CALET Search for electromagnetic counterparts of gravitational waves in O4

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Summary: The latest LIGO/Virgo/KAGRA observing run (O4) started on May 24 in 2023. Many ground and space instruments have participated in follow-up observation and search for electromagnetic counterparts of gravitational waves. Calorimetric Electron Telescope (CALET) on the international Space Station has also searched for electromagnetic counterparts since the observation started in October 2015. Although CALET is a payload for direct measurement of high-energy cosmic rays, CALET has the capability to observe high-energy gamma-rays above 1 GeV with the Calorimeter (CAL) and X-rays / gamma rays in the energy range from 7 keV to 20 MeV with the CALET Gamma-ray Burst Monitor (CGBM). We searched for electromagnetic counterparts of gravitational wave events in the last LIGO/Virgo observing run (O3). Although no candidate was found in CALET data in O3, CAL and CGBM estimated upper limits of gamma-ray / X-ray flux for the gravitational waves in O3. We have been searching for electromagnetic counterparts of gravitational waves in O4 with improved and automated analysis pipelines to deal with many events with high event rates. As of the end of June 2023, the LIGO/Virgo/KAGRA collaboration reported 169 events via GCN/LVC NOTICE, and 15 of 169 events were reported to GCN circular as significant events. Although CGBM and CAL searched for signals associated with the significant events, no candidates were found around the event time of the significant events. We obtained CAL upper limits for eight significant events of which localization high probability region overlapped with the CAL field of view.

Calorimetric Electron Telescope (CALET)

The latest observing run for gravitational wave (O4) started on May 24, 2023, following the engineering run (ER15) for about one month. The first public alert in O4 was distributed via the General Coordinates Network (GCN) and GraceDB on May 18, and many follow-up observations and searches for electromagnetic (EM) counterparts of gravitational waves (GWs) have been performed since the first event in O4 [1, 2]. **CALorimetric Electron Telescope (CALET) has also searched EM counterparts of GWs, in particular, short gamma-ray bursts (GRBs) associated with binary neutron star mergers.**

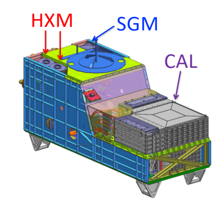

Figure 1. Schematic image of CALET.

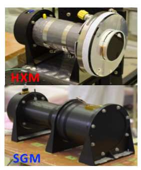

Figure 2. Flight detectors of CGBM

CALET is a payload on the International Space Station (ISS) to observe cosmic rays and gamma rays [3]. Although the primary purposes of CALET are a direct measurement of cosmic rays, CALET has collected gamma-ray data since the observation started in October 2015 with two scientific instruments, **CALorimeter (CAL)** and **Gamma-ray Burst Monitor (CGBM),** which consists of two kinds of scintillation detectors, Hard X-ray Monitor (HXM) and Soft Gamma-ray Monitor (SGM) [4]. The specification of CAL and CGBM for gamma rays are shown in Tables 1 and 2.

Table 1 CGBM specification

	HXM	SGM
Crystal	LaBr3(Ce)	BGO
Number of detectors	2	1
Diameter [mm]	66.1 (small) 78.7 (large)	102
Thickness [mm]	12.7	76
Energy range [keV]	7-1000	40-20000
Field of view	~3 sr	~8 sr

Table 2 CAL specification

	CAL
Energy resolution	~3 % @ 10 GeV
Energy range	1 GeV – 10 TeV
Field of view	~ 2 sr
Angular resolution	~0.5 deg. @ 10 GeV

Note: Typical values are shown in the table, and further information for CAL gamma-ray observations are available in other presentations and published paper [5, 6, 7]

In the counterpart search, CGBM is more important because **CGBM has detected 327 GRBs** thanks to the onboard trigger system as of June 2023. Figure 3 shows the duration distribution of GRBs detected by CGBM/SGM. If we classified GRBs with the intersection of two logarithmic normal distributions, **31 GRBs were classified as short GRBs**. A short GRB is a plausible candidate of EM counterparts of the binary neutron star mergers like GRB 170817A, which is associated with GW 170817 [8, 9, 10, 11].

Although we have checked CAL data for high-energy emissions from GRBs detected by CGBM, only two candidate events were found, and no conclusive event has yet to be found.

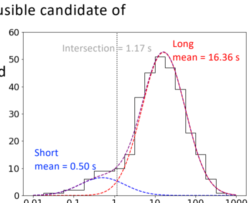

Figure 3. Duration distribution measured by SGM (40 – 1000 keV)

CGBM can observe prompt emissions of short GRBs
CAL has the possibility of observing high-energy emissions of GRBs.

CALET observation in O3 & O4

CGBM has been collecting Time History (TH) data (1/8 s, 4 channels (High Gain) + 4 channels (Low Gain)) with running the onboard trigger system. The onboard trigger system calculates a signal-to-noise ratio (SNR) every 0.25 s.

$$\mathrm{SNR} = \frac{N_{\mathrm{tot}} - \frac{N_{\mathrm{BG}}}{\Delta t_{\mathrm{BG}}}\Delta t}{\sqrt{\frac{N_{\mathrm{BG}}}{\Delta t_{\mathrm{BG}}}\Delta t}}$$

Δt: 1/4, 1/2, 1, 4 s
Δt_{BG}: 16 sec
N_{tot}: GRB + Background counts during Δt
N_{BG}: background counts during Δt_{BG}

Once any SNR exceeds the detection threshold, 8.5 for HXM and 7.0 for SGM, event data is captured, and GCN/CALET NOTICE is distributed. However, **no onboard trigger happened around any GW events shown in Table 3.** The ground search was performed by applying the formula to TH data for T_0 +/- 60 s with more conditions for events, of which summed probability (P_h) above the horizon equals or exceeds 1 %. While the background rate was estimated by averaged counts of before and after Δt in O3, background fitting with a polynomial function was used in O4. **No significant signals were found in CGBM data for any GW events in Table 3.** Although no significant binary neutron star merger events have yet to be reported in O4, CGBM count rates around S230518h and S230627c, which are likely NSBHs, are shown in Figure 4.

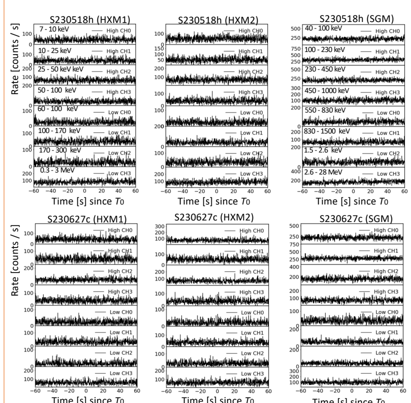

Figure 4. Time history of CGBM count rates around S230518h (Top) and S230627c (Bottom).

In the CAL analysis, we used data from the High-Energy trigger (HE) mode and the Low-Energy Gamma ray (LEG) mode (only enabled at low latitudes or short intervals after CGBM onboard triggers). We searched for gamma-ray events in the data of HE or LEG mode for T_0 +/- 60 s in the case of "Coverage" equals or exceeds 5 % according to the method described in [12, 13]. "Coverage" is the overlapping region of the LIGO/Virgo localization map covered by the CAL field of view during the interval T_0 +/- 60 s. **No gamma rays associated with any GW events in Table 3 were found. However, in case of a null event, we estimated the 90 % confidence level upper limits** for any direction, like Figure 5. Also, the highest upper limits in pixels in the overlapped region are shown as "CAL Upper limits" in Table 3.

More detail of analysis procedures and CGBM upper limits for O3 events were summarized in Adriani et al. 2022 [13].

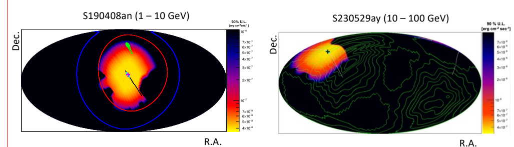

Figure 5. 90 % upper limit maps for S190408an (left) and S230529ay (right). Green contours are LIGO/Virgo localization high probability region. Red and blue circles are the HXM and SGM fields of view ignoring effects of the ISS structures, respectively.

Although the O4 analysis is almost the same as the analysis in O3, **we developed automatic pipelines to process CGBM and CAL data to analyze O4 events with higher event rates.** 169 events have been reported via GCN Notice in ER15 and O4, and the developed pipelines have been triggered by LVC NOTICE and processed CALET data, and enabled us to check many GW events. Also, we prepared a web page for quick-look analyses of CGBM [14] after we confirmed the quick-look analysis results.

Conclusion and Future Prospective

Although no candidate of EM counterparts was found in CALET data in O3 and O4, we will continue to search for EM counterparts of GW events in O4. In particular, we anticipate significant binary neutron star merger events in the CALET field of view. We are developing other pipelines to check CGBM data for events alerted by other GRB instruments (Fermi, Swift, INTEGRAL, KONUS, and MAXI) via GCN Notice to increase the possibility of detecting short GRBs associated with binary neutron star mergers.

Table 3 Summary of CALET observation in O3 (Purple) and O4 (Orange, significant only) [1, 2, 13]

Event ID	Possible Source	Time (T_0)	Coverage	CAL upper limit [erg cm^{-2} s^{-1}]	CGBM Observation	P_h
S230630bq	BBH (97%)	23:45:32	10%	1.5 x 10^{-3} (10 – 100 GeV)	No detection	82%
S230630am	BBH (98%)	12:58:06	40%	3.3 x 10^{-4} (10 – 100 GeV)	HV off	-
S230628ax	BBH (>99%)	23:12:00	0%	-	HV off	-
S230627c	NSBH (49%)	01:53:37	0%	-	No detection	100%
S230624av	BBH (95%)	11:31:03	0%	-	HV off	-
S230609u	BBH (96%)	06:49:58	5%	4.2 x 10^{-5} (1 – 10 GeV)	No detection	87%
S230608as	BBH (>99%)	20:50:47	50%	5.0 x 10^{-5} (1 – 10 GeV)	No detection	100%
S230606d	BBH (>99%)	00:43:05	0%	-	No detection	100%
S230605o	BBH (99%)	06:53:43	0%	-	No detection	69%
S230601bf	BBH (>99%)	22:41:34	15%	1.6 x 10^{-3} (10 – 100 GeV)	HV off	-
S230529ay	NSBH (62%)	18:15:00	15%	6.5 x 10^{-5} (10 – 100 GeV)	HV off	-
S230522n	BBH (99%)	15:30:33	5%	1.5 x 10^{-6} (10 – 100 GeV)	HV off	-
S230522a	BBH (>99%)	09:38:05	-	-	HV off	-
S230520ae	BBH (>99%)	22:48:42	10%	1.5 x 10^{-4} (1 – 10 GeV)	No detection	61%
S230518h	NSBH (86%)	12:59:08	0%	-	No detection	62%

Event ID	Possible Source	Time (T_0)	Coverage	CAL upper limit [erg cm^{-2} s^{-1}]	CGBM Observation	P_h
S200316bj	MassGap (>99 %)	21:57:56.157	0 %	Outside of the FOV	No detection	90%
S200311bg	BBH (>99 %)	11:58:53.398	0 %	Outside of the FOV	HV off	-
S200302c	BBH (89 %)	01:58:11.519	0 %	Outside of the FOV	No detection	81%
S200225q	BBH (96 %)	06:04:21.397	0 %	Outside of the FOV	HV off	-
S200224ca	BBH (>99 %)	22:22:34.406	95 %	9.0 x 10^{-7} (10 - 100 GeV)	HV off	-
S200219ac	BBH (96 %)	09:44:15.195	0 %	Outside of the FOV	No detection	71%
S200213t	BNS (63 %)	04:10:40.328	0 %	Outside of the FOV	No detection	18%
S200208q	BBH (>99 %)	13:01:17.991	0 %	Outside of the FOV	HV off	-
S200129m	BBH (>99 %)	06:54:58.435	5 %	4.8 x 10^{-4} (10 - 100 GeV)	HV off	-
S200128d	BBH (97 %)	02:20:11.903	5 %	4.5 x 10^{-6} (10 - 100 GeV)	No detection	60%
S200115j	MassGap (>99 %)	04:23:09.742	15 %	8.5 x 10^{-5} (10 - 100 GeV)	HV off	-
S200114f	-	02:08:18.239	85 %	1.2x10^{-5} (10 - 100 GeV)	HV off	-
S200112r	BBH (>99 %)	15:58:38.094	5 %	1.1x10^{-6} (10 - 100 GeV)	No detection	67%
S200105ae	Terrestrial (97 %)	16:24:26.057	45 %	3.1x10^{-5} (10 - 100 GeV)	No detection	67%
S191222n	BBH (>99 %)	03:35:37.119	0 %	Outside of the FOV	No detection	60%
S191216ap	BBH (>99 %)	21:33:38.473	0 %	Outside of the FOV	No detection	40%
S191215w	BBH (>99 %)	22:30:52.333	0 %	Outside of the FOV	No detection	83%
S191213g	BNS (77 %)	04:34:08.142	5 %	1.5x10^{-5} (1 - 10 GeV)	No detection	71%
S191205ah	NSBH (93 %)	21:52:08.569	0 %	Outside of the FOV	HV off	-
S191204r	BBH (>99 %)	17:15:26.092	0 %	Outside of the FOV	No detection	4%
S191129u	BBH (>99 %)	13:40:29.197	0 %	Outside of the FOV	No detection	70%

Event ID	Possible Source	Time (T_0)	Coverage	CAL upper limit [erg cm^{-2} s^{-1}]	CGBM Observation	P_h
S191109d	BBH (>99 %)	01:07:17.221	0 %	Outside of the FOV	HV off	-
S191105e	BBH (95 %)	14:35:21.933	0 %	Outside of the FOV	HV off	-
S190930t	NSBH (74 %)	14:34:07.685	0 %	Outside of the FOV	No detection	74%
S190930s	MassGap (95 %)	13:35:41.247	5 %	4.5x10^{-5} (10 - 100 GeV)	No detection	100%
S190924h	MassGap (> 99 %)	02:18:46.847	0 %	Outside of the FOV	HV off	-
S190923y	NSBH (68 %)	12:55:59.646	0 %	Outside of the FOV	No detection	68%
S190915ak	BBH (>99 %)	23:57:02.691	0 %	Outside of the FOV	No detection	100%
S190910h	BNS (61 %)	08:29:58.544	10 %	5.3x10^{-7} (1 - 10 GeV)	No detection	78%
S190910d	NSBH (98 %)	01:26:19.243	0 %	Outside of the FOV	No detection	77%
S190901ap	BNS (86 %)	23:31:01.838	5 %	2.8 x 10^{-5} (1 - 10 GeV)	No detection	82%
S190828l	BBH (>99 %)	06:55:09.887	0 %	Outside of the FOV	No detection	79%
S190828j	BBH (>99 %)	06:34:05.756	0 %	Outside of the FOV	No detection	28%
GBM-180816	sub-threshold	21:22:13.027	25 %	2.8x10^{-5} (10 - 100 GeV)	No detection	66%
S190814bv	NSBH (>99 %)	21:10:39.013	0 %	Outside of the FOV	HV off	-
S190728q	MassGap (52 %)	06:45:10.529	0 %	Outside of the FOV	Outside of the FOV	0%
S190727h	BBH (92 %)	06:03:33.986	0 %	Outside of the FOV	No detection	14%
S190720a	BBH (99 %)	00:08:36.704	0 %	Outside of the FOV	HV off	-
S190718y	Terrestrial (98 %)	14:35:12.068	10 %	1.2x10^{-5} (1-10GeV)	No detection	22%
S190707q	BBH (>99 %)	09:33:26.181	25%	3.8x10^{-6} (1-10 GeV)	No detection	76%
S190706ai	BBH (99 %)	22:26:41.345	0 %	Outside of the FOV	HV off	-
S190701ah	BBH (93 %)	20:33:06.578	0 %	Outside of the FOV	No detection	19%
S190630ag	BBH (94 %)	18:52:05.180	0 %	Outside of the FOV	HV off	-
S190602aq	BBH (>99 %)	17:59:27.089	0 %	Outside of the FOV	No detection	99%
S190521r	BBH (>99 %)	07:43:59.463	0 %	Outside of the FOV	HV off	-
S190521g	BBH (97 %)	03:02:29.447	30 %	7.4x10^{-7} (10-100 GeV)	HV off	-
S190519bj	BBH (96 %)	15:35:44.398	0 %	Outside of the FOV	No detection	100%
S190517h	BBH (98 %)	05:51:01.831	0 %	Outside of the FOV	No detection	86%
S190513bm	BBH (94 %)	20:54:28.747	15 %	4.5x10^{-5} (1-10 GeV)	No detection	100%
S190512at	BBH (99 %)	18:07:14.422	0 %	Outside of the FOV	No detection	100%
S190510g	Terrestrial (58 %)	02:59:39.292	0 %	Outside of the FOV	No detection	16%
S190503bf	BBH (96 %)	18:54:04.294	25 %	7.1 x 10^{-5} (10-100 GeV)	HV off	-
S190426c	Terrestrial (58 %)	15:21:55.337	10 %	9.2 x 10^{-6} (10-100 GeV)	HV off	-
S190425z	BNS (>99 %)	08:18:05.017	10 %	8.5 x 10^{-5} (10-100 GeV)	HV off	-
S190421ar	BBH (97 %)	21:38:56.251	0 %	Outside of the FOV	Outside of the FOV	0%
S190412m *	BBH (>99 %)	05:30:44.166	-	HV off	HV off	-
S190408an	BBH (>99 %)	18:18:02.288	95 %	3.0 x 10^{-7} (1-10 GeV)	No detection	100%

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