PILOT balloon-borne experiment in-flight performance

G. Foënard, A. Mangilli, J. Aumont, A. Hughes, B. Mot, J-Ph. Bernard, A. Lacourt, I. Ristorcelli, L. Montier, Y. Longval, P. Ade, Y. André, L. Bautista, P. deBernardis, O. Boulade, F. Bouquet, M. Bouzit, N. Bray, V. Buttice, M. Charras, M. Chaigneau, B. Crane, E. Doumayrou, J.P. Dubois, X. Dupac, C. Engel, P. Etcheto, Ph. Gelot, M. Griffin, S. Grabarnik, P. Hargrave, Y. Lepennec, R. Laureijs, B. Leriche, S. Maestre, B. Maffei, J. Martignac, C. Marty, W. Marty, S. Masi, F. Mirc, R. Misawa, J.M. Nicot, J. Montel, J. Narbonne, F. Pajot, E. Pérot, G. Parot, J. Pimentao, G. Pisano, N. Ponthieu, L. Rodriguez, G. Roudil, H. Rousseau, M. Salatino, G. Savini, O. Simonella, M. Saccoccio, S. Stever, P. Tapie, J. Tauber, C. Tibbs, C. Tucker

Abstract The Polarized Instrument for Long-wavelength Observation of the Tenuous interstellar medium (PILOT) is a balloon-borne experiment aiming at measuring the polarized emission of thermal dust at a wavelength of 240 μm (1.2 THz). A first PILOT flight (flight #1) of the experiment took place from Timmins, Ontario, Canada, in September 2015 and a second flight (flight #2) took place from Alice Springs, Australia in April 2017. In this paper, we present the in-flight performance of the instrument during these two flights. We concentrate on performances during flight #2, but allude to flight #1 performances if significantly different. We first present a short description of the instrument and the flights. We determine the time constants of our detectors combining in-flight information from the signal decay following high energy particle impacts (glitches) and of our internal calibration source. We use these time constants to deconvolve the data timelines and analyse the optical quality of the instrument as measured on planets. We then analyse the structure and polarization of the instrumental background. We measure the detector response flat field and its time variations using the signal from the residual atmosphere and of our internal calibration source. Finally, we analyze the detector noise spectral and temporal properties. The in-flight performances are found to be satisfactory and globally in line with...
expectations from ground calibrations. We conclude by assessing the expected in-flight sensitivity of the instrument in light of the above in-flight performances.

Keywords PILOT, inflight performances, Interstellar Dust, Polarization, Far Infrared, Point Spread Function, Straylight, Pointing, Background, Responses, Glitches

1 Introduction

Interstellar dust grains account for 1% of the mass of the interstellar medium (ISM). They are involved in different important processes such as photo-electric heating of the neutral interstellar gas, cooling in dense star-forming regions and the formation of molecules, including H$_2$ at their surface. Dust emission is used to trace the Interstellar Medium (ISM) structure of the Milky Way and in the local Universe (e.g., [1, 2, 3]). The thermal dust emission can be modelled using a modified blackbody spectrum in the infrared to sub-millimetre wavelength range. ISM dust grains absorb starlight in the Visible and ultra-violet, which heats them to temperatures of $\simeq 17$ K in the diffuse ISM in our Galaxy. Dust grains probably have an irregular shapes and as they rotate, align their minor axes on the local magnetic field (e.g., [4, 5]). This partial alignment causes a fraction of their thermal emission to be linearly polarized in a direction orthogonal to the magnetic field direction as projected on the sky. For the same reason, non-polarised starlight passing through aligned dust grains also becomes polarized: preferential absorption along the grains long axis leads to extinction that is polarized parallel to the magnetic field lines.

The balloon experiment Archeops [6] mapped the polarized dust emission at 353 GHz with $\sim 13^\prime$ resolution over $\sim 20\%$ of the sky. These measurements indicated high polarization levels (up to 15%) in the diffuse ISM. More recently, the Planck satellite has mapped the polarized dust emission in the wavelength range from 850 mm (353 GHz) to 1.0 cm (30 GHz) over the entire sky (7). The planck satellite data allowed us to confirm the existence of highly polarized regions at high galactic latitudes with polarization fractions up to 20%. As a consequence, polarized dust thermal emission is a dominant foreground contaminant to the observation of the Cosmic Microwave Background (CMB) polarization (see, [3]). The goal of the PILOT observations is to improve our understanding of the thermal dust polarization signal, by measuring it at higher frequencies in the far-infrared.

Following a brief introduction in Sect. 1, the PILOT instrument and the flights and observations are briefly described in Sect. 2.1 and 3 respectively. The use of glitches and our internal calibration source to measure detector time constants is developed in Sect. 4 and 4.3. The in-flight optical quality is discussed in Sect. 5. The instrumental background observed in-flight is described in Sect. 6. Detector response as measured on the residual atmospheric signal and detector noise properties are given in Sect. 7.1 and Sect. 8 respectively. Section 9 summarizes the instrument sensitivity expected given the in-flight performances. Section 10 is devoted to conclusions.

2 The PILOT instrument

2.1 Instrument description

A complete description of the PILOT instrument is available in [9]. In this section, we only give a brief description of the instrument, for completeness. Table 1 summarizes the main characteristics of the instrument.

The optics of the instrument is composed of an off-axis paraboloid primary mirror (M1) of 0.83m diameter and an off-axis ellipsoid secondary mirror (M2). The combination respects the Mizugushi-Dragone condition to minimize depolarization effects (see [9] and [10]). All optics following M1, including M2, is cooled at cryogenic temperature of 2 K.

The Gregorian telescope is followed by a re-imager and a polarimeter through a flat mirror (M3). Two lenses (L1 and L2) are used to re-image the focus of the telescope onto the detectors. A Lyot-stop is placed between the lenses at a pupil plane that is conjugate of the primary mirror. A rotating Half-Wave Plate (HWP), made of Sapphire, is located next to the Lyot-stop. The birefringent material of the HWP introduces a phase delay between the two orthogonal components of the incident light. A polarization analyzer, which consists of parallel metallic wires, is placed at a 45° angle in front of the detectors, in order to transmit one polarisation to the transmission (TRANS) focal plane and reflect the other polarisation to the reflection (REFLEX) focal plane. Observations at, at least two, different HWP angles allow us to reconstruct the stokes parameters I, Q and U. Each of the (TRANS and REFLEX focal planes include 2048 bolometers (8 arrays of 16 X 16 pixels). They are cooled to 300 mK by a closed cycle He fridge. The detectors were developed by CEA/LETI for the PACS instrument on board the Herschel satellite.

In order to reconstruct the pointing of the instrument, we use the Estadius stellar sensor developed by CNES for stratospheric applications and described in [11]. This system provides an angular resolution of a few arcseconds, needed to optimally combine observations of the same part of the sky obtained with various polarization analysis angles. Estadius also remains accurate for scanning at speeds up to a 1 °/s. An internal calibration source (ICS) is used in-flight to calibrate time variations of the detector responses. This device is described in [12] and [13]. The source is located behind mirror M3 and illuminates all detectors simultaneously. It is driven using a square modulated current and the...
current and voltages of the source are measured permanently during flight to monitor the power dissipated in the source.

2.2 Polarisation measurements

Assuming a perfect HWP, the PILOT measurements $m$ are related to the input Stokes parameters $I$, $Q$, $U$ of partially linearly polarized light through

$$m = R_{xy}T_{xy} \times [I \pm Q_{\text{inst}} \cos 4\omega \pm U_{\text{inst}} \sin 4\omega] + O_{xy}, \quad (1)$$

where $R_{xy}$ and $T_{xy}$ are the system response and optical transmission respectively and $O_{xy}$ is an arbitrary electronics offset. For the configuration of the HWP and polarizer in place in the instrument, $\omega$ is the angle between the HWP fast axis direction and the horizontal direction measured counterclockwise as seen from the instrument and the $\pm$ sign is + and – for the REFLEX and TRANS arrays respectively (see [9]). Note that with the above conventions $Q_{\text{inst}}$ and $U_{\text{inst}}$ are defined with respect to instrument coordinates in the IAU convention, with $Q_{\text{inst}}=0$ for vertical polarization. When referring to sky-light polarization $Q_{\text{sky}}$ and $U_{\text{sky}}$, Equ. (1) becomes

$$m = R_{xy}T_{xy} \times [I \pm Q_{\text{sky}} \cos(2\theta) \pm U_{\text{sky}} \sin(2\theta)] + O_{xy}, \quad (2)$$

where $\theta = 2 \times \omega + \phi$ is the analysis angle, $\phi$ is the time varying parallactic angle measured counterclockwise from Celestial North to Zenith for the time and direction of the current observation, and $Q$ and $U$ are in the IAU convention with respect to equatorial coordinates. In practice, maps of $Q$ and $U$ are derived from observing the same patch of sky with at least 2 values of the analysis angle taken at different times in general. Inversion to derive sky maps of $I$, $Q$ and $U$ can be done through polarization map-making algorithms (see for instance [14]). The light polarization fraction $p$ and polarization direction $\psi$ are then defined as:

$$p = \sqrt{Q^2 + U^2} \quad (3)$$

and

$$\psi = 0.5 \times \arctan(U, Q). \quad (4)$$

3 The Pilot flights and observations

PILOT is carried to the stratosphere by a generic gondola suspended under an open stratospheric balloon operated by the French National Space Agency (CNES). PILOT uses 803Z class balloons, with a Helium gas volume of $\sim 800\,000$ m$^3$ at ceiling altitude. The instrument can be pointed to a given direction using the gondola motion around the flight chain and motion around an elevation axis (see [9]). Scientific observations are organized in individual observation tiles (also called observations for short) where a given rectangular region of the sky is scanned by combining the azimuth and elevation axis of the instrument.

The flight plan is built taking into account the various observational constraints such as the visibility of astronomical sources, the minimum angular distance between the instrument optical axis and bright sources such as the sun or the moon, elevation limits due to the presence of the Earth at low elevations and the balloon at high elevations. The expected performance of the instrument are taken into account when establishing the flight plan in order to distribute the observing time according to the science objectives requirements, and to evenly distribute polarization analysis directions (angle $\theta$ in Eq. (2), as well as sky scanning direction angles for any given astronomical target.

3.1 flight#1

The first flight of the PILOT experiment took place from the launch-base facility at the airport of Timmins, Ontario, Canada on September 21, 2015 at 9:00 PM local time. The launch was part of a campaign led by CNES and the Canadian Space Agency (CSA), during which six stratospheric balloon experiments were successfully operated.

The ascent to the stratosphere took 2.5 hr. At ceiling, the altitude of the experiment remained relatively stable between 38 km and 39 km over a time period of 18 hr. The total duration of the flight was 24 hr allowing us to obtain about 15 hr of science data. Approximately 4 hr were spent optimizing the detector readout chain settings, recycling of the $^3$He fridge and slewing between individual observing regions. The focal plane temperature remained stable during the whole ceiling period at temperature of $\sim 321\,mK$ and $\sim 325\,mK$ for the TRANS and REFLEX focal planes respectively. Out of the 8 bolometer arrays, array #1 (TRANS) and array #3 (REFLEX) were not operational during flight#1 due to a failure in the time-domain multiplexing clock signal, a problem which was already experienced during ground calibrations (see [15]).

The scientific observations performed during flight#1 are summarized in Tab. 2. During this flight, scientific observations were performed scanning the telescope at constant elevation, in order to minimize residual atmospheric emission. We collected a total of 5.5 hr of science data on star forming regions, 2.4 hr on cold cores, 1.4 hr on external galaxies, and 4.6 hr on a relatively empty region of the sky. Calibration data were obtained on planets Uranus and Saturn. We also obtained 'skydip' measurements during which we explored the whole range of allowed elevations, in order to characterize the residual atmospheric emission (see Sect. 7). The experiment successfully landed under parachute and was recovered about 350 km East of Timmins in a dry forest.
Table 1: Main optical characteristics of the PILOT instrument.

| Characteristic                          | Value                                           |
|----------------------------------------|-------------------------------------------------|
| Telescope Type                         | Gregorian                                       |
| Equivalent focal length [mm]           | 1790                                            |
| Numerical aperture                     | F/2.5                                           |
| FOV [°]                                | 1.0 x 0.8                                       |
| Ceiling altitude                       | ~3 hPa                                          |
| Pointing reconstruction                | translation = 1", rotation = 6", 1σ            |
| Gondola Mass                           | ~1100 kg                                        |
| Primary mirror type                    | Off-axis parabolic                               |
| Primary mirror dimension [mm]          | 930 x 830                                       |
| M1 used surface projected diameter [mm]| 730                                              |
| Focal length [mm]                      | 750                                              |
| Detector type                          | Multiplexed bolometer arrays                    |
| Number of Detectors                    | 2048                                            |
| Detector temperature [mK]              | 300                                             |
| Sampling rate [Hz]                     | 40                                              |
| Photometric channels                   |                                                 |
| $\lambda_0$ [µm]                       | SW Band 240                                      |
| $\nu_0$ [GHz]                          | LW Band 550                                      |
| $\Delta \nu/\nu_0$                     | 0.27                                            |
| beam FWHM [']                         | 0.31                                            |
| Minimum Strehl Ratio                   | 0.95                                            |
|                                       | 0.98                                            |

Fig. 1: The PILOT experiment on the tarmac before launch for flight#1 from Timmins, Ontario, Canada on September 21 2015.

area. The instrument had suffer some damages, essentially on electrical harness and optical baffle, due to collision with trees and branches. The mechanical structure of the gondola has well protected the payload. Inspection of the instrument and analysis of a video recorded during the flight showed that the front baffle of the instrument deteriorated during the day part of the flight. This was caused by a defect in the thermal insulation of the baffle. It produced additional straylight which, despite substantial subtraction during data processing, limited the quality of the science data obtained during this flight. Deteriorations of the instrument were fixed during the preparation for its second flight (see Sect. 3.2).
Table 2: Summary of the observations obtained during flight#1.

| Source          | Observation Time [min] | Map size [deg x deg] | Total depth [deg$^2$/h] |
|-----------------|------------------------|----------------------|-------------------------|
| Taurus          | 117                    | 12 x 8               | 53                      |
| Orion           | 145.3                  | 10 x 10              | 47.8                    |
| Aquila Rift     | 46                     | 8 x 8                | 94                      |
| Cygnus OB7      | 21                     | 7 x 7                | 166.5                   |
| L1642           | 44                     | 2 x 2                | 9.5                     |
| G93             | 61                     | 2 x 2                | 6.3                     |
| L183            | 41                     | 2 x 2                | 9.5                     |
| M31             | 84                     | 3 x 3                | 6.1                     |
| Polaris         | 160                    | 5 x 5                | 12.3                    |
| Cosmo field     | 116                    | 16 x 16              | 160                     |
| Uranus          | 31                     | 3 x 2                | 19                      |
| Saturn          | 12                     | 2 x 2                | 34                      |
| SkyDip          | 10                     | n/a                  | n/a                     |

3.2 Improvements between flights

Following flight#1, a series of modifications were made to the instrument. In particular, the cryostat was tested in the laboratory for operations with stronger pumping on the $^4$He bath, which allowed reaching lower detector temperatures and increased the cryogenic lifetime of the cryostat from $>27$ hr to $>33.5$ hr. We also increased the size of the optical field-stop located in the cryostat, which was producing parasitic reflections affecting the polarization curves for pixels at the edges of the focal planes. We modified the thermal insulation of the optical front baffle to avoid deformation under sunlight exposure. We also decided to implement the possibility of scanning the sky at an arbitrary angle with respect to the horizon. This leaves residual atmospheric emission signal in the data that would need to be removed but can be used to calibrate the instrument response (see Sect. 7.1). It also allows us to obtain observations at different scan angles on the sky, which is important for optimal removal of low frequency noise through destriping, without waiting for the sky to rotate. The new scanning mode was obtained by subordinating the elevation scan speed to the cross-elevation scan speed to obtain the desired scan angle. It was tested on the ground with the actual gondola, in order to check that this did not excite oscillation modes of the flight chain. We also modified the on-board computer software to allow scanning only the rectangular region around the target defined by the observer, and implemented a more flexible calibration sequence scheduler, in order to reduce overhead times. All of these changes were successfully implemented for flight#2.

3.3 flight#2

The second flight was conducted from the USA-operated launch base of Alice Springs, Australia. The launch was carried out as part of a launch campaign led by CNES, which enabled successful flights of 3 stratospheric gondolas. The flight lasted approximately 33 hr, during which 24 hr of scientific observations were obtained. The launch took place at 6:30 AM local time. The experiment reached ceiling altitude about 2 hr after take-off. The instrument reached an altitude of 39 km slowly decreasing to 36 km during the first day of the flight. The altitude decreased down to 31-34 km during the night due to the lower ascensional force of the balloon and despite getting rid of a fraction of the available balast. During the second day, the altitude rose again to reach 38-40 km. The focal planes temperatures evolved slightly with altitude during the ceiling period and remained in the range $\simeq 304 - 307$ mK and $\simeq 308 - 312$ mK for the TRANS and REFLEX focal planes respectively. Out of the 8 bolometer arrays, array #1 (TRANS), array #3 (REFLEX) and array #5 (TRANS) were not operational during flight#2 for similar reasons as during flight#1.

The scientific observations obtained during flight#2 are summarized in Tab. 3. Appart from the Orion molecular cloud and planets, all targets observed are specific to southern hemisphere. We mapped two regions along the inner Galactic plane near the Galactic center (L0) and near $l = 30^\circ$ (L30). We also obtained maps of several known molecular clouds. A large integration time was allocated to map a fraction of the Large Magellanic Cloud (LMC). We also obtained long measurements of the empty field observed by the BICEP2 ground experiment ([16]) in order to attempt constraining the polarization properties of dust in a typical region of low galactic foreground to the CMB.

The flight trajectory was Eastward during most of the flight. We successfully used the two telemetry antennas located in Alice Springs and in Longreach. The gondola was recovered about 850 km East of the launch site, in a desertic area and brought back to the Alice Springs base using an helicopter and a truck. The gondola and the instrument suffered no major damage from landing or recovery, which was later confirmed by a thorough inspection following the return of the instrument to France.
4 Glitches and time constants

The PILOT data are affected by ‘glitches’, which are characterized by an abrupt deviation in the signal timeline of a bolometer followed by an exponential decay. These features can be positive or negative, and they are caused by energetic particles striking the detector absorber or the walls of the integration cavity surrounding the detectors (see [17]). Removal of glitches from the PILOT timelines is important since they do not follow the same Gaussian distribution as the detector noise, and hence produce a bias in statistical descriptions of the data, e.g. the signal mean. They are also a significant source of artifacts for steps in the PILOT data processing that are performed in Fourier space. Finally, the decay following glitches can be used to constrain the time constant of individual bolometers. In this section, we give a brief description of our method for identifying glitches, a preliminary analysis of the glitch properties and the use of glitch decay to constrain detector time constants.

4.1 Glitch identification

We emphasize that our goal at this stage is to identify and suppress the most significant anomalous features in the signal timelines (i.e. those that noticeably affect the accuracy of our detector noise estimation) in an efficient, automated fashion across the entire flight, and to identify strong glitches that can be used to measure the detector time constants (Sect. 4.3). More sophisticated methods for glitch identification and signal reconstruction will be tested and applied to the PILOT data in future works that present the PILOT science data.

We identify glitches in the PILOT timelines using the following procedure. First, we construct an estimate of the high frequency (HF, 40 Hz ~ 1 sample) noise by shifting the timeline for each bolometer by 1 sample, and subtracting this shifted timeline from the original timeline. We refer to the resulting timeline as the ‘shifted data timeline’. We then replace the value of each sample in the shifted data timeline with a local estimate of the median absolute deviation, which is calculated using adjacent samples within a rolling window of 5 seconds. We refer to the resulting timeline as the ‘local HF noise timeline’. Next, we divide the shifted data timeline by the local HF noise timeline. Large (positive or negative) values in this glitch signal-to-noise (S/N) timeline provide a preliminary list of glitch candidates. Since glitches are characterized by a sharp change followed by an exponential decay, we expect positive glitches to appear in the shifted data and glitch S/N timelines as a large positive value, followed immediately by a (lower amplitude) negative value (and vice versa for negative glitches). In practice, however, this idealized characteristic signature is complicated by the presence of detector noise (for weaker glitches), very strong glitches (that saturate the detector for longer than one sample) and glitches that fall exactly between two samples. We reduce our list of preliminary glitch candidates by rejecting candidates with S/N < 5. We further impose a criterion that a positive value in the S/N timeline should be followed by a negative value of comparable amplitude. We define ‘comparable amplitude’ using an exponential softening function ($|\text{thresh}| = -0.75\exp(-1 + S/N/5)$) that depends on the S/N of the glitch candidate, such that it rejects moderate significance glitch candidates ($5 < S/N < 8$) if they do not exhibit the characteristic positive-negative (or negative-positive) signature. For glitch candidates with high S/N ($S/N \geq 10$), the range of allowed values for the next sample becomes sufficiently relaxed that essentially all such candidates are retained.

4.2 Glitch statistics

The glitch intensity histogram averaged over the whole focal plane for both positive and negative glitches during flight#2 is shown in Fig. 2. The statistics for glitches below $\sim 150$ ADU is affected by noise excursions also detected by the detection method. Both positive and negative glitches are detected, with a ratio of 86.8% for positive glitches (13.2%...
for negative glitches) above an absolute glitch intensity of 150 ADU. This ratio is similar to what has been observed for glitches on the PACS/Herschel detectors as reported by [17]. For glitches above 150 ADU, the glitch rate observed during flight#2 is about 0.68 gli/pix/hr. This figure goes up to 2.24 gli/pix/hr for positive glitches with intensity above 100 ADU. These values are comparable to those obtained for the PACS instrument on board Herschel by [17]. The glitch rate is observed to be roughly constant during flight#2 and the distribution across the focal plane is mostly homogeneous. Figure 3 shows the average profile of the signal decay following positive glitches for the various arrays, obtained by stacking signal around glitch locations, for glitches with intensity above 150 ADU. Above the threshold, individual pixels receive about 10 such glitches during flight#2, which allows to constrain bolometer time constants, as described in Sect. 4.3. As can be seen on the figure, most arrays show similar decay profiles, except for array #6 which shows significantly longer time constants.

4.3 Detectors time constants

During the calibration sequences with the ICS, the bolometric signal following each extinction of the source gradually decreases with a characteristic time $\tau_{cal}$. This progressive decay results from the convolution of the square pulse controlled by the current injected into the ICS with the transfer function of the ICS and that of the bolometers. A similar decrease follows the absorption of high energy particles (glitches) by the detectors, which can also be used to determine the response of individual detectors.

In the following, we assume that the transfer functions of the ICS and the bolometers can be described by an exponential decay of the form $e^{-t/\tau}$, where $\tau$ is the time constant. We call $\tau_{ics}$ the time constants of the ICS and $\tau_{det}$ that of the individual bolometers.

Because the glitch rate is low, determining $\tau_{det}$ from glitch transients alone would lead to a noisy determination. Instead, we use a combination of the glitch and ICS transients described below. The array-averaged values determined for each array are summarized in Tab. 4.

In a first step, we measure a first estimate of the detectors time constant using glitches, which we call $\tau_{gli}$. We averaged the measurements over 15 samples following positive glitches with intensity larger than 150 ADU. The average values derived for each array are given in Tab. 4 and the focal plane distribution of $\tau_{gli}$ is shown on Fig. 4. The time constant derived using glitches are around 0.7 samples (17.5 ms) for most arrays, except for array #6 for which it is around 1.5 samples (37.5 ms).

In a second step, we measure the time constant of the ICS using calibration sequences. We stack all decays of the signal following the extinction of the ICS and compute the corresponding average ICS downward profile viewed by each pixel. We then deconvolve this profile in Fourier space, using the transfer function $e^{-t/\tau_{ics}}$. We then average this profiles over pixels and fit the average profile with an exponential function and derive a value of $\tau_{ics}$ of 0.41 samples (10.25 ms). This can be compared to the value of 9.23 ms

| Array | 2 | 6 | Avg | 7 | 4 | 8 | Avg | Avg |
|-------|---|---|-----|---|---|---|-----|-----|
| $\tau_{gli}$ | 0.61 | 1.51 | 1.06 | 0.69 | 0.74 | 0.68 | 0.70 | 0.85 |
| $\tau_{det}$ | 0.61 | 0.89 | 0.75 | 0.58 | 0.63 | 0.58 | 0.58 | 0.60 | 0.66 |

Table 4: Array-averaged values of the detector time-constants as measured using glitches and using ICS downward decay assuming an intrinsic ICS time constant of $\tau_{ics}$=11 ms (see text).
Fig. 4: Top: Focal plane distribution of the bolometer time constants as measured from glitches $\tau_{gli}$. Bottom: Focal plane distribution of the bolometers time constants $\tau_{det}$ as measured using the ICS downward transitions. The four arrays shown on the left (resp. right) belong to the TRANS (resp. REFLEX) focal planes, such that arrays #6 and #4 (or arrays #2 and #8) are optical conjugates. In this representation, elevation increases towards the top-left and cross-elevation increases towards the top-right corner of each focal plane. The same convention and array numbering is used for all figures of the paper.

measure by [12] for a device similar to our source and operated under similar conditions.

In the last step, we determine the final values of $\tau_{det}$. We proceed in the same way as for the measurement of $\tau_{ics}$, except that we use here the above value of $\tau_{ics}$ as parameter for the deconvolution kernel and fit the downward profile of each pixel in order to derive the values of $\tau_{det}$ for each pixel. The array-averaged values of $\tau_{det}$ are given in Tab. A and are of the order of 0.60 samples (15.00 ms). On average, array #6 is slower than other arrays, with an average $\tau_{det}$ of 0.89 samples (22.25 ms). The focal plane distribution of $\tau_{det}$ is shown on Fig. 4.

5 Point Spread Function

Most of the optical elements in the PILOT instrument, except the primary mirror M1, are cooled below 3K inside a cryostat (the photometer). The overall optical quality of the system is therefore sensitive to the positioning of the pri-
mary mirror with respect to the cryostat. External conditions can modify the relative positioning of the optics in-flight, in particular thermo-elastic and bending under gravity effects in the mechanical structure holding the primary mirror. To minimize thermal effects, the pre-flight optical alignment was based on the flight thermal modeling and thermo-elastic analysis of the instrument and in-flight temperature predictions [18]. Checking the optical quality using in-flight measurements is therefore of particular importance.

During each flight of the instrument, we observed planets which can be assimilated to point sources at the resolution of PILOT and can therefore be used to assess the optical quality through a measurement of the instrument Point Spread Function (PSF). Planet maps were constructed with a pixel size of 0.1′ for each detector array and for each scan through the planet (referred to as planet crossings). All the data have been corrected for the responses calculated on the skydips, as described in Sect. 7.1 and corrected for the effects of the time constant of the detectors through deconvolution of the time constants as measured in Sect. 4.3.

The parameters of the PSF were deduced using an elliptical Gaussian fit applied to the individual crossing images. Figure 5 shows the values obtained for the major and minor axis dimensions of the PSF obtained on Jupiter. We obtain an average full-width half maximum (FWHM) size of 2.25′±0.15′, taking into account the apparent size of the planet (44.2′′). The uncertainties were derived from the statistics between the planet crossings.

Figure 6 shows the normalized average total intensity image over all crossings of Jupiter obtained with array #2 and array #6 during one observation of flight#2. The PSF shows no particular elongation along the scan direction, indicating accurate accounting for the detectors time constant. However, we can see that the PSF images are boxy, which likely reflects that they result from the convolution of the optical PSF with a square pixel.

To understand the origin of the ”box effect” which may be induced by the convolution of the PSF and the size of the bolometers pixels, we simulated timelines calculated as the integral of the flux received by a square detector with a pixel size matching that of PILOT (1.4′) observing a Gaussian diffraction-limited optical PSF with the expected size for PILOT (≈1.4′) centered at the predicted position of the planet. The resulting map is compared to the observed PSF in Fig. 6. The simulated PSF also shows the observed ”box effect”. This confirms the hypothesis that they result from the convolution of the optical PSF with a square pixel. By applying to this simulation the same analysis as to the data, we measure a FWHM of 2.31′±0.07. The value obtained in the simulation is therefore consistent with the value measured in-flight.

Figure 6 also shows the circular average profile of the PSF measured on array #2 and array #6 and the comparison with the simulations. The profiles are quite similar, except for the presence of more intense PSF wings in the measurements, an effect that was also observed during ground tests.

6 Instrumental Background

We estimated the background level in-flight using a combination of calibration measurements obtained at ceiling altitude and during ground tests. These calibration measurements involve, firstly, a short sequence of data recorded with difference detector settings, from which we obtain an empirical conversion between the signal measured in ADU and its equivalent in Volts. This procedure is relatively quick, and was repeated during ground tests and at the beginning of
both PILOT flights. A second – much longer – ground calibration measurement procedure is required to establish the relation between the output voltage of each bolometer and the intensity of the background incident on the detectors. These measurements were performed during tests in front of a controlled black body at cryogenic temperature at the CEA in 2012 and 2016.

6.1 Background Level

Figure 7 shows examples of the background image obtained during flight#1 and flight#2 using the technique described above.

The typical background value measured during flight#1 and flight#2 were in the range 13-16 pW per pixel towards the center of the focal plane. These absolute values are quite uncertain due to the limited sampling of the calibration measurements, which could only be conducted for a finite set of detector settings and incident background levels and the difficulties in interpolating for the in-flight settings. As seen in the top row of Fig. 7, this is evident from the unphysical offsets between the array-averaged background levels that we infer (i.e. the average background on arrays #2 and #4 is lower than on the other arrays). Nevertheless, it seems likely that the background during both PILOT flights was somewhat higher than the values predicted using our instrument photometric model of 8 pW per pixel at the center of the focal plane. Variations in the background level were monitored throughout each flight, and were found to be relatively stable except for variations related to residual atmospheric emission and HWP position, due to the background polarization (see Sect. 6.2). The background distribution in the focal plane is shown in the bottom row of Fig. 7 where we have normalised the pixel values by the average background level measured on each array. The shape of the background follows a similar distribution as observed during ground calibrations, with values raising by about a factor of two from the center to the corners of the focal plane, a distribution that is explained by the absorption in the lens located just in front of the focal plane.

6.2 Background polarization

Figure 8 shows the variations of the signal observed on each array as a function of HWP positions as measured during flight#2. During this observation, the half wave plate was moved successively from position 1 to position 8 and then back to position 1. The signal adopts a sinusoidal shape in phase opposition between the arrays in transmission and the TRANS and REFLEX arrays. We used this data to derive the polarization properties of the background. The signal amplitude varies by about $2 \times 10^{-3}$ ADU, which corresponds to 0.5 pW, corresponding to 2.5% of the measured background level. The maximum signal on the TRANS array (or minimum signal on the REFLEX arrays), is at around HWP position 5, which corresponds to the fast axis of the HWP being roughly vertical in the instrument restframe. Given the orientation of the polarizer in the instrument, this implies a polarization direction roughly horizontal. Figure 9 shows the histogram of the polarization angle in the instrument rest-frame, deduced using a fit of the data using Eq. 1, with $\omega$...
Fig. 7: Example focal plane images of the background derived during flight#1 (left) and flight#2 (right), each from \(\sim\) 30 seconds of observation. The top row shows an estimate for the absolute background level, the bottom row shows the background level normalized by the average on each array. In each panel, the four arrays on the left (resp. right) belong to the TRANS (resp. REFLEX) focal planes, such that arrays #6 and v4 (or arrays #2 and #8) are optical conjugates.

Fig. 8: Variation of the background signal as a function of the HWP for all arrays during one observation of flight#2. The sine curve with opposite phase on the TRANS and REFLEX arrays is due to the polarization of the instrumental background emission.

being the HWP angle in the instrument reference frame, increasing counterclockwise when looking at the sky. The polarization angle values are well peaked around 100°, indicating that the polarization direction is roughly horizontal and constant over the focal plane. Very similar polarization angles and fractions were observed during flight#1.

Fig. 9: Histogram of the polarization angle \(\psi\). The black, red and blue lines show the curves for all pixels and the TRANS and REFLEX pixels respectively.

Note that a similar polarization of the background was observed during ground calibrations as reported in [15]. Within the large uncertainties on the absolute value of the background level, the polarization fraction on the ground was similar to that observed in flight. However, the polarization angle is markedly different, with horizontal polarization in-flight and at around \(\psi = -45°\) during ground calibration. We currently attribute this rotation to a different origin of the background in the two situations. While the in-flight background is mostly due to the instrument, the background measured during ground calibrations is dominated by the room
atmosphere in the few first centimeters in front of the entrance window of the cryostat. The fact that the angles are strongly rotated indicates that polarization probably arises from propagation of the unpolarized background through the instrument, with a differential rotation depending on where in the instrument the background is originating.

7 Detector response

The response of bolometers, which measures their ability to convert flux variation into an electrical signal variations, varies with their temperature and with the optical background they receive. It is important to accurately quantify these variations in order to calibrate the data, in particular for polarization measurements, which, for the PILOT instrument, rely on combining data taken by different detectors at different times and with different HWP positions. We use our Internal Calibration Source (ICS) to precisely measure the time variations of the response, and we use the variations of the residual atmospheric signal in order to measure the spatial variations of the responses (or response flat-field) in the focal plane.

7.1 Response time variations

The ICS source is turned on at regular intervals during flights, at the end of individual mapping scans and occasionally during instrument manoeuvres. Calibration sequences typically accounts for ≃ 5 ON-OFF cycles. The source is driven with a square modulated current with a period of ≃ 1 sec, and the current (I) and voltage (V) are recorded continuously. The ground calibration tests have showed that the ICS optical flux measured by the detectors is proportional to the electrical power P = V × I dissipated in the source (see [13]).

In practice, in order to correct for amplitude drifts unrelated to the ICS signal, we subtract drifts due to the residual atmospheric emission in each timeline, using a correlation with pointing elevation and apply a low-pass filter to the bolometer signal timelines. In order to mitigate the effects associated with the time constants of the bolometers, a few data samples at the beginning and end of each ICS sequence are discarded. We only consider ICS sequences when the HWP is not moving and discard truncated ICS sequences with less than 4 ON-OFF cycles. We then compute the response of each bolometer to the ICS signal for a given calibration sequence as

\[ \rho_{ICS} = \frac{\Delta_{on-off}^{ICS}}{R_{ICS}(\langle I_{ON} \rangle^2 - \langle I_{OFF} \rangle^2)} R_{ref}^2, \]

where \( \Delta_{on-off}^{ICS} \) is the observed average signal difference in ADU between the ON and OFF states of the source, \( R_{ICS} \) is the source impedance and \( \langle I_{ON} \rangle \) and \( \langle I_{OFF} \rangle \) are the time-average currents during the ON and OFF periods of the calibration sequence respectively. \( R_{ref} = 300 \Omega \) and \( I_{ref} = 1.8 \ mA \) are the reference impedance and current values used for normalization. \( R_{ICS} \) is measured as the time-average of \( V_{ICS}/I_{ICS} \) over the ON periods.

Figure 10 shows the time variations of the array-averaged detector response to the ICS signal for individual arrays during flight#2. In general, array #6 has the best response and is ≃ 25% more responsive than arrays #2 and #8. The variations in the array-averaged response with time are about 10% for all arrays. Step-like variations are clearly seen in both the TRANS and REFLEX focal plane arrays. These variations are mostly caused by variations of the background level on the various detectors between individual observations. Some of these variations are due to observation elevation, which changes the intensity of the residual atmospheric emission and therefore the optical background in the same way on both focal planes. Some variations are caused by observing with different HWP angles, which, due to the polarized instrumental background (see Sec. 6.2), changes the optical background in opposition on the two focal planes, causing reversed variations of the detector responses.

To better characterize the origin of the response time variations, we performed a linear regression of \( \rho_{ICS} \) with house-keeping information for 9 parameters impacting the optical background or focal plane temperature. In particular, we included in the fit \( \cos(4\omega) \) and \( \sin(4\omega) \) describing changes of the background with HWP angles due to the background polarization, the observation elevation and the altitude of the experiment which impact the residual atmospheric contribution to the background. We also included the temperatures of several optical elements such as the primary mirror, the cryostat entrance window and the cryostat cold shield at 77 K and the measured temperature of the focal plane. The array averaged ICS response model is defined as:

\[ \rho_{ICS}^{model} = \sum_{i=1}^{9} \alpha_i \frac{x p_i}{\langle x p_i \rangle} + c, \]

Table 5: Coefficients \( \alpha_i \) for the various house-keeping templates included in the ICS array-averaged response model for array #6 shown in Fig. 11 and defined in Sec. 7.1.

| Template | \( \alpha_i \) |
|----------|---------------|
| \( \cos(4 \times \omega) \) | -0.064594 |
| \( \sin(4 \times \omega) \) | 0.481638 |
| 90°-elevation | -0.395260 |
| altitude | 0.240485 |
| \( T_{500} \) | 0.22408 |
| \( T_{win} \) | 0.260774 |
| \( T_{win} \) | 0.32954 |
| \( T_{77} \) | 0.145752 |
where $x_{p_i}$ is the template of a given house-keeping parameter averaged over the calibration sequence, $\langle \rangle$ designates averaging over all sequences and $c$ is an arbitrary constant.

Figure 11 compares the prediction of the above model with the time evolution of the average response to the ICS signal for array #6. The uncertainties shown on the figure were computed from the statistics of the individual ON-OFF measurements in each calibration sequence. In general, the model describes the data with good accuracy over the whole flight for all the arrays. The median difference between the model and the data is around 2%. A few exceptions for which the model does not match very well the data are visible in Fig. 11 which are associated to a larger uncertainty in the response estimate. These observations are located (around the calibration sequence 200 in the Figure) just after the recycling of the $^3$He fridge which caused very large fluctuations of the 300 mK stage.

The $\alpha_i$ coefficients are given in Tab. 5 in order of decreasing magnitude. The main correlations are with the HWP angle, indicating a strong dependence to the background level through its polarisation. Atmospheric parameters come second also showing a significant impact of the residual atmospheric emission to the response. Temperatures of the instrument explain the low frequency variations observed in Fig. 11.

7.2 Response spatial variations

The thermal emission from the residual atmosphere is clearly detected even at high altitude in the stratosphere. This strong
signal is in principle extended and can therefore be used to measure the response flat-field of the detectors. In addition, since this signal is in principle unpolarized, it can be used to intercalibrate detectors of the TRANS and REFLEX focal planes.

We measure the detector response using the residual atmospheric emission as the slope of the correlation between the bolometer signal and the pointing elevation. This was done both for dedicated 'skydip' measurements where the pointing elevation is changed continuously and during normal science observations obtained at variable elevation angles during flight#2. Figures 12 and 13 show the focal plane map of the mean response computed on the atmospheric signal during the skydips and all the observations during flight#2, respectively. Both maps present similar patterns. This pattern is also similar to that observed during ground test where the focal planes were operated in front of an extended black-body, indicating that the structures observed are intrinsic pixel-to-pixel variations of the response across the focal planes. The accuracy of the response map is improved at the 1% level or better when using all observations, due to the increased statistics with respect to skydip observations alone. This confirms the advantage of using a scanning strategy with varying elevation as implemented for flight#2.

8 Detector noise

We present in this section the instrumental noise properties for flight#2. The noise properties during flight#1 were similar to those of flight#2 in terms of spectral shape, noise levels and stability.

8.1 Flight-averaged noise power spectra

We compute the noise power spectra during flight#2 for each detector and during each observation scan. For this purpose, the raw data are first corrected for the response time variations derived in Sect. 7.1 and converted to watts using the detector-averaged ground calibration value of $2.16 \times 10^{10}$ V/W derived from ground calibrations of the detectors alone in front of an absolute black body. The calibrated timelines are corrected for the atmospheric signal to first order, by removing their linear correlation with observation elevation as calculated over each observation, taking into account only scan data (ie, excluding time samples associated to the calibrations, slews, etc...). Given the noise levels, we can assume that, after the atmospheric signal removal, the individual detector timelines are dominated by instrumental noise.
We compute the mean timeline among valid pixels of each array and scale it by the square root of the number of valid detectors in each array to keep a single-detector normalization. The array-averaged power spectra $P_{m,s}(v)$ are computed for each detector array $m$ and each scan $s$ from these array-averaged timelines, in $\text{W}/\sqrt{\text{Hz}}$, in the range of frequencies $v \in [0.02, 20]$ Hz. Finally, we take the median value of $P_{m,s}(v)$ among the scans $s$ as the flight-averaged noise power spectra.

Similarly, we compute the half-pixel difference (HPD) noise power spectra by removing a common mode to all the detector timelines. For this purpose, we split each detector array in two subsets with the same number of pixels, chosen randomly, and compute the half-difference of the two detector-averaged timelines. From these HPD timelines, for each detector array and each scan, we compute the HPD power spectra $P_{m,s}^\text{HPD}(v)$, which do not contain the common mode.

The flight-averaged noise power spectra are shown in Fig. 14 for array #6. The spectra are qualitatively similar for other detector arrays. For both the array-averaged spectrum $P_{m,s}(v)$ and the HPD spectrum $P_{m,s}^\text{HPD}(v)$, two regimes can be
identified. At high frequency, a flat spectrum component is observed, corresponding to white noise, presumably caused by photon noise. At low frequency, a $1/\nu$ and $1/\sqrt{\nu}$ components are observed for $P_{m,i}(\nu)$ and $P_{m,HPD,i}(\nu)$, respectively. The former contains residuals from atmospheric emission and possibly variations of the focal plane temperature that contribute to the low-frequency rise of the spectrum. In the HPD case, we can consider that all atmospheric and temperature variations are removed with the per-array common mode.

8.2 Noise stability

In order to study the noise stability during flight#2, we build time-frequency diagrams for $P_{m,i}(\nu)$ and $P_{m,HPD,i}(\nu)$, shown for array #6 in Fig. 15. These diagrams are qualitatively similar for the other arrays.

In the array-averaged time-frequency diagram, some observations can be identified, having a larger low-frequency component. This is due to the simple atmospheric emission removal we have implemented here, that sometimes fails to properly subtract the low-frequency contribution. At higher frequency, a good stability of the white noise is observed outside these observations. In the HPD case, where the common mode for all the detectors belonging to the same array has been removed, the stability is remarkable for both low and high frequencies, during the whole duration of flight#2.

8.3 High-frequency noise levels

To assess the high-frequency noise level statistics during flight#2, we repeat the initial steps presented in Sect. 8.1. However, instead of averaging the signal among the detectors for each array, we compute the noise power spectra $P_{i,s}(\nu)$ for each detector $i$ and each scan $s$. For each detector, we compute the flight-averaged spectrum $P_i(\nu)$ as the median over all the scans. The high frequency noise levels are then taken to be the mean value of $P_i(\nu)$ in the range $\nu \in [0.02, 20]$ Hz.

The statistics of these high-frequency noise levels are presented in Tab. 6. The focal plane median high-frequency noise level is $4.6 \times 10^{-16}$ $W/\sqrt{Hz}$. Array #6 is the most sensitive with a median sensitivity corresponding to a high-frequency noise level of $1.9 \times 10^{-16}$ $W/\sqrt{Hz}$. Arrays #2, #4, #7 and #8 have similar sensitivities (ranging from 4.5 to $6.10^{-16}$ $W/\sqrt{Hz}$).

9 Expected sensitivities

We present the signal to noise ratio predictions for the polarization fraction $p (SNRp)$, based on the simulations that are done with the flight#2 observing strategy and parameters. The expected sensitivities are calculated as described in [9], based on simulations where the Stokes parameters $I, Q, U$ are taken from the Planck polarization maps at 353 GHz [7], and extrapolated to the PILOT frequency using a modified black body spectrum with a dust emissivity index and dust temperatures also determined from analysis of the Planck data [20]. We use the median value of the high frequency noise as measured during flight#2, corresponding to a total NEP $= 4.6 \times 10^{-16}$ $W/\sqrt{Hz}$ (see Tab. 6). These predictions assume that the final maps accuracy will be limited by the high frequency noise, as expected if the systematics effects are fully suppressed and the map making is optimal. Figure 16 shows the maps of the expected $SNRp$ for the Galactic Center and the Rho-Ophiuchi regions. We expect to obtain $SNRp \approx 10$ on the weakly polarized region of the Galactic Center at 2' resolution and a $SNRp \approx 6$ for the bright Rho-Oph sources at 5' resolution. We expect $SNRp \approx 16$ when integrating over the whole BICEP2 diffuse field, when assuming 20% of polarization in agreement with the Planck measurement at 353GHz. The observations of the Large Magellanic Cloud will allow to study the polarisation in this region at intermediate scales (30').

10 Conclusions

The two flight of the PILOT experiment from Timmins, Ontario Canada in September 2015 and Alice Springs, Australia in April 2017 have been successful. We have been able to observe all targets included in our flight plan, including nearby star forming regions, molecular clouds, cold cores,
| ARRAY   | MIN  $[10^{-16} \text{ W/}\sqrt{\text{Hz}}]$ | MAX  $[10^{-15} \text{ W/}\sqrt{\text{Hz}}]$ | AVG  $[10^{-16} \text{ W/}\sqrt{\text{Hz}}]$ | MED  $[10^{-16} \text{ W/}\sqrt{\text{Hz}}]$ | STDEV $[10^{-16} \text{ W/}\sqrt{\text{Hz}}]$ |
|---------|-------------|-------------|-------------|-------------|-------------|
| 2       | 2.852       | 9.075       | 5.955       | 5.034       | 6.971       |
| 6       | 1.161       | 2.092       | 2.178       | 1.918       | 1.367       |
| TRANS average | 2.006   | 5.384       | 4.086       | 3.476       | 4.109       |
| 7       | 3.419       | 8.083       | 6.598       | 6.287       | 4.994       |
| 4       | 2.722       | 2.111       | 4.665       | 4.586       | 1.354       |
| 8       | 3.144       | 6.936       | 5.578       | 5.196       | 4.364       |
| REFLEX average | 3.095  | 5.710       | 5.614       | 5.356       | 3.571       |
| Average | 2.659       | 5.659       | 4.995       | 4.604       | 3.810       |

Table 6: High frequency noise statistics for each array during flight#2 W/\sqrt{\text{Hz}}.

Fig. 15: Time-frequency behaviour of the total array-averaged power spectra (top panel) and of the half-pixel difference power spectra (HPD, bottom panel) for array #6 during flight#2, in units of $\log_{10}(\text{W/}\sqrt{\text{Hz}})$. Individual noise power spectra are computed for the array-average total signal or half-pixel differenced signal, for each individual observing scan.

the M31 and LMC galaxies, and diffuse ISM regions, including the BICEP2 region. We also have observed planets and performed skydip for calibration purposes. The analysis of the house keeping and scientific data has shown a nominal behavior of the instrument. We accurately measured the time constant of our detectors using glitches and the decay light of our internal calibration source. The optical quality was checked on planets and found to be consistent with expectation, with a PSF FWHM of 2.25'. The in-flight instrumental background intensity is difficult to measure accurately but is found to be higher than predicted with our photometric model. As during ground calibration, the in-flight instrumental background appears to be polarized. The background polarization fraction is at the same level as during ground calibrations but with a markedly different polarization direction. The polarization of the background as well as the residual atmosphere emission contribute to a variable instrumental background in-flights. The response of the de-
Fig. 16: Maps of the expected SNR ratio on the polarization fraction $p$ for the Galactic center region at 2′ resolution (left) and the Rho-Ophiuchi region (right) at 5′ resolution.

Detectors, as measured in-flight on the ICS signal, is found to be variable, which is mostly attributed to variations of the background level on the detectors and to variations of the focal plane temperatures. A simple parametric model based on house-keeping measurements reproduces the observed variations of the response to a few percents. The in-flight detector noise is at the expected level, with low frequency noise raising as $1/\sqrt{\nu}$ when a common mode is removed and flattening at high frequency. The spectral shape and amplitude of the noise is found to be stable in-flight. From the above performances, we re-evaluated the PILOT expected sensitivity to polarization, which our found sufficient to fulfill our science goals.

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