PROCEEDINGS OF SCIENCE

Overview of the GRB observation by POLAR

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POLAR is a dedicated Compton scattering polarimeter to detect Gamma-Ray Bursts (GRBs) in the energy range of about 50 to 500 keV, which was launched on-board the Chinese space laboratory Tiangong-2 (TG2) on Sep 15, 2016. Since then, POLAR has detected 55 GRBs jointly with other telescopes as of Apr 1, 2017. Meanwhile, more GRBs detected by POLAR only will be revealed as the burst search and identification program gets more sophisticated to deal with the complicated background. After subtracting the non-observation period due to varies reasons in the commissioning phase, the effective observation time is about 3180 hours, thus the GRB detection rate of POLAR is estimated to be about 150 GRBs/year, demonstrating that POLAR is one of the most sensitive GRB detectors in operation. Thanks to the high sensitivity, large FOV (about 1/2 of the all-sky) and unique capability of polarization measurement, POLAR is a very important detector in the search for high-energy electromagnetic counterpart for Gravitational Wave Bursts (GWB), High Energy Neutrinos (HEN) and Fast Radio Bursts (FRB). In this paper, we summarized the GRB observation by POLAR, including GRB search and identification, joint observation and Gamma-ray Coordinates Network (GCN) alerts, data analysis, GRB catalogues and so on.

35th International Cosmic Ray Conference — ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

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PoS(ICRC2017)640

1. Introduction

Gamma-Ray Bursts (GRBs) are the most violent explosions in the cosmos since the big bang. They are classified into two types according to the observed duration of the X/gamma-ray emission (dubbed prompt emission) [1]: Short GRBs, which have duration less than 2 s, are believed to originate from the coalescence of two compact objects, such as neutron stars and neutron star, or neutron star and black hole, whereas the long GRBs (duration longer than 2 s) are thought to generate by the collapse of massive star. According to the current theoretical models, the prompt high-energy emission are radiated from the relativistic jets launched by the central engine which is usually a black hole or a massive, fast rotating magnetar. In contrast to the short-lived, high energy prompt emission, the afterglow emission lasts much longer but usually spans in lower energies (soft X-ray, optical and radio band, but also seen in GeV occasionally), which is produced by the collision of the jets with interstellar medium (ISM) around the progenitor of the GRB [2].

Despite of nearly a half century of observation and research, the GRBs still remain mystery with many open questions in the jet composition, radiation mechanism, central engine and progenitor [2]. Many competing theoretical models can interpret the current observed temporal and spectral features of the GRBs. Therefore, new observations, especially the polarization measurements, are required to distinguish these models [3].

POLAR is a dedicated GRB polarimeter sensitive in 50-500 keV, aiming to measure the polarization degree and polarization angle for a large sample of GRBs with an unprecedented accuracy. It consists of 25 detector modules, each of which employs an array of 64 plastic scintillators read out by a multi-anodes photomultiplier (MAPMT). More information about POLAR mission and its preliminary science results could be found in [4, 5, 6, 7].

Due to the limited telemetry resources for POLAR, there is a latency of about 5 to 20 hours for the POLAR Science Data Center (PSDC) to receive the observation data. After downlinked, the data will be synchronized as soon as possible between the PSDC in the Institute of High Energy Physics in China, and the University of Geneva and the Paul Scherrer Institut (PSI) in Switzerland within the POLAR collaboration.

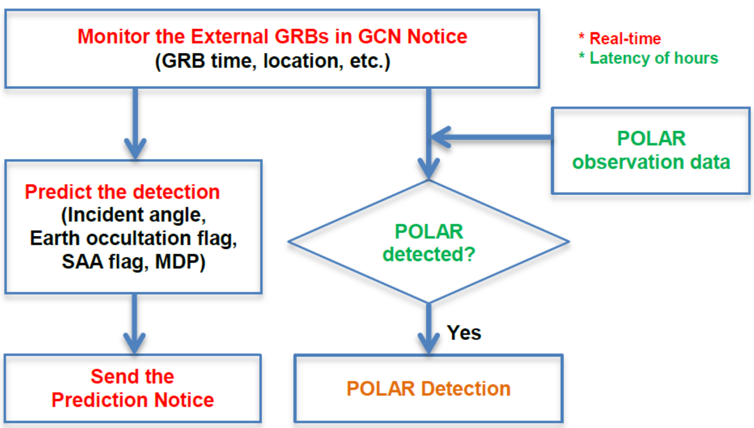

Figure 1: flow chart for external triggers

2. GRB search and identification

Since there is no real-time data downlink, POLAR cannot provide real-time triggers for GRBs. Nevertheless, in order to maximize the GRB science return, we implemented two approaches for POLAR to give the GRB detection information as soon as possible. The first approach is initiated by external GRBs reported in GCN Notice by other telescopes, while the second one is triggered by the ground search of the POLAR data. They will be presented in details in following sections.

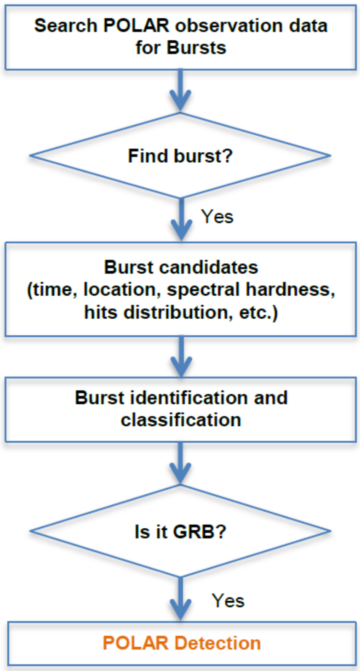

Figure 2: flow chart for internal triggers

2.1 External triggers

Many telescopes report GRBs with GCN Notice in (nearly) real-time, which we called external triggers or external GRBs. But POLAR data suffers hours of delay, this prevents us from checking, in real time, whether POLAR detect the external GRBs or not. However, since the attitude and orbit of POLAR is well predictable according to the operation plan, we can predict whether and how well POLAR would detect the external GRBs immediately after receiving the GCN Notice. Such prompt prediction information might be useful in the follow-up observations; therefore we plan to share it with the GRB community by sending the POLAR prediction GCN notice.

To do so, we developed software to automatically monitor external GRBs reported in GCN Notice and calculate whether the GRB fall inside the FoV of POLAR. In addition, based on the fluence and duration of the GRB, the incident angle to POLAR, and the background rate of POLAR, we further estimate how well POLAR will measure the polarization of the GRB, i.e. Minimum Detectable Polarization (MDP).

When the POLAR observation data come in, we directly check the data around the time of the external GRB and compare the real observation to the prediction mentioned above. As of Apr 1, 2017, POLAR have detected 55 GRBs (Table 3) using this approach.

2.2 Internal triggers

POLAR is able to monitor GRBs occurred in all sky unblocked by the Earth and the TG2 spacecraft, thus we expect POLAR can not only detect GRBs jointly with other telescopes, but also discover new GRBs not found by any others. We developed the burst search program to blind search the POLAR data for GRBs, i.e. internal triggers or internal GRBs. Just like other GRB missions, the search algorithm is to find out the sources above the fluctuation of background. The search is implemented for 8 timescales (i.e. 64 ms, 128 ms, 256 ms, 1.024 s, 2.048 s, 4.096 s and 8.192 s) with 4 phases for each timescale, and for different energy ranges.

According to the pre-flight simulation, the majority of the in-flight background comes from the charged particles in the space environment. Due to the relatively high inclination angle of POLAR (43 degree), the in-flight background variation is quite complicated with significant amount of bumps and spikes probably caused by the space environment. These non-GRB events are difficult to distinguish from GRBs just based on the light curve, therefore, in order to efficiently identify and classify GRBs from these non-GRB events, joint criteria, which include the spacecraft location, spectral hardness, hits distribution in 1600 bars and localization of the burst, is required. Such criteria are not easy to establish due to the elusive low-energy particle events in the orbit. We expect to find out more GRBs in POLAR data once the search and identification program get more sophisticated.

3. GRB analysis

For every GRB detected by POLAR, a series of analysis is planned to do by the Burst Advocate (BA), as shown in Fig. 3. The first analysis is to produce the background-subtracted light curve and calculate the duration (T90), peak rate and total counts for this burst. BA is responsible to publish these analysis by sending out a GCN Circular. To date, 49 Circulars have been published by POLAR [8].

POLAR has the localization capability using the signal distribution (counts) among 1600 bars [9]. Since the ground calibration is just finished [10] and the in-flight calibration for 1600 bars is still on-going [11, 12], localization, spectral analysis and polarization analysis for GRBs are not finalized. We will publish these results in the forthcoming papers.

4. POLAR in the Multi-wavelength and Multi-messenger Era

Searching for high energy Electromagnetic (EM) counterpart is critically important for Gravitational Wave Bursts (GWBs) [13], High Energy Neutrinos (HENs) and Fast Radio Bursts (FRBs). Thanks to the unique capability of unprecedented accurate polarization measurement, a very wide FoV and high sensitivity, POLAR can play a very important role in the multi-wavelength and multi-messenger era by monitoring the hard X-ray and soft gamma-ray emission from GWBs, HENs and FRBs, and providing insight to the radiation mechanism and progenitors of these celestial sources.

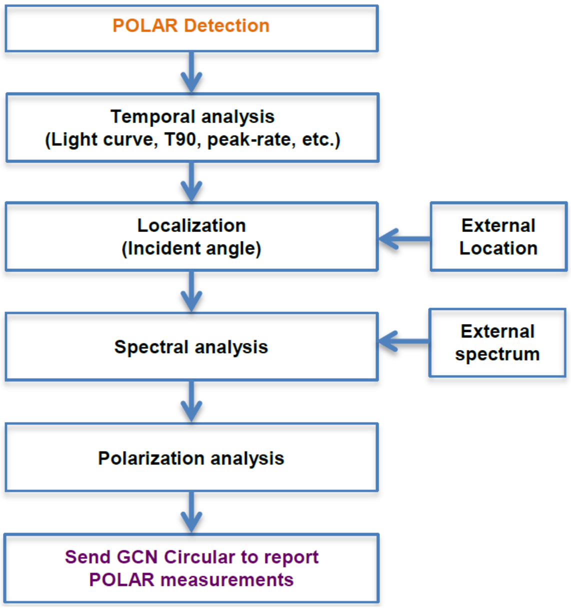

Figure 3: flow chart for GRB analysis

POLAR is originally designed to measure polarization using the Compton Scattering effect which will produce at least two hits in the detector array of 1600 bars, therefore, events with two or more hits are fully record and almost all events with only one hit are discarded. This data acquisition is called regular mode. However, recording those events just hit one bar, called single-bar mode, could significantly improve the detection sensitivity for EM counterpart, as shown in Fig. 4. Therefore, we enabled the single-bar mode once the TG2 onboard storage allows. As of Apr 1, 2017, the single-bar mode has been implemented for a total observation time of 1644 hours, as shown in Table 1.

Table 1: Summary of POLAR observation time as of Apr 1, 2017

Items	Time (hr)	Notes
Total time	4567	from Sep 22, 2016 to Apr 1, 2017
Time without data	993	instrument turned off or data lost
Time with data	3574	observation time, SAA passages included
Bank50 regular	1536	bank50 setting, regular data acquisition
Bank50 single-bar	1644	bank50 setting, single-bar data acquisition
Bank20	394	bank20 setting, mainly for calibration

5. GRB catalogue

As of Apr 1, 2017, the time allocation of POLAR is shown in Table 1. As one can see, POLAR has taken data for a total time of 3574 hours (the normal SAA passage included). Mainly two operation settings, i.e. Bank50 and Bank20, were used, where Bank50 is for science observation and Bank20 for calibration. The total science observation time is 3180 hours, during which 55

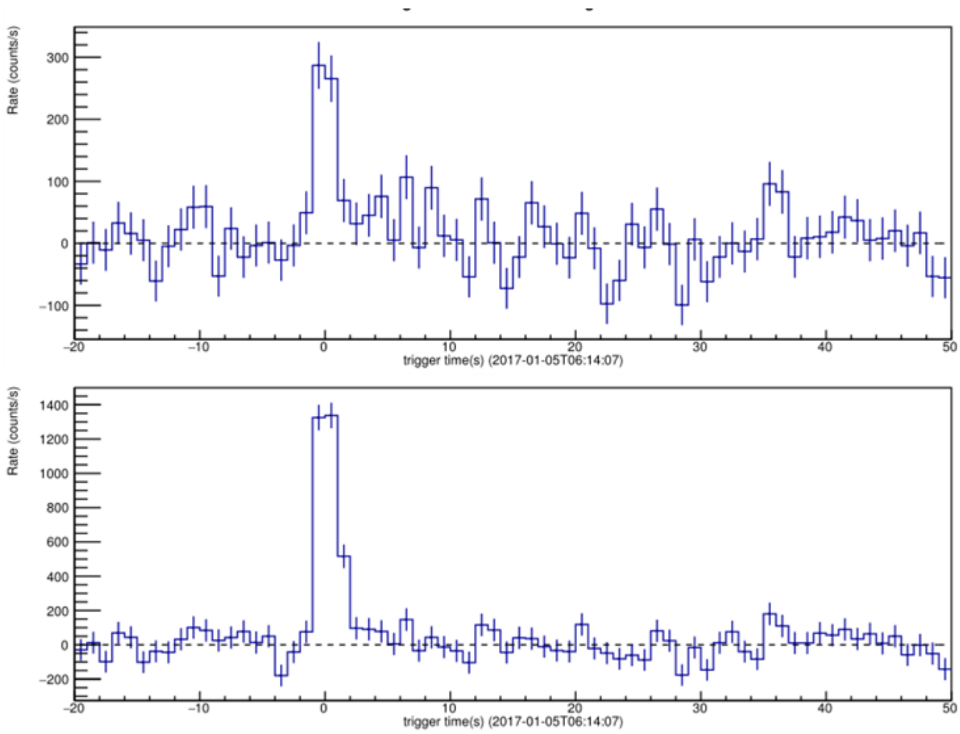

Figure 4: Light curves (backgroud-subtracted) for regular mode (top) and single-bar mode (bottom) for GRB 170105A.

GRBs were detected by POLAR together with other telescopes, for example Fermi/GBM, Swift, SPI-ACS, Konus-Wind (denoted as KW), as shown in Table 3. This corresponds to a discovery rate of about 150 GRBs/year, showing that POLAR is one of the most sensitive GRB detectors in operation.

Out of these 55 GRBs, there are about 10 bright GRBs that are very suitable for polarization measurement, with the typical MDP of about 10%, as shown in Table 2. We note that this is the largest sample of GRBs with high accurate polarization measurements to date, which is foreseen to shed new light on the nature of the GRB phenomenon.

Table 2: Bright GRBs detected by POLAR as of Apr 1, 2017

GRB Name	T90 (s)	Total Counts	Theta (deg)	Phi (deg)	MDP (1 σ)
GRB 161218A	6.8	6644	24.3	356.6	11%
GRB 161218B	26.3	29340	77.76	252.2	12%
GRB 161229A	35.77	35134	87.6	-103.7	15%
GRB 170101A	2.82	5379	6.04	72.86	6%
GRB 170114A	8.0	26800	26.4	4.9	15%
GRB 170127C	22.0	3600	41.8	157.6	13%
GRB 170206A	1.2	12918	19.5	148.7	6%
GRB 170207A	39.47	63182	70.6	-2.2	6%
GRB 170210A	67.27	106099	80.6	130.9	7%
GRB 170305A	0.3	2400	31.4	239.1	10%

6. Conclusion

Since the launch on Sep 15, 2016, POLAR has detected 55 GRBs jointly with other telescopes during 3180 hours of data taken, which is equivalent to about 150 GRBs/year. About 10 bright GRBs are expected to have good polarization measurements with MDP of about 10%. After the in-flight calibration is finished, polarization analysis will be finalized. A catalogue of all POLAR GRBs will also be released at the end of the mission. In addition to the regular data acquisition mode (record events with two or more hits in 1600 bars) designed to measure the polarization, the single-bar mode (record events with one or more hits in 1600 bars) has been enabled to improve the detection sensitivity to the Electromagnetic Counterparts for Gravitational Wave Burst (GWB), Fast Radio Burst (FRB) and High Energy Neutrino (HEN) events.

Acknowledgments

This work is supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB23040400). S. L. Xiong was also supported by the Hundred Talents Program of the Chinese Academy of Sciences (Grant No. 292016BRJH03).

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Table 3: GRBs detected by POLAR as of Apr 1, 2017

Number	GRB Name	Trigger time (UTC)	Joint observation
1	GRB 160924A	2016-09-24T06:04:09.040	Fermi/GBM, SPI-ACS
2	GRB 160928A	2016-09-28T19:48:05.000	Fermi/GBM, SPI-ACS, KW
3	GRB 161009651	2016-10-09T15:38:07.190	Fermi/GBM
4	GRB 161011217	2016-10-11T05:13:44.420	KW
5	GRB 161012989	2016-10-12T23:45:11.380	KW
6	GRB 161013948	2016-10-13T22:44:40.100	Fermi/GBM
7	GRB 161120401	2016-11-20T09:38:33.520	SPI-ACS
8	GRB 161129A	2016-11-29T07:11:40.000	Swift/BAT, Fermi/GBM, AstroSAT
9	GRB 161203A	2016-12-03T18:41:07.750	KW,SPI-ACS, CALET/CGBM, AstroSAT
10	GRB 161205A	2016-12-05T13:27:18.000	Fermi/GBM
11	GRB 161207A	2016-12-07T20:42:55.000	Fermi/GBM, CALET/CGBM
12	GRB 161207B	2016-12-07T05:22:44.000	Fermi/GBM
13	GRB 161210A	2016-12-10T12:33:54.000	Fermi/GBM
14	GRB 161212A	2016-12-12T15:38:59.000	Fermi/GBM
15	GRB 161213A	2016-12-13T07:05:02.000	Fermi/GBM, SPI-ACS
16	GRB 161217B	2016-12-17T03:03:44.000	Fermi/GBM
17	GRB 161217C	2016-12-17T03:53:15.000	KW
18	GRB 161218A	2016-12-18T03:47:34.634	Swift/BAT
19	GRB 161218B	2016-12-18T08:32:41.341	Fermi/GBM
20	GRB 161219B	2016-12-19T18:48:39.000	Swift/BAT
21	GRB 161228A	2016-12-28T09:43:24.000	Fermi/GBM
22	GRB 161228B	2016-12-28T13:15:40.000	Fermi/GBM, SPI-ACS
23	GRB 161228C	2016-12-28T00:46:20.000	Fermi/GBM
24	GRB 161229A	2016-12-29T21:03:49.000	Fermi/GBM
25	GRB 161230A	2016-12-30T12:16:07.000	Fermi/GBM
26	GRB 170101A	2017-01-01T02:26:00.660	Swift/BAT
27	GRB 170101B	2017-01-01T02:47:18.270	Fermi/GBM
28	GRB 170102A	2017-01-02T02:51:18.000	KW
29	GRB 170105A	2017-01-05T06:14:07.000	SPI-ACS, KW
30	GRB 170109A	2017-01-09T03:17:35.000	Fermi/GBM
31	GRB 170112B	2017-01-12T23:16:09.000	Fermi/GBM
32	GRB 170114A	2017-01-14T22:01:10.000	Fermi/GBM
33	GRB 170114B	2017-01-14T19:59:12.000	Fermi/GBM, KW
34	GRB 170120A	2017-01-20T11:18:30.000	Fermi/GBM
35	GRB 170121A	2017-01-21T01:36:55.200	Fermi/GBM
36	GRB 170124A	2017-01-24T20:58:06.000	Fermi/GBM, KW, CALET/CGBM
37	GRB 170127C	2017-01-27T01:35:49.000	Fermi/GBM, Fermi/LAT, AGILE, AstroSAT
38	GRB 170130A	2017-01-30T07:14:45.000	Fermi/GBM
39	GRB 170131A	2017-01-31T23:14:59.000	Fermi/GBM, Swift, KW
40	GRB 170202B	2017-02-02T07:19:54.000	KW
41	GRB 170206A	2017-02-06T10:51:57.700	Fermi/GBM, Fermi/LAT, SPI-ACS
42	GRB 170206C	2017-02-06T11:40:10.000	SPI-ACS
43	GRB 170207A	2017-02-07T21:45:04.000	Fermi/GBM, IPN, KW
44	GRB 170208C	2017-02-08T13:16:33.000	Fermi/GBM, SPI-ACS
45	GRB 170210A	2017-02-10T02:47:37.000	Fermi/GBM, IPN, KW
46	GRB 170219A	2017-02-19T00:03:07.000	Fermi/GBM, CALET/CGBM, SPI-ACS, KW, IPN
47	GRB 170220A	2017-02-20T18:48:01.000	KW
48	GRB 170228B	2017-02-28T18:32:56.000	Fermi/GBM
49	GRB 170305A	2017-03-05T06:09:06.800	Fermi/GBM, KW, SPI-ACS, Swift/BAT
50	GRB 170306B	2017-03-06T14:07:20.000	Fermi/GBM, Fermi/LAT, SPI-ACS
51	GRB 170309A	2017-03-09T12:26:42.000	CALET/CGBM
52	GRB 170315A	2017-03-15T13:57:53.000	Fermi/GBM
53	GRB 170317A	2017-03-17T09:45:56.000	Swift/BAT
54	GRB 170320A	2017-03-20T03:42:39.000	SPI-ACS, KW
55	GRB 170325B	2017-03-25T21:50:01.000	KW