LSPE: a large-scale polarization survey of the CMB

Silvia Masi
Sapienza Università di Roma & INFN Roma
for the LSPE collaboration
B-mode from Space
@ Max-Planck-Institut für Astrophysik
Munich, December 16–19, 2019
The LSPE collaboration

Scientists from institutions in Italy, UK, USA, Spain, Chile:

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**Matarrese**

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<th>Ade</th>
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<td>Farsian</td>
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UniMI, INFN-MI
UniMIB, INFN-MIB
INAF-BO
INAF-OAT
UniTS
Oxford
JPL
Caltech
IAC
UniChile
UniGE, INFN Ge
INFN Pi
Sapienza Roma, INFN Roma
IFAC CNR
UniCardiff
UniManchester
SISSA
ASI
LSPE in a nutshell

• The Large-Scale Polarization Explorer is an experiment to measure the polarization of the CMB at large angular scales.

• **Science drivers / targets:**
  – The B-modes from inflation are mainly at large scales ($r$)
  – Polarization signatures from reionization ($\tau$) are mainly at large scales
  – Rotation of the polarization angles (related to new physics)
  – Sensitive polarized dust survey at $f$ close to the CMB ones
  – Sensitive polarized synchrotron survey at $f$ close to the CMB ones

• **Instrumental approach:**
  – Frequency coverage: 40 – 250 GHz (5 bands)
  – 2 instruments covering the same northern sky
  – **STRIP** is a ground-based instrument working at 43 and 90 GHz
  – **SWIPE** works from near-space (balloon) at 145, 210, 240 GHz
90 GHz (ground) Atmospheric monitor

43 GHz (ground) Monitor polarized synchrotron

210 + 240 GHz (balloon) Monitor level, slope and possible rotation with frequency of polarized dust emission.
To date: extrapolated from single frequency (Planck 353 GHz)

145 GHz (balloon) Main CMB channel
LSPE: Sky Coverage

STRIP
Ground telescope at 43 and 95 GHz located in Tenerife. Will measure for two years. Based on coherent polarimeters.

SWIPE
Balloon borne telescope at 143, 220 and 240 GHz. Will take measurements for two weeks during a LDB nocturnal flight around the North Pole. Based on TES bolometers.

Credit A. Mennella
Credit L. Pagano, F. Piacentini
LSPE-STRIP in a nutshell

- Survey TeneRlfe Polarimeter
- Target: Polarized Synchrotron
- Two arrays of coherent polarimeters: 49 @44 GHz (QUIET) plus 7 @ 90 GHz.
- The measured response of the corrugated feedhorns confirms the expected performance down to -55 dB
- 1.5 m telescope (Clover)
- PI M. Bersanelli UNIMI

<table>
<thead>
<tr>
<th>Instrument</th>
<th>STRIP</th>
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<tbody>
<tr>
<td>Site</td>
<td>Tenerife</td>
</tr>
<tr>
<td>Freq (GHz)</td>
<td>43 90</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>17% 8%</td>
</tr>
<tr>
<td>Angular resolution FWHM (arcmin)</td>
<td>20 10</td>
</tr>
<tr>
<td>Detectors technology</td>
<td>HEMT</td>
</tr>
<tr>
<td>Number of detectors $N_{\text{det}}$</td>
<td>49 6</td>
</tr>
<tr>
<td>Detector NET ($\mu K_{\text{CBM}} \sqrt{s}$)</td>
<td>515 1139</td>
</tr>
<tr>
<td>Mission duration</td>
<td>2 years</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>50%</td>
</tr>
<tr>
<td>Sky coverage $f_{\text{sky}}$</td>
<td>37%</td>
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<tr>
<td>Map sensitivity $\sigma_{Q,U}$ ($\mu K_{\text{CBM}} \cdot \text{arcmin}$)</td>
<td>102 777</td>
</tr>
<tr>
<td>Noise power spectrum $(N_{E,B}^{E,B})^{1/2}$ ($\mu K_{\text{CBM}} \cdot \text{arcmin}$)</td>
<td>171 1330</td>
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</table>

Provides essential information on polarized synchrotron
LSPE-STRIP in a nutshell

Receiver under test. Telescope being finalized.
**LSPE-SWIPE in a nutshell**

- SWIPE is a multiband (145, 210, 220 GHz) array of Stokes polarimeters (163).
- Is flown on a stratospheric **balloon**, to avoid atmospheric noise at high $f$, including polarized radiation from ice crystals in tropospheric clouds (e.g. Takakura et al. 2018). **38%** of the sky covered in a 15d flight.
- SWIPE uses 326 **multimoded detectors** to improve the sensitivity wrt to Planck-HFI. The focal planes collect 8800 radiation modes. The resolution of each multimoded beam is $1.4^\circ$ FWHM.
- Combined sensitivity: **10 $\mu$K arcmin per flight**
- SWIPE uses an **HWP-based polarization modulator** as the first optically active element, to solve several issues important at large scales (beam asymmetry leakage, bandpass mismatch, $1/f$ noise … etc.)
- SWIPE uses a **single large polarizer, common** to the entire focal plane, to define the main axis of the polarimeter with high precision ($< 0.1^\circ$): accurate absolute reconstruction of the pol. directions.
- PI P. de Bernardis (Sapienza)
LSPE/SWIPE: photon background

To fully exploit the low radiative background: thin window

Receiver window 60 cm diam. (forebaffle removed)

Credits: F. Piacentini

145 GHz 210 GHz 240 GHz

Room pressure -> 3 mbar

Dewar vacuum -> 3 mbar

Credits: G. D’Alessandro

Thick LAB window (removable at float)

Thin flight window

Dewar vacuum
Background power on each detector:
\[ W = \int f_y \alpha A \Omega I_y \, dy \]

Optical throughput:
\[ A \Omega = n_{\text{modes}} \lambda^2 \]

Photon noise:
\[ \text{NEP}^2_{\text{ph}} = 2 \int f_y \alpha A \Omega I_y h \nu \left(1 + \frac{f_y \alpha c^2 I_y}{h \nu^3}\right) \, dy. \]

Detector noise:
\[ \text{NEP}_{\text{detector}} = \sqrt{4k_B T_c^2 G F} \]

The power of multimoded bolometers ...
LSPE: ideal performance forecast

- TOD simulations > Components separation > Power spectra > Parameters \((r, \tau)\)
- Forthcoming LSPE paper. Preview of Results:

**Table 7.** Component separation weights for each component in each channel for the minimal case: Planck + LSPE (STRIP, SWIPE).

<table>
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<tr>
<th>(f) (GHz)</th>
<th>Probes</th>
<th>(W_{\text{CMB}})</th>
<th>(W_{\text{Dust}})</th>
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<tr>
<td>30</td>
<td>P</td>
<td>-1.5 \times 10^{-2}</td>
<td>2.7 \times 10^{-3}</td>
<td>8.7 \times 10^{-1}</td>
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<tr>
<td>43</td>
<td>ST</td>
<td>-2.6 \times 10^{-3}</td>
<td>-4.5 \times 10^{-4}</td>
<td>3.9 \times 10^{-1}</td>
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<tr>
<td>145</td>
<td>SW</td>
<td>1.4</td>
<td>-4.1 \times 10^{-1}</td>
<td>-1.6</td>
</tr>
<tr>
<td>210</td>
<td>SW</td>
<td>-1.9 \times 10^{-1}</td>
<td>2.4 \times 10^{-1}</td>
<td>2.8 \times 10^{-2}</td>
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<tr>
<td>240</td>
<td>SW</td>
<td>-2.02 \times 10^{-1}</td>
<td>1.6 \times 10^{-1}</td>
<td>3.4 \times 10^{-1}</td>
</tr>
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Credit: Krachmalnicoff, Farsian

Credit: Pagano

Credit: Piacentini

After components separation
No cosmic variance!

\(\tau=0.06\)

\(r=0\)

\(r=0.03\)
LSPE: ideal performance forecast

- TOD simulations > Components separation > Power spectra > Parameters ($r, t$)
- Forthcoming LSPE paper. Preview of Results:

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After components separation
No cosmic variance!

Credit: Krachmalnicoff, Farsian
Credit: Pagano
**Ideal vs nonideal Stokes Polarimeter**

- Ideal operation: staring at a given sky pixel with polarization vector \((I_s, Q_s, U_s, V_s)\), the signal \(W\) measured by the detectors (sensitive to horizontal or vertical polarization) is

\[
\begin{align*}
\Rightarrow W_H &= \frac{1}{2} [I_s + Q_s \cos(4\gamma + 2\theta) + U_s \sin(4\gamma + 2\theta)] \\
\Rightarrow W_V &= \frac{1}{2} [I_s - Q_s \cos(4\gamma + 2\theta) - U_s \sin(4\gamma + 2\theta)]
\end{align*}
\]

- \(\gamma\) = angle of the fast HWP axis wrt the instrument vertical (geometrical, mechanical)
- \(\theta\) = angle of the instrument vertical wrt the meridian

- So, the measured signal should be at \(f_{HWP,\text{opt}} = 4f_{HWP,\text{mech}}\)

- However, real HWPs are nonideal ...

- .... and optical systems are also not ideal.

- Real-world nonidealities produce spurious optical signals at \(f_{HWP}, 2f_{HWP}, 3f_{HWP}, 4f_{HWP}, 5f_{HWP}, 6f_{HWP} \ldots\)

- Moreover, the sky scan modulates the input signal, encoding the sky polarization signal in *two narrow sidebands* of \(4f\).
- These must be free from spurious signals.

- We have adjusted \(f_{HWP}\) and \(f_{\text{scan}}\) to approximate this condition.
Bolometer time constant effects

- Bolometric detectors are slow (especially the large area ones used for multimode detectors, with $\tau \sim 30$ ms)
- So $4f_{\text{HWP}}$ should be low enough that a 30 ms delay in the response of the bolometer is nearly irrelevant, or can be corrected precisely.
- Otherwise, such a delay would mimic a systematic offset $\Delta \gamma$ in the knowledge of the rotation angle $\gamma$ of the HWP: this would result in a leakage of E-modes in B-modes (see e.g. Pagano et al. 2009):

$$C_{\ell}^{BB,L} = C_{\ell}^{EE} \sin^2(2\Delta \gamma)$$

- In order to target $\sigma_r=0.01$, the rotation angle must be known better than $\Delta \gamma=10$ arcmin.
- The delay due to the time constant of the bolometer can be compensated deconvolving the bolometer transfer function in the analysis pipeline. This procedure, however, requires a precise knowledge of the time constant.
- In our case, if $\tau=30$ms and $f_{\text{HWP}}=0.5$ Hz, it is required $\sigma_\tau<1$ms, a reasonable target for both ground-based and in-flight calibration.
- This drives us to select $f_{\text{HWP}}=0.5$Hz (0.5 rps, $T_{\text{HWP}}=2$s), with an optical signal around 2Hz.
- The payload spin in azimuth (scan frequency $f_{\text{scan}}$) is adjusted so that most of the signal of interest is well within the $[3f_{\text{HWP}} - 5f_{\text{HWP}}]$ interval. In this way it is not cut by the notch filters used to remove synchronous systematics.
Signal-only simulations of SWIPE signals for different HWP & scan strategies:
Based on $\tau_{\text{bol}} = 30\text{ms}$:

- $f_{\text{HWP}} = 0.5\text{ Hz mech.} \rightarrow 2\text{Hz optical}$
- TOD simulations suggest $f_{\text{scan}} = 1.93\text{ mHz}$
- #modulations per FWHM = 4.5.

With this choice...

Most of the signal of interest (EE & BB) is NOT contaminated by $f, 2f, 3f, 4f, 5f, \ldots$ (---) systematics

Credits: F. Piacentini
The signal of interest (black line) is encoded in the peaks at $4f_{\text{HWP}} + f_{\text{scan}}$, $2f_{\text{scan}}$, $3f_{\text{scan}}$, ... . The intermediate frequencies contain only noise, and can be filtered out using custom notch filters (for example removing the interval $[4f_{\text{HWP}} - f_{\text{scan}} ... 4f_{\text{HWP}} + f_{\text{scan}}]$).

The noise from both the detector (magenta) and the speed instability (green) are for 1s of integration and are reduced when increasing the integration time, while the signals (black, blue, red, orange) will remain where they are.

Detector noise (magenta) will also decrease including data from more than 1 detector.
Reduction of the amplitudes of HWP-synchronous systematic effects

In a real Stokes polarimeter, the optical devices produce polarized emission, which can be in part modulated by the rotation of the HWP (e.g. Salatino & de Bernardis 2010, Columbro et al. 2019)

- Polarized emission/transmission of the lens, stop, field optics: mitigated using the HWP as the first optical element skywise.

- The HWP can have slightly different efficiencies for the fast and slow axes. This results in polarized emission & transmission of the HWP, modulated by the polarizer, i.e. a $2f_{\text{HWP}}$ signal (5 mK!). Mitigated by filtering the output signal (bandpass around $4f_{\text{HWP}}$)

- The polarizer emission can be reflected by the HWP and modulated: this results in a small $4f_{\text{HWP}}$ signal. Mitigated by reducing the temperature of the polarizer (here 1.6K, so few $\mu$K). Can be removed by a dedicated pipeline (e.g. Ritacco & 2017).

- The polarized emission of the HWP can be reflected by the polarizer and by the HWP. This is a small $4f_{\text{HWP}}$ signal. In our case is very small, since the polarizer is tilted 45° wrt the HWP.
Reduction of the amplitudes of HWP-synchronous systematic effects

• There are other subtle systematic effects, an additional ones will be discovered.

• One of the main reasons of interest for this experiment is that we have the opportunity to study experimentally the performance of a Stokes polarimeter with cryogenic spinning HWP, a configuration which will be used in several ultresensitive experiments, including LiteBIRD.

• Real experimental tests are badly needed, in addition to simulations, to validate a very difficult measurement!
LSPE: HW implementation & status
Mission Requirements:

SWIPE limits (68% CL) to the tensor to scalar ratio versus integration time (including foregrounds separation):

- Long integration time (8 days minimum, 15 days goal)
- Night flight (to cover a large sky fraction with a telescope spinning in azimuth)
LSPE/SWIPE : polar night flight

- Uses the winter stratospheric polar vortex
- Less stable than the summer vortex used in Antarctica
- Reliable forecast tools needed

16/Dec/2019: polar vortex

16/Dec/2019: flight forecast: 14 days

Credit: earth.nullschool.net

Credit: Piacentini
LSPE/SWIPE: night polar flight

- Flight managed by ASI, scheduled for end of 2021
- Longyearbyen – Svalbard or Kiruna Sweden
- Several test flights already carried out
SWIPE: solar illumination issues

- With a careful choice of the launch date and launch site the length of the illuminated portions of the flight can be minimized.
- We do not plan to carry out science measurements during these periods, but the instrument should be prepared to survive short solar illumination periods.

F. Piacentini
SWIPE: ground shield

The ground shield is very large .. .... but not impossible :

Polar night flight: sun below the horizon for most/all the flight

OLIMPO, flown from LYR on July 14th, 2018
Rendering without ground/sun shields
- 1.6 tons payload
- Gondola design certified.
- Gondola parts being machined.

Electronics (readout, data acquisition, ACS, communications) and batteries
SWIPE: Simple ACS

- ACS based on the successful pivot flown on BOOMERanG and OLIMPO.
- Azimuth spin of the entire payload up to 3 rpm (with 3A current for a 1600kg load).
- Attitude determination from the same gyros and star sensors flown on Archeops (Nati et al. A fast star sensor for spinning balloon payloads Review of Scientific Instruments, 74, 4169-4175, 2003)

Azimuth Pivot (Boscaleri, IFAC). Same as OLIMPO. Test @ 6 rpm
SWIPE - receiver

- A Stokes (HWP + polarizer + power detector) polarimeter, panoramic
- Simple implementation
- Two large focal planes (8800 modes), at 0.3K, in a large cryostat, cooling also the lens (490mm diam. and a 460 mm diam. cold stop) and the polarization modulator (HWP at about 10-15 K).
- FOV: 20° split by a 500mm diam., 45° tilted wire grid into 2 Focal Planes 300 mm diam (f/1.75)
- Most components being machined, some ready
• Is a cold (2K), large (50 cm useful dia.), wide-band meta-materials HWP, placed immediately behind the window and thermal filters stack.

• HWP characteristics for the ordinary and extraordinary rays are well matched: \((T_o-T_e)/T_o < 0.001, \chi_{pol}<0.01\), over the 100-300 GHz band.

• Simulations show that continuous rotation has advantages in terms of 1/f noise mitigation and angles coverage.

• A custom superconductive rotator has been developed.

SWIPE – HWP rotator

~670mm

Permanent magnet ring

Pros
- NO stick-slip friction
- NO extra-effort to cool HTSs
- Passive stable levitation
- Low Coefficient of friction
- Continuous rotation (0-10Hz)

Cons
- Variable magnetic field
- Clamp mechanism at 4K

High Temperature Superconductors

1T field strength in the gap. Total mass 9 kg.
SWIPE – HWP rotator – parts procured

Stator with YBCO bulks

Groove ring for C/R

Rotor with permanent magnets

smaller diameter
Prototype
arXiv:1706.05963v3
SWIPE – HWP rotator – clamp/release

Stator

Rotor

Clamp / Release (1/3)

Frictionless actuator for operation @ 2K

Fabio Columbro, Paolo de Bernardis, and Silvia Masi

A clamp and release system for superconducting magnetic bearings

Custom brushless synchronous motor & control electronics:

- 8 phases
- 64 equalized coils (stator)
- 8 magnets (rotor)
- Smooth phased currents to minimize EMI & induced eddy currents
- 64-slits optical encoder
- High accuracy optical fibers readout ($\Delta t=50\mu s$)

Credit: P. de Bernardis
Room-T testbed for motor & control: OK
Working for:
• Optimization of start
• Optimization of feedback algorithm (frequency, phase and amplitude)
• Minimization of driving currents
• FPGA board for precision time stamping
• Thermal/vac test
Power Dissipation Tests @ room-T and extrapolation to cryo-T

From spin-down test:

\[ \tau_f(\omega) = \frac{P_f(\omega)}{\omega} \rightarrow P_f(\omega) = -\omega I \frac{d\omega}{dt} \]

<table>
<thead>
<tr>
<th>@ ( f_{HWP} = 1\text{Hz} )</th>
<th>( P ) [mW] - 300 K</th>
<th>( P ) [mW] - 1.6 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>Optimized</td>
<td>Expected</td>
</tr>
<tr>
<td>8 magnets</td>
<td>9.2</td>
<td>G10 ring 0.8</td>
</tr>
<tr>
<td>Main magnet</td>
<td>6.2</td>
<td>No tilt 1.3</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Joule</td>
<td>1200 ( &lt;\tau &lt;i &lt;W )</td>
<td>645</td>
</tr>
<tr>
<td>Harness</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bearing</td>
<td>41.5</td>
<td>41.5</td>
</tr>
<tr>
<td>Total</td>
<td>1260</td>
<td>690</td>
</tr>
</tbody>
</table>

Credit: Fabio Columbro
SWIPE: Cryogenic Testbed

Based on a pulse-tube cooler

A. Rocchi
Single lens 490mm in dia: plano-convex lens curved focal plane

Constraints:
- Thermal filters max c.a. diameter = 500 mm
- Wire Grid (WG @45 deg tilt) max c.a. diameter = 500 mm
- HWP max c.a. diameter = 500 mm

Dimensions:
- HDPE Lens (L1) diameter = 480 mm
- Aperture Stop (AS) = 440 mm
- Entrance Pupil = 450 mm
- FOV = 20 deg
- f/1.88
- Curved Focal plane (CFP_T o CFP_R) diameter = 300 mm
- Lens thickness = 65 mm
- HDPE lens with AR by porous PTFE
Single lens 490mm in dia: plano-convex lens

curved focal plane

Corrected focal plane vs bands
SWIPE: Simple Optical Design

800 mm

M. De Petris
The SWIPE pixel multimode assembly

![Diagram of the SWIPE pixel multimode assembly]

<table>
<thead>
<tr>
<th>BP+FC</th>
<th>SCH</th>
<th>MSWG</th>
<th>STT</th>
<th>ABS+BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal freq (GHz)</td>
<td>Bandwidth</td>
<td>Min freq (GHz)</td>
<td>Max freq (GHz)</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>30%</td>
<td>119</td>
<td>161</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>5%</td>
<td>214.5</td>
<td>225.5</td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>5%</td>
<td>234</td>
<td>246</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 – main features of the SWIPE bandpasses (source: C. Tucker, Cardiff Univ.)

<table>
<thead>
<tr>
<th>Channel</th>
<th>$v_{\min}$ (GHz)</th>
<th>$N_{\text{modes}}(v_{\min})$</th>
<th>$v_{\max}$ (GHz)</th>
<th>$N_{\text{modes}}(v_{\max})$</th>
<th>$v_{\text{eff}}$ (GHz)</th>
<th>$N_{\text{modes}}(v_{\text{eff}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>119</td>
<td>10</td>
<td>161</td>
<td>17</td>
<td>140</td>
<td>12</td>
</tr>
<tr>
<td>220</td>
<td>214</td>
<td>28</td>
<td>226</td>
<td>31</td>
<td>220</td>
<td>30</td>
</tr>
<tr>
<td>240</td>
<td>234</td>
<td>32</td>
<td>246</td>
<td>35</td>
<td>240</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 2 – number of coupled modes $N_{\text{modes}}$ at the center and at the edges of each SWIPE band. The total optical throughput at frequency $v$ is $N_{\text{modes}}c^2/v^2$. 

L. Lamagna
SWIPE: Horn beam

Lamagna et al., Proc. 36° ESA Antenna Workshop, manuscript 110138 (2015)
Measurements of pixel assembly beam

- Not an easy task. Custom cold absorber needed to limit radiative background.
- Beam vignetted by test cryostat window. However, multimode regime demonstrated.
- Will be redone with the large flight cryostat.

Columbro et al. LTD18
SWIPE focal planes: 50% 140 GHz, 25% 220 GHz, 25% 240 GHz
Total 330 detectors, with $A\Omega = 10\lambda^2, 21\lambda^2, 23\lambda^2$ @140,220,240
SWIPE: Focal Planes real estate

- The distribution of colors in the pixels has been optimized with a simplified scheme for foregrounds (dust) removal.
- This distribution provides sufficient precision to extrapolate the dust signal from high frequency down to 150 GHz.
- This configuration totalizes 4400 radiation modes for each focal plane (transmitted and reflected).
LSPE/SWIPE: telescope

- Whole system multi-mode
- Full EM simulation described in: Legg, Lamagna, Coppi, de Bernardis, Giuliani, Gualtieri, Marchetti, Masi, Pisano, Maffei, Development of the multi-mode horn-lens configuration for the LSPE-SWIPE B-mode experiment Proc. SPIE 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 991414 doi:10.1117/12.2232400
  - Resulting beam approximately top-hat. 1.5° FWHM.
  - Good polarization properties.

L. Lamagna. M. De Petris
Large Throughput multimode detectors: 8800 modes collected by 330 sensors.

Focal plane detector flanges (gold plated Al6061, 40 cm side).
Focal plane detector flanges (gold plated Al6061, 40 cm side).

Large Throughput multimode detectors: 8800 modes collected by 330 sensors.
SWIPE - multimode absorbers & TES

- The absorbers are large Si$_3$N$_4$ spider-webs (8 mm diameter, multimode)
- Sensors are Ti-Au TES
- Photon noise limited
- $\tau = 10\text{–}30$ ms
SWIPE - multimode absorbers & TES

- IV curves acquired with SQUID VTT J3, with $M=36 \ \mu A/\phi$
- Voltage bias generated onto a shunt resistor of 7.34 m$\Omega$
- The analysis allows to calculate the effective thermal conductance $G$ and the NEP, including the electro-thermal feedback.

<table>
<thead>
<tr>
<th>Vbias (uV)</th>
<th>G ($10^{-11}$ W/K)</th>
<th>NEP ($10^{-17}$ W/Hz$^{0.5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>5</td>
<td>2.6</td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
<td>3.8</td>
</tr>
<tr>
<td>1.5</td>
<td>20</td>
<td>5.3</td>
</tr>
<tr>
<td>2.0</td>
<td>28</td>
<td>6.3</td>
</tr>
</tbody>
</table>

F. Gatti
SWIPE - multimode absorbers & TES

- Very large spider-web absorbers: long time constant, even with large electrothermal feedback
- Minimize heat capacity by using Bi metalization of the spider-web
- Optimization of resistance per square versus heat capacity
- Expected around 10-30 ms
Cosmic Rays

• In the stratosphere: abundant primaries, and secondaries from both atmospheric and instrument interactions.

• Very rough estimate:
  – In BOOMERanG LDB in Antarctica: typical 8 mHz rate, for a spider web with 2.6 mm diameter and 5% filling factor (Masi et al. 2006, 2010).
  – Scaling from here, for a 8 mm diameter and 6% filling factor absorber with similar thickness, we expect a 90 mHz rate.

• Forecast basically confirmed by physics simulations carried out by the Pisa group (G. Signorelli et al. : 250 mHz).

• With a time constant of $\tau=30$ ms, and flagging data for 6 $\tau$s for each event, this rate would result in a loss of $<5\%$ of the data.
SWIPE - TES readout (mux)

Wiring and connections from 300 mK to 250 K

326 TES
16 x 3 twisted to TES per sector

G. Signorelli

INFN PISA
Istituto Nazionale di Fisica Nucleare Sezione di Pisa
SWIPE - TES readout (mux)

- 14 Si chips, 2 Nb 15 μH inductors each, 5 open-circuited
- 28 SMD capacitors, ranging from 220 pF to 100 nF
- SMD resistors with $R = 1 \Omega$, $R_{\text{shunt}} = 100 \text{ mΩ}$
- Readout with SQUID in FLL
- Tested @ 4 K

Test of a readout channel

G. Signorelli
SWIPE - TES readout (mux)

- Altera Cyclone V SoC
  - FPGA with 110'000 logic elements
  - 925 MHz dual-core micro-controller
- Mezzanine plug-ins for DAC and ADCs
  - 2 LTC1668 DACs (low noise, low power consumption)
  - 1 LTM9001-GA ADCs (16-bit, 25 MSPS)
- Gbit interface for data communication
- CAN & I2C interfaces to control low noise amps

FDM board tested and working
First comb generation algorithm

G. Signorelli
LSPE-SWIPE
- Aluminum cryostat
- Large cold volume (1m$^3$)
- 2 vapor cooled shields
- Fiberglass support system
- 270L of superfluid $^4$He @ 1.6K
- > 15 days hold time
- $^3$He refrigerator 0.28K
  (Coppi et al. 2016SPIE.9912E..65C)

LSPE/SWIPE: cryogenic system
LSPE/SWIPE: cryogenic system

Expected performance versus gas exchange efficiency (30 s.i. shields)

<table>
<thead>
<tr>
<th>$T_{ext}(K)$</th>
<th>Efficiency</th>
<th>$T_{shield1}(K)$</th>
<th>$T_{shield2}(K)$</th>
<th>Hold time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>0.7</td>
<td>106</td>
<td>270</td>
<td>13</td>
</tr>
<tr>
<td>290</td>
<td>0.8</td>
<td>100</td>
<td>255</td>
<td>15</td>
</tr>
<tr>
<td>290</td>
<td>0.9</td>
<td>93</td>
<td>250</td>
<td>16</td>
</tr>
<tr>
<td>220</td>
<td>0.7</td>
<td>76</td>
<td>194</td>
<td>22</td>
</tr>
<tr>
<td>220</td>
<td>0.8</td>
<td>71</td>
<td>190</td>
<td>25</td>
</tr>
<tr>
<td>220</td>
<td>0.9</td>
<td>67</td>
<td>187</td>
<td>27</td>
</tr>
</tbody>
</table>

Heat loads and heat lifts

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Supports (mW)</th>
<th>harness (mW)</th>
<th>radiation (mW)</th>
<th>Heat Lifts (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>194K</td>
<td>120</td>
<td>75</td>
<td>1900</td>
<td>2100</td>
</tr>
<tr>
<td>76K</td>
<td>420</td>
<td>330</td>
<td>600</td>
<td>1350</td>
</tr>
<tr>
<td>1.6K</td>
<td>150</td>
<td>30</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25 lit/h</td>
</tr>
</tbody>
</table>
Cryostat development
parts being machined
Main Cryogenic System

- Outer shell assembled and vacuum tested to $10^{-10}$ mbar l s
- Inner shell being welded
- Delivery in February 2020.

- Detectors harness defined
- Manufacturing started.
- Finalized in-synch with cryostat.
Calibration Plans
SWIPE Calibration Plan

• τ calibration / ground

• Beam calibration/ ground
  • Gunn sources (G1: 145, G2: 210-240) in the far field (200-350 m), on a drone. High S/N

• Polarimetry calibration / ground
  • Full beam calibrator (+ NDF) see below

• Responsivity calibration / ground
  • Full beam chopper + NDF) + calibration lamp for calibration transfer

• Noise calibration / ground
  • Data acquisition with closed window, NDF, subsystems on/off

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>145 GHz</th>
<th>210 GHz</th>
<th>240 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td>205</td>
<td>296</td>
<td>339</td>
</tr>
<tr>
<td>Power (W)</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Phase (deg)</td>
<td>11.7</td>
<td>12.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Power (W)</td>
<td>5.89E-07</td>
<td>1.31E-07</td>
<td>1.00E-07</td>
</tr>
</tbody>
</table>
Absolute orientation accuracy

array of discrete elements. \( \Delta \theta = O(1^\circ) \)

Photolitographed array – high precision within the tile. \( \Delta \theta = o(0.1^\circ) \)

large polarizer (50 cm) in front of a discrete array \( \Delta \theta = o(0.01^\circ) \)

This accuracy promise should be validated with a custom precision measurement
Full-beam Calibrator

1% polarized thermal signal to receiver
See e.g. O.Dell, Swetz, Timbie (2003)

\[ Q = T_H + (T_H - T_C)(R_{TE} - R_{TM}) + (T_S - T_C)(\varepsilon_{TE} - \varepsilon_{TM}) \]

\[ U = 0 \]

TE // to dielectric sheet

Modulated polarized power expected on multimode detector (220 GHz band + 1% NDF, based on accurate measurements of 125 \( \mu \)m mylar sheet): 4x10^{-14} W : >> NEP

We expect to measure the direction of the polarimeter axis with 1’ accuracy.
In-flight Calibration

• Correlation with Planck T for gain calibration
• Crab nebula (culmination at 31°) to check the polarimetry calibration
• the Moon edges (if moon visible, culmination around 25°) can be used to check beam and polarimetry in the high-end of the dynamic range
• Edge polarization convoluted with main beam detected during the scan, needs modelling to recover both beam and polarization characteristics.
Summary

• LSPE (STRIP and SWIPE) will provide:
  • good internal foregrounds removal capabilities
  • good control of systematic errors
  • accurate calibration

• Sensitive polarization maps for CMB, synchrotron and dust, with high orientation accuracy

• Target $r = 0.01$ looks feasible and robust.

• Best way to learn how Stokes polarimeters with cryogenic spinning HWP work in the field.
  • Commissioning in Tenerife for STRIP: end 2020
  • Launch of SWIPE: end 2021
  • Full data-set in hands: 2022