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TAIGA-IACT telescopes for the Multi-Messenger observations

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In the era of multi-messenger astronomy it is extremely important to obtain data from many instruments to get the most complete information about transient and short-lasting phenomena. The TAIGA observatory has also started observations in multi-messenger regime. The TAIGA observatory is a hybrid detector complex for high-energy gamma-ray astronomy and cosmic ray physics that combines the detection of extensive air showers with different detector systems: timing array TAIGA-HiSCORE, scintillation array TAIGA-Muon and imaging atmospheric Cherenkov telescopes of the TAIGA-IACT installation. The General Coordinates Network (GCN), that distributes online alerts from different instruments around the world, makes it possible to observe GRBs with TAIGA-IACTs to search for very high energy gamma-quanta. This work presents the current status of the TAIGA-IACT telescope control and alert system for GRB observations as well as its performance.

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1. Introduction

TAIGA (Tunka Advanced Instrument for Gamma-ray and cosmic ray Astrophysics) is a hybrid installation designed to address gamma-ray astronomy at energies from a few TeV to several PeV, cosmic ray physics from 10 TeV to several EeV, as well as for search for axion-like particles, Lorentz violations and another evidence of New Physics[1–4]. The key idea of the TAIGA experiment is to combine the detection of extensive air shower (EAS) with different detector systems: timing wide-angle Cherenkov array, scintillation detectors and imaging atmospheric Cherenkov telescopes (IACTs). The timing Cherenkov array allows ones to determine the main parameters of an EAS: a shower axis direction, a core position and energy, while IACTs can be used for the cosmic-ray background suppression. The current 1 km^2 TAIGA installation consists of 120 TAIGA-HiSCORE wide-angle Cherenkov stations, three Imaging Atmospheric Cherenkov Telescopes (IACT) and 250 m^2 of scintillation particle detectors of Tunka-Grande and TAIGA-MUON [5] arrays. The number of IACTs on the site will be soon increased up to 5. The installation is located near lake Baikal in Tunka valley, Siberia, Russia at an altitude of 675 m above the sea level (51°48′35′′ N, 103°4′2′′E) on the site, where the Tunka-133[6] installation is deployed.

Detection of the TeV energy gamma-rays from gamma-ray bursts (GRBs) are one of the main targets for current and next generation Imaging Atmospheric Cherenkov Telescopes (IACTs). Its observations is challenging for IACTs, as they have a narrow field of view. Following up observations of GRBs by IACT telescopes is possible due to wide-angle detectors that provide trigger to narrow field of view instruments. Experiments as MAGIC[7], H.E.S.S.[8], VERITAS[9] have pioneered the ground-based very high energy (VHE) GRB observations with IACTs and have detected several ones up to TeV energies. The relatively recently installed Large Size Telescope prototype of CTA project has also started its GRB follow up program[10]. Detection of TeV energy gamma-quanta from GRB is a critical task for understanding the processes of their formation and is possible for GRBs with a small red shift. The brightest one is GRB 221009A ($z = 0.151$), also detected by LHAASO collaboration [11] where they detected more than 64, 000 photons above 0.2 TeV up to 18 TeV. Even 251 TeV gamma-like event was detected by Carpet-2 array form this GRB[12]. Thus, the observation of GRBs by the IACT telescopes of the TAIGA experiment is an extremely important task. GRB following up is possible thanks to GCN[1] (General Coordinates Network), that distributes real-time alerts containing information about possible GRB/GW/neutrinos from different experiments. This work presents our first steps to the multi-messenger observations with the TAIGA-IACT telescopes and the current status of the control and alert system.

2. TAIGA-IACT telescopes

The TAIGA-IACT telescopes are imaging atmospheric Cherenkov telescopes with alt-azimuth mount and 4.3 m diameter Davis-Cotton design reflector. The focal length of the telescope is 4.75 m. In the focus of the telescope a camera based on photomultiplier tubes (PMTs) is installed. Each PMT is equipped with a Winston cone to increase the light collection area. The field of view of the camera is 9.6° and its pixel resolution is 0.36°. The detailed description of TAIGA-IACT camera

[1] https://gcn.nasa.gov

and data acquisition system is presented in [2]. The TAIGA-IACT telescope pointing accuracy is of about 0.02°[13].

The energy threshold of a TAIGA-IACT telescope is about 2-3 TeV, depending on the zenith angle at which the gamma-ray source is visible. At energies above 10 TeV, it becomes possible to use the stereoscopic approach: EASs from gamma-rays are detected by two or more telescopes [14]. At energies above 40 TeV, a new hybrid approach to gamma-ray detection becomes possible – registration of EASs both by TAIGA-IACT telescopes and by the TAIGA-HiSCORE installation[15]. During a gamma-source observation TAIGA-IACT telescopes operate in wobble mode[16]. In this mode the position of a gamma-ray source on the TAIGA-IACT camera is not in its center but shifted by 1.2°. The direction of the shift is changed every 20 min[17]. This procedure makes it possible to estimate the background of cosmic-rays from the same data set and in the same conditions as the signal from the gamma-ray source. The results of analysis of the Crab Nebula data can be found in [18–21].

2.1 Drive system

Each axis is rotated by hybrid stepper motors Phytron ZSH107/4.200.12,5 through 2 gearboxes with total gear ratio of 2000. The maximum allowable motor speed is 2000 rpm, which corresponds to the movement of the telescope at a speed of $6\,^{\circ}\,\mathrm{s}^{-1}$. Two limit switches are installed on each axis, allowing the drive system controller to stop the telescope if it goes beyond the permissible angles. For the azimuth axis, in addition to the limit switches, a locking mechanism is provided that limits the rotation of the axis, and in the event of an emergency, it will prevent the breakage of the cable installed inside the cable channel of the azimuth axis. This locking mechanism allows the azimuthal axis to rotate in the range $[-60°, 360°]$, counting the angle from north to east. The position of the axis is readout by absolute 17-bit shaft encoders with a resolution of about $10''$. To minimize the backlash of the worm gear, a special system of counterweights is installed on the telescope. The maximum speed of stable operation of the drives, obtained experimentally, is $4.5\,^{\circ}\,\mathrm{s}^{-1}$, which is limited due to the decrease in the torque of stepper motors at high speeds. The value $0.5\,^{\circ}\,\mathrm{s}^{-2}$ is used for telescope axis acceleration.

3. TAIGA-IACT control and automation software

The telescope control software is developed using EPICS[2] (Experimental Physics and Industrial Control System). It provides access to telescope subsystems over Cannel Access (CA) protocol, including drive control, CCD and data acquisition control, auxiliary systems[13]. Until November 2022, the configuration and launch of tasks for observing gamma-ray sources and calibration measurements were performed by telescope operators through the interface developed using EPICS Qt framework.

[2]https://epics-controls.org

3.1 Observation planner

To optimize the effective operation time of the telescopes a special program for the observation planning was developed. The software is developed using the django[3] framework and PostgreSQL[4] database management system. Thus it has a web interface. It is possible to add tasks both for observing regular gamma-ray sources and tasks for calibration procedures.

Each task in the observation planner has its own priority and can be assigned to all or to a specific telescope. Tasks with a higher priority will stop a task with a lower priority if it is currently running. A task with a specified telescope has a higher priority than a task with the same priority value but scheduled for all telescopes. The ability to complete tasks is calculated based on the positions of the sun, the moon and the source. For tasks with equal priorities, the current position of the telescope is taken into account (with equal priority, a task is issued for which the telescope needs less time to redirect). To make it clear to the operator in what order the tasks will be performed, the system implements the possibility of discrete-event simulation of task execution.

To provide access to the observation planner for other components of the system, as well as the calculation and receipt of the current task, taking into account priorities, a REST API has been implemented, available via HTTPS in json format. It also includes functions to notify the system when tasks start and finish. Access to the API is provided only for the user authorized through a token. As an algorithm for calculating which task should be performed at the current time, the same one is used as in discrete-event simulation of task execution.

3.2 Alert system and GCN monitor

GRB alert notifications (called GCN Notices) come to the system through GCN Kafka to the TAIGA GCN monitor program (see figure 1). The RA and Dec coordinates, error radius and other information are extracted from these GCN notices. If the source with the obtained RA and Dec coordinates can be observed within 3 days after the trigger time (i.e. if there is such a period of time within 3 days where the zenith angle of direction to the GRB is less than 50°, the sun is below the horizon by 15.5°, and the moon is below 0°), then a separate group of users (responsible for alert analysis) receives a notification by e-mail and telegram, and the corresponding record appears in the database. Authorized users have access to database records through the web interface. The GCN Monitor program collects information from notifications and automatically updates the RA, Dec coordinates in case of a notification with a smaller error radius.

If, after a GCN notice arrives, the error radius of the GRB becomes less than 2° and this GRB can be observed, then the task of observing this GRB is automatically added to the observation planner with a higher priority than regular sources and the telescopes will automatically receive the task to observe this GRB. Since a high gamma-ray flux is expected mainly at the beginning of the burst, the system automatically adds the task of observing the GRB for 1 hour. Planning a longer observation, re-observation or observation with an error radius of more than 2° degrees is possible by the operator / responsible employees through the web interface on the page of the corresponding GRB.

[3]https://www.djangoproject.com
[4]https://www.postgresql.org

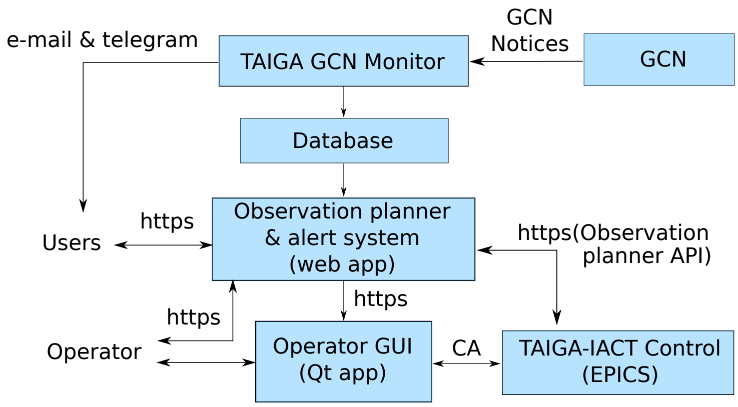

Figure 1: Diagram of the interaction between the telescope control system, the observation planner and TAIGA GCN monitor.

4. TAIGA-IACT telescope redirection performance

The procedure for stopping a tracking and camera data acquisition, as well as performing the necessary calculations and configuring the next tracking, from the moment a new task is received (implementation of spring 2023), takes about 12 s. Restarting the camera data acquisition system takes at least 25 s, but is performed in parallel. So a minimum redirection and restarting time is approximately 25 s, while redirection and restarting, if a complete 360° rotation is required, will take about 100 s. Taking into account the above and the ranges of working azimuth angles of the telescope from −50° to 350°, distribution functions of the redirection and restarting time are obtained for different velocities under the assumption of uniform current azimuth and zenith angles of the telescope and directions for a new task. These distribution functions are shown in figure 2. For a speed of 4.5 ° s^{-1}, the expectation is 55 s, and the 95th percentile is 92 s. These estimates are valid for the operation of the system after updates made in the spring of 2023.

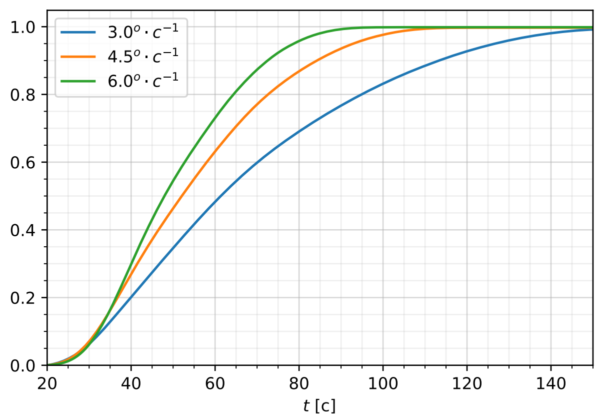

Figure 2: Probability distribution functions of the redirection and restarting time of TAIGA-IACT telescopes for different speeds of the azimuth axis.

5. The first GRB observations

The deployment and first adjustment of the automatic GRB follow up system based on GCN notices for the TAIGA-IACT telescopes were performed in December 2022. Since this time several updates and optimizations were carried out. Priority for our observations are long gamma-ray bursts (supernova with core collapse) with a very high gamma-ray intensity according to space observatories (possibly a nearby gamma-ray burst). During the period since December 2022 until summer 2023 the TAIGA GCN monitor program processed notices[5] from FERMI GBM[22], FERMI LAT[23] and SWIFT BAT[24] instruments. In this period 5 observations of real alerts were performed (three of which were issued automatically by the system):

1. *Radio galaxy NGC 1275.* On December 21, 2022, at 22:29 UT, telegram [25] was published, which reported an increase in the gamma-ray flux for energies >0.1 TeV from the radio galaxy NGC 1275 ($z = 0.0175$) according to the data of the LST telescope of CTA project with a significance of more than 10σ, a telegram [26] from the MAGIC experiment about a signal at a level of 30σ for 2 hours of observations and later from the MACE telescope [27]. In the period from 22 to 24 December, the meteorological conditions did not allow observations due to overcast clouds and snowfall. On the night of December 25, 2022, the task for observing of NGC 1275 was manually entered and the telescopes performed observations of the galaxy NGC 1275.

2. *Long GRB 221226A.* At T_0 = 2022-12-26 16:44:27 UT Fermi-GBM issued a trigger for a long GRB with an error of 5.82°, and after T_0 + 9.3 min, the position uncertainty was 1.2° according to telegram[6]. On this date, one of the conditions for automatic GRB observation was an error of less than 1° and at T_0 + 53 min an operator manually issued a task to observe GRB 221226A with the TAIGA-IACT telescopes. The previous observation task was stopped and observation of the GRB was performed within 1 hour.

3. *Long GRB 230116E*[7]. Fermi-GBM issued a trigger[8] at T_0 = 2023-01-16 13:48:15 UT for a long two-peak GRB. After T_0 + 27 min 15 s, the value of the error of the position of the GRB dropped to 1.41°. The height of the GRB direction at that time was 42° above the installation. At T_0 + 27 min 52 s, the task for observing the GRB was automatically issued, and at T_0 + 30 min 55 s, the TAIGA-IACT telescopes began data acquisition for 1 hour.

4. *Flare from the Be/X-ray binary pulsar LS V +44 17.* The telescope of the Swift-BAT space observatory at T_0 = 2023-01-26 11:53:14 UT issued a trigger[9] from a pulsar flare in the Be/X-ray binary system LS V +44 17. At this moment, the altitude of the source for TAIGA-IACT was 72.7°, but the moon was above the installation. The observation task was issued automatically, and with the onset of dark time, the TAIGA-IACT telescopes automatically started data acquisition at T_0 + 4 hour with a duration of 1 h. In the X-ray range, the flare

[5] https://gcn.nasa.gov/notices
[6] https://gcn.gsfc.nasa.gov/other/221226A.gcn3
[7] https://user-web.icecube.wisc.edu/ grbweb_public/Individual_GRB_webpages/GRB230116E*.html
[8] https://gcn.gsfc.nasa.gov/other/695569700.fermi
[9] https://gcn.gsfc.nasa.gov/other/1150965.swift

lasted about 2 months. The VERITAS collaboration conducted 10.5 hours of observations from January 24, 2023 to January 27, 2023, and no signal was found at the LS V +44 17 position for energies above 0.2 TeV.

5. *Long GRB 230321B*. Fermi-GBM at T_0 = 2023-03-21 02:24:09 UT triggered a long GRB[10]. The position error was 1°. With the onset of night at T_0 + 10 h 35 min, the TAIGA-IACT telescopes automatically started data acquisition for 1 hour.

Processing of the obtained data is continuing.

6. Conclusion

For the multi-messenger observations with the TAIGA-IACT telescopes several additional components of the control system were developed. Their first version was included in the installation operation in December 2022, after that a number of updates were carried out. The expected time to point the telescopes to GRB for the described configuration should be up to 100 seconds after a GCN Notice with enough localization accuracy arrived. Since December 2022 several observations of GRB were performed. For the next steps it is planned to perform additional optimization of the software performance, VHE GRB search strategy, as well as including search of VHE gamma from neutrinos and gravitational wave alerts.

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PoS(ICRC2023)939