Preliminary in-flight performance and calibration status of POLAR

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On behalf of the POLAR collaboration
Outline

- Introduction to POLAR experiment
- Status of in-orbit operation and tests
- Status of in-flight calibration
- Summary and outlook
1. Introduction—R&D history and mission goals

Project: aboard TG-2, CN-EU collab (China, Switzerland, Poland)

• R&D history:

• Original scientific goal:
  – Precise polarization (PL&PA) measurement of GRB prompt emissions

• Extended scientific goals:
  – Test of pulsar navigation with POLAR data
  – Search of gravitational wave high-energy electromagnetic counterpart
  – Observation of Solar Flare
1. Introduction—instrument, installation, launch

Detector (OBOX)  Electric cabinet (IBOX)

Installation on TG-2  Launch of TG-2  Docking of TG-2 and Shenzhou-11 space ship
1. Introduction - instruments composition

- **IBOX**
- **OBOX**
- **DMU**
  - Back Plate
  - CFRP Socket (1 mm thick carbon prepreg)
  - 64 Bars
  - Back Seal
  - PMT Seal
  - End Cap
  - MAPMT
  - FEE
- **CT**
- **LVPS**
- **HVPS**
- **DMUs**
- **Naked DMU**
- **PS bar screen**
- **PS target assembly**
- **PS targets**
1. Introduction-detection theory

**Klein-Nishina equation:**

\[
\frac{d\sigma_p}{d\Omega} = \frac{1}{2} r_0^2 \varepsilon^2 (\varepsilon + \varepsilon^{-1} - 2 \sin^2 \theta \cos^2 \eta)
\]

**Compton Scattering with polarization**

**Distribution function**

\[ C(\xi) = A \cos(2(\xi - \varphi + \frac{\pi}{2})) + B \]

**Detection principle of POLAR**

**Modulation curve**

**Modulation factor**

\[ \mu = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}} \]

**Polarization level**

\[ P = \frac{\mu}{\mu_{100}} \]
2. In-orbit Operation and Tests

- Sep. 16th/2016, first powering on - IBOX
- Sep. 22nd, powering on of OBOX, start the commissioning phase

Summary of tests during POLAR commissioning phase (until April 1st/2017)

<table>
<thead>
<tr>
<th>Summary</th>
<th>Time (hrs)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total time</td>
<td>4567</td>
<td>2016.9.22~2017.4.1</td>
</tr>
<tr>
<td>Time without data</td>
<td>993</td>
<td>Power off or data missing</td>
</tr>
<tr>
<td>Time with data</td>
<td>3574</td>
<td>Obs. time including SAA</td>
</tr>
<tr>
<td><strong>Normal obs. time</strong></td>
<td>1536</td>
<td>Normal mode observation</td>
</tr>
<tr>
<td><strong>Single bar obs. time</strong></td>
<td>1644</td>
<td>Single bar mode observation</td>
</tr>
<tr>
<td><strong>In-orbit calibration time</strong></td>
<td>394</td>
<td>In-orbit calibration</td>
</tr>
</tbody>
</table>

- In-orbit calib.: response of detector, efficiency, system time precision, etc.
- GRB detection: 55 confirmed GRB, 49 GCN circulars
- Crab pulsar detection: more than 27 million pulsar photons
- Solar Flare detection: ~9 obvious SFL events
2. In-orbit Operation and Tests

- During the commissioning phase
  - 6.5TB total data size, 5188 data files: 6.4TB 0B data, 99GB 0C data
  - Implemented ~60 times commands upload operation, all succeeded
2. In-orbit Operation and Tests

- POLAR detected 55 confirmed GRBs, ~132 GRBs per year

List of GRBs detected by POLAR (confirmed by other instruments)

<table>
<thead>
<tr>
<th>Number</th>
<th>GRB Name</th>
<th>Trigger time (UTC)</th>
<th>Joint observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GRB 160924A</td>
<td>2016-09-24T06:04:09:040</td>
<td>Fermi/GBM, SPI-ACS</td>
</tr>
<tr>
<td>2</td>
<td>GRB 160928A</td>
<td>2016-09-28T19:48:05:00</td>
<td>Fermi/GBM, SPI-ACS, KW</td>
</tr>
<tr>
<td>3</td>
<td>GRB 16100951</td>
<td>2016-10-09T15:38:07:1900</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>4</td>
<td>GRB 161011217</td>
<td>2016-10-11T05:13:44:420</td>
<td>KW</td>
</tr>
<tr>
<td>5</td>
<td>GRB 16101289</td>
<td>2016-10-12T23:45:11:380</td>
<td>KW</td>
</tr>
<tr>
<td>6</td>
<td>GRB 161013948</td>
<td>2016-10-13T22:44:40:100</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>7</td>
<td>GRB 161120401</td>
<td>2016-11-20T09:38:33:520</td>
<td>SPI-ACS</td>
</tr>
<tr>
<td>8</td>
<td>GRB 161129A</td>
<td>2016-11-29T07:11:40:0000</td>
<td>Swift/BAT, Fermi/GBM, AstroSAT</td>
</tr>
<tr>
<td>9</td>
<td>GRB 161203A</td>
<td>2016-12-03T18:41:07:750</td>
<td>KW, SPI-ACS, CALET/CGBM, AstroSAT</td>
</tr>
<tr>
<td>10</td>
<td>GRB 161205A</td>
<td>2016-12-05T13:27:18:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>11</td>
<td>GRB 161207A</td>
<td>2016-12-07T20:42:55:000</td>
<td>Fermi/GBM, CALET/CGBM</td>
</tr>
<tr>
<td>12</td>
<td>GRB 161207B</td>
<td>2016-12-07T05:22:44:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>13</td>
<td>GRB 161210A</td>
<td>2016-12-10T12:33:54:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>14</td>
<td>GRB 161212A</td>
<td>2016-12-12T15:38:59:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>15</td>
<td>GRB 161213A</td>
<td>2016-12-13T07:05:02:0000</td>
<td>Fermi/GBM, SPI-ACS</td>
</tr>
<tr>
<td>16</td>
<td>GRB 161217B</td>
<td>2016-12-17T03:03:44:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>17</td>
<td>GRB 161217C</td>
<td>2016-12-17T03:55:15:000</td>
<td>KW</td>
</tr>
<tr>
<td>18</td>
<td>GRB 161218A</td>
<td>2016-12-18T03:47:34:634</td>
<td>Swift/BAT</td>
</tr>
<tr>
<td>19</td>
<td>GRB 161218B</td>
<td>2016-12-18T08:32:41:341</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>20</td>
<td>GRB 161219B</td>
<td>2016-12-19T18:48:39:000</td>
<td>Swift/BAT</td>
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<tr>
<td>21</td>
<td>GRB 161228A</td>
<td>2016-12-28T09:43:24:000</td>
<td>Fermi/GBM</td>
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<tr>
<td>22</td>
<td>GRB 161228B</td>
<td>2016-12-28T13:15:40:000</td>
<td>Fermi/GBM, SPI-ACS</td>
</tr>
<tr>
<td>23</td>
<td>GRB 161228C</td>
<td>2016-12-28T00:46:20:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>24</td>
<td>GRB 161229A</td>
<td>2016-12-29T21:03:49:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>25</td>
<td>GRB 161230A</td>
<td>2016-12-30T12:16:07:000</td>
<td>Fermi/GBM</td>
</tr>
<tr>
<td>26</td>
<td>GRB 170101A</td>
<td>2017-01-01T02:26:00:6600</td>
<td>Swift/BAT</td>
</tr>
<tr>
<td>27</td>
<td>GRB 170101B</td>
<td>2017-01-01T02:47:18:2700</td>
<td>Fermi/GBM</td>
</tr>
</tbody>
</table>
2. In-orbit Operation and Tests

T90 distribution of the 49 GCN circulated GRBs detected by POLAR

S. Xiong report. 2017
2. In-orbit Operation and Tests

- **10 relatively bright GRBs detected by POLAR**

<table>
<thead>
<tr>
<th>GRB Name</th>
<th>T90 (s)</th>
<th>Total Counts</th>
<th>Theta (deg)</th>
<th>Phi (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 161218A</td>
<td>6.8</td>
<td>6644</td>
<td>24.3</td>
<td>356.6</td>
</tr>
<tr>
<td>GRB 161218B</td>
<td>26.3</td>
<td>29340</td>
<td>77.76</td>
<td>252.2</td>
</tr>
<tr>
<td>GRB 161229A</td>
<td>35.77</td>
<td>35134</td>
<td>87.6</td>
<td>-103.7</td>
</tr>
<tr>
<td>GRB 170101A</td>
<td>2.82</td>
<td>5379</td>
<td>6.04</td>
<td>72.86</td>
</tr>
<tr>
<td>GRB 170114A</td>
<td>8.0</td>
<td>26800</td>
<td>26.4</td>
<td>4.9</td>
</tr>
<tr>
<td>GRB 170127C</td>
<td>22.0</td>
<td>3600</td>
<td>41.8</td>
<td>157.6</td>
</tr>
<tr>
<td>GRB 170206A</td>
<td>1.2</td>
<td>12918</td>
<td>19.5</td>
<td>148.7</td>
</tr>
<tr>
<td>GRB 170207A</td>
<td>39.47</td>
<td>63182</td>
<td>70.6</td>
<td>-2.2</td>
</tr>
<tr>
<td>GRB 170210A</td>
<td>67.27</td>
<td>106099</td>
<td>80.6</td>
<td>130.9</td>
</tr>
<tr>
<td>GRB 170305A</td>
<td>0.3</td>
<td>2400</td>
<td>31.4</td>
<td>239.1</td>
</tr>
</tbody>
</table>

*POLAR GRB catalogue – 10 relative bright ones*

*S. Xiong et al. 2017, Proc. of ICRC*
2. In-orbit Operation and Tests

• Light curves of the 10 bright GRBs
3. In-orbit calibration

• POLAR in-orbit calibration requirements:

(1) Performance variation of the detector

- Gain variation due to the shipment, launch and space environment modification
  - Gain of PMT
  - Coupling status between PS target and PMT
- Light output reduction of PS bars due to the irradiation effect in space
  - ~5% reduction in 2 years for estimation
- Aging effect
  - PS bars, PMT and electronics

(2) Influence of the performance variation

- Direct influence
  - Pedestal and noise, gain, crosstalk, etc.
- Indirect influence
  - Low threshold, and even polarization measurement error!

• Therefore, we need calibration for POLAR during flight!
3. In-orbit calibration

- **POLAR in-orbit calibration includes:**
  
  1. **Energy calibration**
     - Gain vs HV
     - Energy vs ADC channel
  
  2. **Systematic effects calibration**
     - Pedestal and noise, crosstalk, nonlinearity, threshold
  
  3. **Temperature dependence calibration**
     - Study on the calibration parameters vs temperature in space
  
  4. **Timing calibration**
     - POLAR instrument system timing calibration with Crab pulsar signals
  
  5. **GRB Localization**
     - Cross check with other satellites
  
  6. **Detection efficiency**
     - By using the GRB data
  
  7. **Events filtering**
     - To exclude the bad or abnormal events
3. In-orbit calibration

- **Energy calibration**
  - 4 $^{22}$Na radioactive devices
  - Total activities $\sim 350$ Bq
3. In-orbit calibration

- **Energy calibration**
  - Applied 5 different HVs to measure the *gain vs HV*
  - Application of gain vs HV to normal GRB observation mode

\[
\log_{10} CE = p_0 + p_1 \cdot \log_{10} HV
\]

Compton edge positions of 1600 channels
3. In-orbit calibration

- Systematic effects calibration

- Pedestal
- Intrinsic noise
- Nonlinearity

- Common noise
- Crosstalk matrix
- Low threshold
3. In-orbit calibration

- Temperature dependence calibration

**Pedestal vs temp.**

\[
\chi^2 / \text{ndf} = 0.2945 / 6 \\
p_0 = 446.8 \pm 2.986 \\
p_1 = 1.544 \pm 0.1261
\]

**Intrinsic noise vs temp.**

\[
\chi^2 / \text{ndf} = 6.657 / 6 \\
p_0 = 7.064 \pm 0.1152 \\
p_1 = -0.04218 \pm 0.004853
\]

**Gain vs temp.**

\[
\chi^2 / \text{ndf} = 0.152 / 3 \\
p_0 = 11.27 \pm 0.5999 \\
p_1 = -0.06824 \pm 0.02397
\]

**Common noise vs temp.**

\[
\chi^2 / \text{ndf} = 0.7861 / 6 \\
p_0 = 81.63 \pm 3.286 \\
p_1 = -1.757 \pm 0.139
\]

**Low threshold vs temp.**

\[
\chi^2 / \text{ndf} = 0.3722 / 5 \\
p_0 = 196.9 \pm 6.053 \\
p_1 = 1.614 \pm 0.1894
\]

Nonlinearity and crosstalk vs temp. can be negligible

Zhengheng Li, et al. 2018, submitted
3. In-orbit calibration

- **Timing calibration with Crab pulsar**
  - Precision better than 100 μs

- **GRB localization**
  - Cross calibration with other instruments in-orbit, precision ~ 5 degrees

- **Events filtering**
  - Cosmic events will be tagged and removed during the data analysis
  - The post cosmic events are mostly abnormal therefore need to be tagged and filtered out also. A method has been developed to filter out more than 95% such events

*Figure 3: Panel (a): the evolution of the spin frequency of the Crab pulsar observed by POLAR. Each data point is subtracted by \((29.648422 - \tau + 3.68 \times 10^{-10})\) to show the details of its frequency evolution. The green line represents the fitted result. Panel (b): The time residuals of the Crab pulsar observed by Fermi and POLAR, as represented by the blue and red squares respectively.*
4. Summary and outlook

• POLAR has accomplished the commissioning phase tests: has finished the in-flight calibration and data analysis (a paper has been submitted), detected 55 confirmed GRBs, detected the Crab pulsar signals and carried on the preliminary navigation study, detected ~ 9 obvious SFL events

• First GRB polarization analysis results are almost ready

• Outlook
  – GRB polarization data analysis and MC simulation
  – Crab pulsar navigation study and polarization analysis
  – SFL data analysis

Fore more info., please refer to and contact http://polar.ihep.ac.cn
E-mail: wubb@ihep.ac.cn, or sunjc@ihep.ac.cn

Thank you for your attention!