Jonathan Aumont
IRAP — Toulouse, France
J.-Ph. Bernard (PI), A. Mangilli, A. Hughes, G. Foënard, I. Ristorcelli, G. De Gasperis, H. Roussel, on behalf of the PILOT Collaboration
CMB Foregrounds - Tenerife - October 16th 2018
1.2 THz far-infrared polarization experiment

- Reveal the structure of the magnetic field in our Galaxy and nearby galaxies
- Characterize the geometric and magnetic properties of the dust grains
- Understand polarized foregrounds
- Complete the Planck observations at a higher frequency where the dust polarization has never been observed over large sky regions

**PILOT**

![Image of the Planck satellite in space, with a bright starry sky in the background. A diagram illustrates the frequency response of various astrophysical components: CMB, Synchrotron, Thermal dust, and Spinning dust. The graph shows the RMS brightness temperature in microkelvin (µK) as a function of frequency in GHz. The CMB (teal) is the lowest temperature, followed by the Synchrotron (green) and Thermal dust (red) components. The Spinning dust component is also shown (light green). The Planck Collaboration, X 2015, provided the maps of maximum posterior amplitude polarization derived from the Planck observations between 30 and 353 GHz. The left and right columns show the Stokes Q and U parameters, respectively. Rows show, from top to bottom: CMB; synchrotron polarization at 30 GHz; and thermal dust polarization at 353 GHz. The CMB map has been highpass-filtered with a cosine-apodized filter between $\lambda = 20$ and 40, and the Galactic plane (defined by the 17% CPM83 mask) has been replaced with a constrained Gaussian realization (Planck Collaboration IX 2015).}

**Planck 2015 cosmology results**

Since their discovery, anisotropies in the CMB have contributed significantly to defining our cosmological model and measuring its key parameters. The standard model of cosmology is based upon a spatially flat, expanding Universe whose dynamics are governed by General Relativity and dominated by cold dark matter and a cosmological constant ($\Lambda$). The seeds of structure have Gaussian statistics and form an almost scale-invariant spectrum of adiabatic fluctuations. The 2015 Planck data remain in excellent agreement with this paradigm, and continue to tighten the constraints on deviations and reduce the uncertainty on the key cosmological parameters.

The major methodological changes in the steps going from sky maps to cosmological parameters are discussed in Planck Collaboration XII (2015); Planck Collaboration XIII (2015). These include the use of Planck polarization data instead of WMAP, changes to the foreground masks to include more sky and dramatically reduce the number of point source "holes," minor changes to the foreground models, improvements, etc.
Multiplexed bolometer arrays with a total of 2048 detectors at 240 μm (1249 GHz), 2′ resolution

Observations at more than 2 HWP angles to reconstruct the Stokes parameters $I$, $Q$, $U$

Detectors cooled down to 0.3 K through closed-cycle $^3$He fridge

NEP $\sim 4 \times 10^{-16}$ W/Hz$^{1/2}$

Control of systematics and detector response at 1% level
1st 2015
Timmins Canada
24 h

2nd 2017
Alice Springs Australia
33 h

3rd 2019?
Timmins Canada

PILOT DPC
Toulouse, France

You are here
PILOT – 2nd flight
PILOT — 2nd flight

April 16th, 2017 from Alice Springs, Australia

* Total flight time: 33.5 h
* Scientific data: **23.8 h**
* Ceiling altitude: 32-40 Km

Galactic plane, 1.7 h, 7.1%
Star forming regions, 9.9 h, 41.6%
Galaxies, 6.1 h, 25.6%
Diffuse field, 4.8 h, 20.2%
Planets, 0.8 h, 3.5%
Calibrations in all these scenes, 1.2 h, 5%

Total: **23.8 h**

Note: most of these sources are not observable in balloon from South Pole (e.g. BLASTPol, SPIDER)
PILOT — Scanning strategy

- HWP rotation
- Slew
- Elevation and azimuth adjustments
- Scan
- ICS calibration sequence
- Focal plane footprint on the sky
- Target region


★ In-flight good optical quality and nominal resolution

[The PILOT Collaboration, Foënard et al. 2018]
In-flight good optical quality and nominal resolution

In-flight background has a similar shape but is a factor ~2 stronger than ground measurements. Polarized at 4-10% level

Variation of the detector responses due to polarized background & atmosphere variations. Modelled and corrected to better than 2%
In-flight good optical quality and nominal resolution

In-flight background has a similar shape but is a factor ~2 stronger than ground measurements. Polarized at 4-10 % level

Variation of the detector responses due to polarized background & atmosphere variations. Modelled and corrected to better than 2 %

Pointing offset varies during flight. Pointing model constructed from elevation + temperatures and Herschel comparison, better than 1’

Spurious polarization measured on Jupiter of ~ 3 %

[The PILOT Collaboration, Foënard et al. 2018]
In-flight good optical quality and nominal resolution

In-flight background has a similar shape but is a factor ~2 stronger than ground measurements. Polarized at 4-10% level

Variation of the detector responses due to polarized background & atmosphere variations. Modelled and corrected to better than 2%

Pointing offset varies during flight. Pointing model constructed from elevation + temperatures and Herschel comparison, better than 1’

Spurious polarization measured on Jupiter of ~ 3%

In-flight white noise levels as expected; noise stability over the whole flight

Significant improvements in ongoing analyses

[The PILOT Collaboration, Foënard et al. 2018]
PILOT — Preliminary $I$ maps

**L0**

Galactic longitude

-154° -152° -150° -148°

0° 1° 359°

Galactic latitude

-20° -19° -18° -17° -16° -15° -14° -13° -12° -11° -10° -9° -8° -7° -6° -5° -4° -3° -2° -1° 0° 1° 2° 3° 4° 5° 6° 7° 8° 9° 10° 11° 12° 13° 14° 15° 16° 17° 18°

**L30**

Galactic longitude

356° 355° 354° 353°

29° 30° 31° 32°

Galactic latitude

-1°30' -1°00' -0°30' 0°00' 0°30' 1°00' 1°30'

**Orion**

**ρ-Ophiuchi**
PILOT — Preliminary polarization maps

★ Stokes parameters $I$, $Q$ and $U$ in the L0 Galactic plane region
★ Strong signal but low polarization fraction

[The PILOT Collaboration, Mangilli et al. 2018 in prep.]
$\psi = \frac{1}{2} \cdot \text{atan} \left( \frac{U}{Q} \right)$

[The PILOT Collaboration, Mangilli et al. 2018 in prep.]
\[ \psi = \frac{1}{2} \cdot \text{atan} \left( \frac{U}{Q} \right) \]

[The PILOT Collaboration, Mangilli et al. 2018 in prep.]
\[ \psi = \frac{1}{2} \cdot \tan^{-1} \left( \frac{U}{Q} \right) \]

[The PILOT Collaboration, Mangilli et al. 2018 in prep.]
PILOT — Direction of the magnetic field

[The PILOT Collaboration, Mangilli et al. 2018 in prep.]
PILOT — “BICEP” region
PILOT — “BICEP” region

★ 4.8 h of data during flight2
★ BICEP field observed with 4 tiles, each of them being observed at least twice with 2 different HWP positions
★ Goal signal to noise ratio of ~20 on the polarized intensity integrated over the whole field
★ Unique data for constraining the SED or for correlation analyses in CMB observations
**coPILOT**: modification of PILOT will allow very accurate measurements of C+ (158 µm) total intensity. Dark molecular gas distribution in solar neighborhood, nearby galaxies. CNES Phase A.

**IDS** (Inflation and Dust Surveyor): CMB B-modes + dust, to be submitted again to NASA. Contribution to provide PILOT attitude control + internal calibration source

**SPICA-Pol**: polarized instrument on SPICA. Design and science case strongly inspired from PILOT. Accepted in pre-phaseA/0.

**BOOST** proposal (IRAP) to lower detector temperature to 150 mK. Increase in sensitivity by 2.7 for PILOT, up to 14 for coPILOT
PILOT – Summary

★ Operational and instrumental success of the PILOT two flights
★ Unique experiment: observation of the dust polarization at 1.2 THz over large regions of the sky relevant for cosmology
★ PILOT legacy for future instruments
★ Data analysis in progress. No showstopper for the moment but we are a small team!
Backup
PILOT — Improvements after 1st flight

+ arrays #1 and #3 were repaired
  ★ ground tests: array #3 ok, arrays #1 and #5 not working
  in flight: arrays #1, #3 and #5 not working: -17%

+ autonomy tests at 300 mK accomplished
  ★ detectors were operated 20 mK lower than flight#1 (305 mK): +26%
  ★ in-flight autonomy was longer than the long flight (>33.5 hr)

+ Field stop size increased to avoid edge effects in polarization
  ★ polarization now ok everywhere: gain of 0.6 arrays: +10%

+ Longer flight (flight#1: 14.8hr, flight#2: 23.8 hr): +60%

+ Front baffle thermal insulation was re-designed
  ★ no deterioration observed in flight. No sign of external straylight.

+ More efficient observing strategy implemented
  ★ scans at varying elevation (better control of response variations + de-stripping)
  ★ region of interest mapping (saves 20% of of target time)

= Total: +100%
★ important qualitative improvements: less straylight, more scan directions more HWP positions, more strong pointing sources
PILOT — “BICEP” region

\[ \log_{10}(N_{\text{hits}}) \]

Range: 2.0 to 3.2