way, the optical signal produced by alternating two black bodies (one at room temperature and one at 77 K) in front of the cryostat window, produces a Rayleigh-Jeans signal of $0.01 \times (220 - 77)\text{K} = 2.2\text{K}$. As a representative example, the left panel of Fig. 2 shows the detector signals for an optical modulation at 12 Hz, as measured in the I (in-phase) and Q (in-quadrature) channels [21]. Noise measurements were taken closing the cryostat window with a metal mirror, and acquiring 50 s-long signal timestreams. The noise spectra were obtained via Fourier transform of these timestreams (see the right panel of Fig. 2). The optical responsivities and the noise equivalent temperature in the Rayleigh-Jeans approximation (NET_{RJ}) measured for the Q channel and averaged over the arrays are collected in Tab. 1.

Channel [GHz]	Responsivity [rad/K]	NET_{RJ} [$\mu\text{K}/\sqrt{\text{Hz}}$]
150	0.171 ± 0.018	300 ± 35
250	0.305 ± 0.024	370 ± 45
350	0.187 ± 0.022	370 ± 20
460	0.168 ± 0.022	570 ± 40

Table 1. Array-averages of the responsivity and NET_{RJ} measured during the pre-flight calibration.

These values indicate a good performance, validating the use of these detectors for the flight, where, due to the lower background and noise, an even better performance is expected.

3.2. In-Flight Performance

During the first 3 hours of the flight, we tuned the detectors bias power by checking their noise performance. We found that the performance of the detectors improved with respect to the tests we performed in the laboratory, due to a combination of better tuning, reduced background and reduced electromagnetic and mechanical interference.

The performance was evaluated using the thermal signal from a cryogenic calibration lamp [28]. Its signal illuminates the entire focal plane and it is accurately reproducible. Comparing the signal produced by the lamp and the corresponding noise level, as measured in laboratory and during the flight, we estimated the in-flight NET_{RJ} , which resulted 2, 8, 3.5, 4.5 times smaller than those measured on the ground at 150, 250, 350, and 460 GHz, respectively. The in-flight NET values are compatible with photon-noise-limited performance, in the radiative background produced by the CMB, the residual atmosphere, the warm optical system of OLIMPO [29].

Cosmic ray hits are visible in all the detector arrays [29]. Ballistic phonons, produced by the energy released in the Si wafer by the cosmic ray hits, are in principle free to spread across

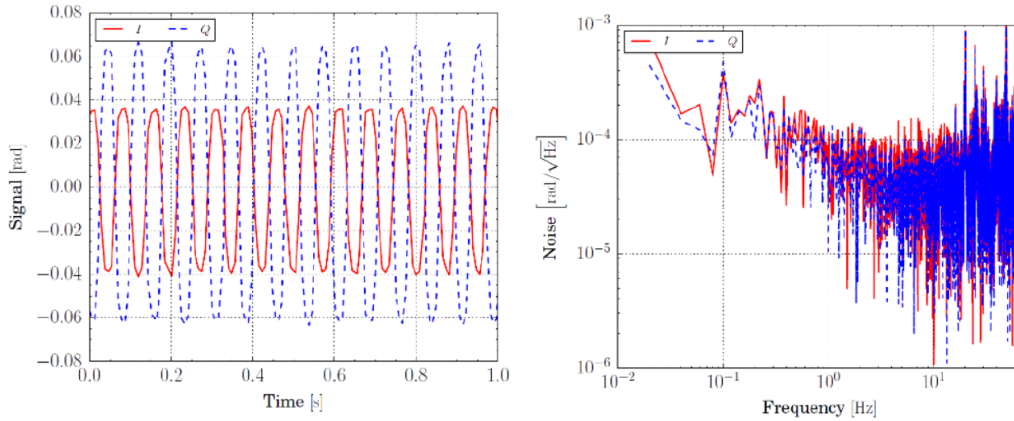


Figure 2. Left: Stream of the ΔT_{RJ} optical signal, modulated at 12 Hz, read out in the I (red solid line) and Q (blue dashed line) channels for 1 pixel per array. Right: Noise spectra of the I (red solid line) and Q (blue dashed line) channels obtained from 50 s long signal time streams.

the entire array. In order to reduce this effect we inserted an Aluminum layer on the back side of the wafer, acting at the same time as “phonon-trap” and radiation backshort, which reflects back towards the absorber the radiation not absorbed at the first passage. For the 250, 350 and 460 GHz arrays, the hits are shorter than our signal sampling interval of 8 ms as in the example shown in the left panel of Fig. 3, the amplitudes are consistent with the expected ones, and the measured decay time is consistent with the quasiparticles recombination time of ~ 0.1 ms measured in the laboratory. For the cosmic rays hits on the 150 GHz array we find a time constant $\tau \sim 17$ ms. As representative examples, in Fig. 3, we plot the responses of pixel 28 of the 460 GHz array (left panel) and pixel 9 of the 150 GHz array (right panel).

Cosmic rays hits are limited to a single or to at most two neighbouring pixels in the case of the 250, 350 and 460 GHz arrays. For the 150 GHz array, instead, most of the hits produce a detectable signal in the majority of the pixels. Our hypothesis is that the 150 GHz wafer thermalization on the metal holder, obtained by means of 4 springs and a number of wedge bonds, worsened in flight, so we are detecting thermal effects related to cosmic rays hits. In any case, the fraction of the data contaminated by the presence of cosmic rays hits is at most 3% for the 150 GHz and 250 GHz arrays, and less than 0.1% for the 350 GHz and 460 GHz arrays.

4. Conclusion

The first flight of the OLIMPO experiment has demonstrated that LEKID technology can be effectively used in the stratospheric environment, with photon-noise limited performance even in low-background conditions. We have shown that the performance of the detectors has improved during the flight, probably due to the reduction of the background noise, and electromagnetic and mechanical interferences. We have also shown that OLIMPO-like KIDs are not significantly affected by the interactions with cosmic rays. The fraction of contaminated data is smaller than a few percent for all the detectors. This result is very promising for the global quality of the OLIMPO data and qualifies KIDs arrays for operation in space.

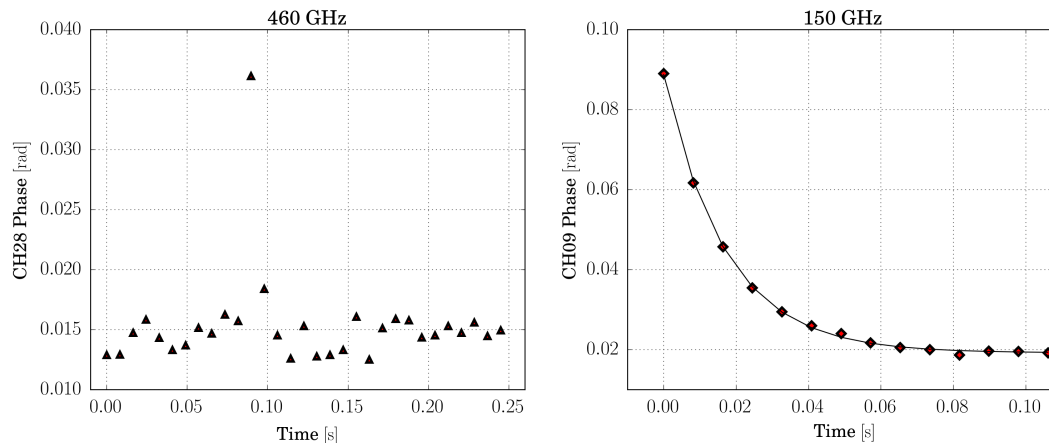


Figure 3. Left: Representative example of a cosmic ray hit in the timestream of a pixel of the 460 GHz array. Right: Representative example of a cosmic ray hit of a pixel of the 150 GHz array (diamonds), and best-fit exponential decay (continuous line, $\tau \sim 17$ ms).

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