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ABSTRACT

PILOT (Polarized Instrument for Long wavelength Observations of the Tenuous interstellar medium) is a balloon-borne astronomy experiment designed to study the polarization of dust emission in the diffuse interstellar medium in our Galaxy. The PILOT instrument allows observations at wavelengths 240 µm and 550 µm with an angular resolution of about two arcminutes. The observations performed during the two first flights performed from Timmins, Ontario Canada, and from Alice-springs, Australia, respectively in September 2015 and in April 2017 have demonstrated the good performances of the instrument. Pilot optics is composed of an off axis Gregorian type telescope combined with a refractive re-imager system. All optical elements, except the primary mirror, which is at ambient temperature, are inside a cryostat and cooled down to 3K. The whole optical system is aligned on ground at room temperature using dedicated means and procedures in order to keep the tight requirements on the focus position and ensure the instrument optical performances during the various phases of a flight. We'll present the optical performances and the firsts results obtained during the two first flight campaigns. The talk describes the system analysis, the alignment methods, and finally the inflight performances.

Keywords: Pilot Telescope, astronomical observation, sub-millimetric instrument, optical alignment, LaserTracker.

1 INTRODUCTION

PILOT (Polarization Instrument for the Long-wavelength Observations of the Tenuous ISM: http://pilot.irap.omp.eu) is a balloon-borne mission dedicated to the study of the dust polarized emission from the diffuse ISM in our Galaxy [1,2]. PILOT has two major scientific objectives: Firstly, allow us to constrain the large-scale geometry of the magnetic field in our Galaxy and to study in detail the alignment properties of dust grains with respect to the magnetic field, secondly, to complement the Planck satellite results at higher frequency. In particular, these new observations will provide data with a better angular resolution, which is critical in crowded regions such as the Galactic plane. For these purposes, the PILOT optics has been designed to provide a large instantaneous field of view of 0.8°x1°, using a large primary mirror, combined with a cooled optical system at 2K and 300mK bolometer arrays. The alignment of the primary mirror with the cold optics located within the cryostat, has been identified as a critical point, and therefore dedicated studies and methods have been developed.

2 OPTICAL LAYOUT AND ALIGNMENT

2.1 Optical layout and requirements

The PILOT optics is composed of three major parts: a telescope, a re-imager and a polarimeter (see Figure 1). The telescope is of tilted Gregorian type fulfilling the Mizuguchi-Dragone condition to form an equivalent on-axis parabolic telescope minimizing the instrumental polarization effect [3,4]. Its primary mirror (M1) is an off-axis parabolic mirror with a projected aperture of 830 mm while the secondary mirror (M2) is an off-axis elliptical mirror. All mirrors and their mounts are made of aluminum to reduce thermo-elastic effects that will affect the image quality. The re-imager is a telecentric objective formed by the lenses L1 and L2; it conjugates the telescope focal plane onto the bolometers arrays. The polarimeter is composed by a step by step rotating Half-Wave-Plate and an analyzer. All optical elements except the primary mirror M1, that is at ambient temperature, are cooled down to 2K.

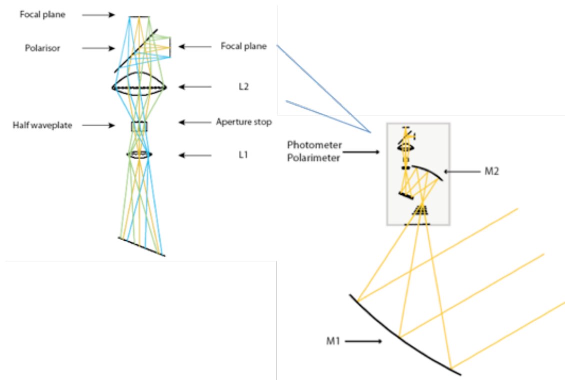


Figure 1 : PILOT Optical Layout. Only the M1 mirror is located outside the photometer.

Optical modeling using the Zemax software has been made to analyze the sensitivity to the positioning of each optical component of the PILOT telescope. In order to be diffraction limited image quality at 240µm, the primary mirror and the secondary mirror focal points should be within a position tolerance of ±0.3 mm along each of their axis and their tilt angle within ±0.03°. These requirements have to be reached during the whole observations at ceiling altitude, while the temperature evolves producing thermo-elastic deformation and the elevation of the pointed payload is changed.

Fulfilling this requirement implied a series of actions: First, precise characterizations of the mechanical and optical properties of the primary mirror and of the photometer have been carried out separately [5,6]. Second, specific tools and an efficient procedure have been developed to align the two subsystems, both for ground test and flight configurations. To perform this alignment, the primary mirror was mounted on an aluminum hexapod system that gives six degrees of freedom to the mirror. We used a method based on a CATIA CAD model of the hexapod and laser tracker measurements in order to adjust the primary mirror. Third, despite the fact that the whole mechanical structure and the M1 mirror are made of aluminum which limits differential expansion, no perfect compensation of thermo-elastic effects is possible because of the tilted Gregorian design. A thermo-mechanical model of the instrument has been developed that provide a prediction of the optical alignment evolution during a flight. Corrections have been applied accordingly before launch, compensating to first order the effect of the thermal expansion of the mechanical structure expected at ceiling altitude.

2.2 Ground end to end tests

During the PILOT performance tests campaign [2, 7, 8], we have performed a series of defocusing between the primary mirror and the photometer along three orthogonal axis around the best-estimated focus supplied by the Zemax model. These systematic explorations were performed along three orthogonal axes within typically ±0.8 mm along X and Y axis, and ±1.6 mm along Z axis with a pitch about 0.2 mm (Z is along the optical axis of the photometer, X is included in the optical symmetry plane). For each focus, we estimated the impact on the optical performances, then the source PSF was fitted (see Figure 2) in order to measure the changes in the Full Width Half Maximum (FWHM) and encircled energy. The best focus position was set as the position of minimum PSF FWHM.

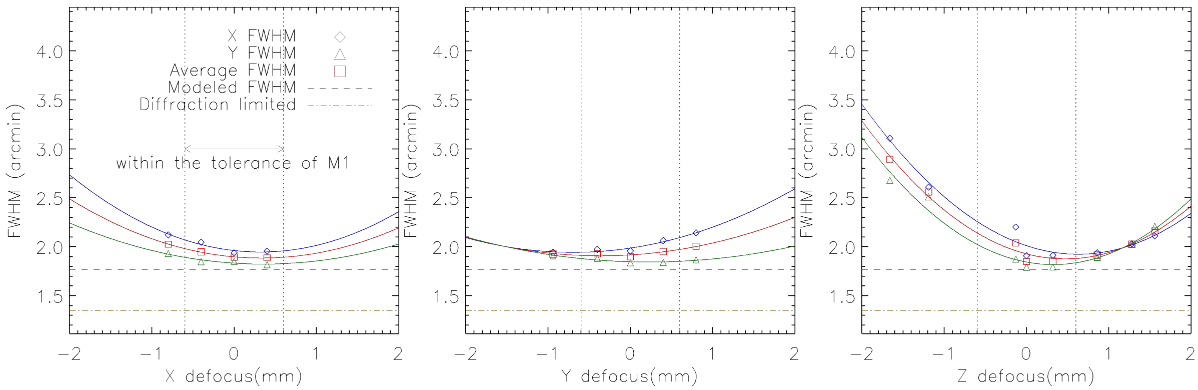
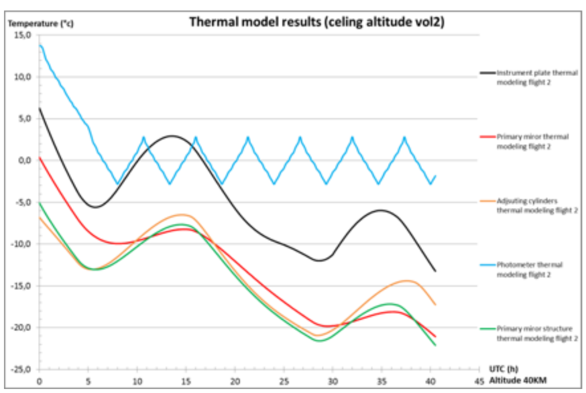


Figure 2 : Example of measured FWHM (on the array #2) as a function of defocusing distance along the X axis (right), Y axis (center), Z axis (left). For each axis, a defocus of 0mm corresponds to the best theoretical focus.

2.3 Optical alignment in flight configuration

The PILOT telescope does not have homothetic deformations because of the temperature gradient between the cold optics (temperature regulated to 2K) and primary mirror (at ambient temperature). In addition, there is a temperature gradient within the mechanical structure of the instrument (mainly due to the electronics power dissipation and to the Sun radiations).

To be compliant with the specifications on the optical alignment, we considered the thermo-elastic deformations of the system that were estimated by a thermal model of the PILOT gondola. The following Figure 3 shows the predicted temperature evolution of the main elements of the PILOT telescope during the second flight.



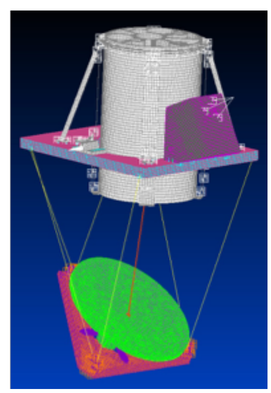


Figure 3 : Estimated temperature for the main elements of the telescope based on the CNES thermal modeling.

The thermo-elastic model (using FEMAP NASTRAN software) based on the average temperature predicted by the thermal model gives an estimate of the defocus that would be due to the thermal effects.

The alignment performed for the flight took into account this predicted defocus values in order to obtain the best focus position during the flight.

3 OPTICAL PERFOMANCES DURING THE SECOND FLIGHT

3.1 Point Spread Function

The second flight was launched by the CNES in April 2017 from Alice-Springs, Australia. Its duration was about 33 hours for 29 hours at celling altitude. It allowed to get scientific observations during approximatively 24h.

In order to check PILOT optical quality, several measurements where performed on various bright sources. The Point Spread Function of the instrument on Jupiter is 2.3', as shown by the following Figure 4.

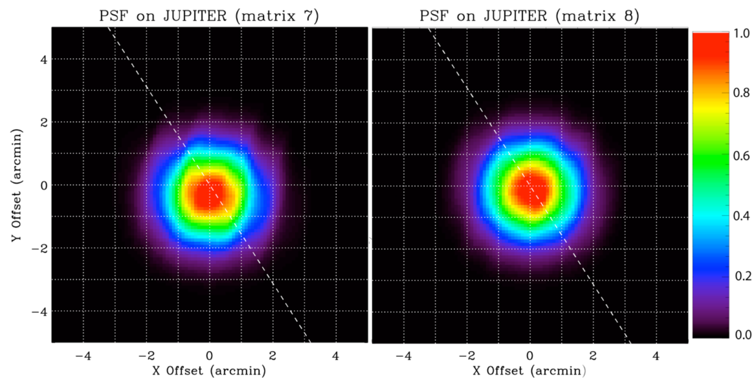


Figure 4: Point spread function of the PILOT telescope obtained during the second flight.

The images taken from planets and bright sources several time during the flight show that the optical quality was as expected during the whole second flight.

3.2 Pointing reconstruction

The knowledge of the pointing is critical to measure the linear polarization with PILOT. The method used to reconstruct a-posteriori this pointing is to correlate PILOT and Herschel images (see Figure 5). That allows to compute the average offset between the Estadius star tracker and PILOT optical axis.

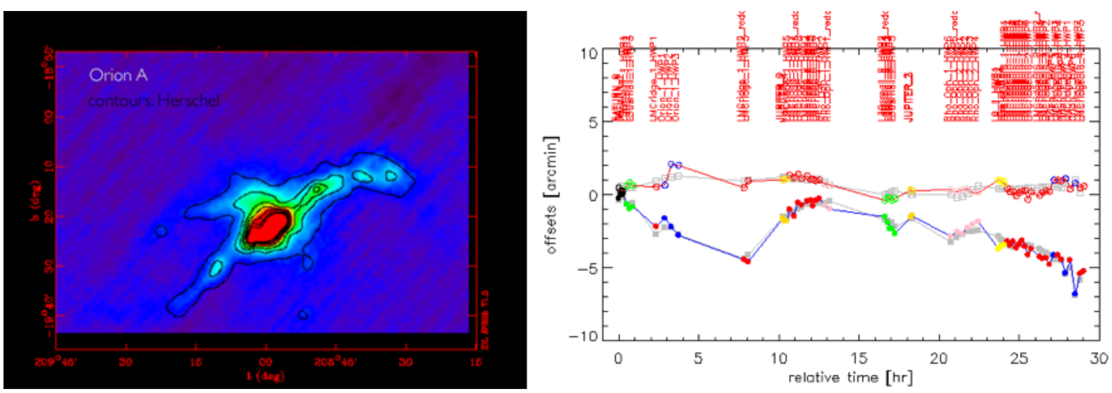


Figure 5: Left: The image shows Orion seen by PILOT and the contours are from Herschel. Right: Evolution of the pointing average offsets, cross-elevation (open circles), elevation (filled circles). In grey, the preliminary pointing model predictions.

The distortion of the alignment between the stellar sensor and the instrument is mainly due to the thermo-elastics effects and to the deflexion of the telescope with elevation. A simple linear model describes the offset evolution to better than 1' over the whole second flight.

4 CONCLUSION

PILOT is a balloon-born astronomy experiment with its specific complexity of optics and observation environment.

The PILOT optical alignment for its second flight is successful and the image quality is as expected. Those have been achieved thanks to the alignment methods. The pointing model allows to stack data and to combine observations for diffuse regions of the sky.

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