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First results of the tracking system calibration of the TAIGA-IACT telescope

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Abstract. In TAIGA Observatory (Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy) we are commissioning the first Imaging Atmospheric Cherenkov Telescope (IACT). The telescope has an alt-azimuth mount and 17-bit shaft encoder for each axis, stepper motors are used for axis control. For the pointing calibration of the telescope a CCD-camera is installed on the dish of the telescope and its position allows to capture



simultaneously both the Cherenkov camera with LEDs and the sky with observed source. Since October 2017, the telescope has been operating in tracking mode. In this work the TAIGA-IACT telescope pointing calibration approach and first results of the tracking operations are described.

1. Introduction

The TAIGA observatory [1] (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) is located in the Tunka valley at a distance of 50 km from Lake Baikal and is developed to solve problems of high energy gamma-ray astronomy and cosmic-ray physics. This unique complex system of ground-based detectors is designed to detect extensive air showers (EAS) generated by high-energy gamma-quanta and cosmic-ray particles. The TAIGA observatory facility consists of various detectors, including wide-angle detectors of Cherenkov radiation, radio-antennas, detectors of electrons and muons of EAS [2]. In addition, the TAIGA-IACT (Imaging Atmospheric Cherenkov Telescope) is installed in Tunka valley and it has been operating in tracking mode since October 2017. It is planned to install more IACT telescopes by 2019 [3]. In contrast to other methods, IACT technique provides a robust separation of hadron and gamma showers by their image of Cherenkov radiation [4]. For the correct operation of the TAIGA-IACT telescope the high pointing and tracking accuracy for long exposure time is required.

2. The TAIGA-IACT telescope hardware

The first TAIGA-IACT telescope (see Figure 1) is installed near the TAIGA facility center. It has an alt-azimuth mount and a camera in the focus of the segmented Davis-Cotton design reflector with diameter of 4.3 m. The camera consists of 560 photomultiplier tubes (PMTs) each in a Winston cone and has a field of view of 9.5° (0.36° per pixel). On the camera of the telescope 8 positioning LEDs are installed along the perimeter to determine the position of the camera by the CCD-camera.

The CCD-camera Prosilica GC1380 installed at a distance of 1 m from the telescope optical axis on the dish near the mirrors. The position of the CCD-camera allows us capturing on the same image the sky with the observed source and the telescope camera with the positioning LEDs (see Figure 2). The CCD-camera is used to determine the telescope pointing direction by its images. It has 1360×1024 pixels resolution and $31.4^\circ \times 23.6^\circ$ field of view, i.e. 83 arc-second per pixel.

Each axis of the telescope is equipped with a Phytron hybrid stepper motor, a 17-bit shaft encoder and limit switches connected to the PhyMOTION control unit. Taking into account the gear ratio the telescope the axes rotate by $9 \cdot 10^{-4}$ degree per 1 full step of the motor. The control unit supports micro-step mode that is set up to 1/20 value to perform smooth tracking.

The telescope hardware is connected to the TAIGA data acquisition (DAQ) center over the Ethernet and can be controlled remotely.

3. The telescope software

As framework for the software development of the TAIGA-IACT telescope pointing and control system EPICS software tools are used [5]. The main control software runs on the computer in the DAQ center. For remote operation of the telescope, a graphical user interface based on the EPICS Qt Framework was developed.



Figure 1. The TAIGA-IACt telescope located in the Tunka valley. The telescope is on the parking position and directed to the north.

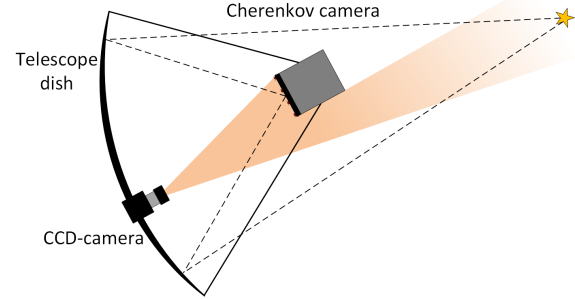


Figure 2. CCD-camera field of view that allow capturing both the telescope camera with the positioning LEDs and the observed source.

3.1. Telescope tracking software

The drive system control software uses the appropriate drivers for the motor controller. The observed source trajectory in horizontal coordinate system is calculated with 1 second step using the SOFA software[6]. After that, to transform trajectory to the telescope's coordinate system, a pointing model is applied and the result is loaded to the driver, where the trajectory is interpolated using cubic splines. To provide smooth and accurate tracking the driver controls velocity of the motors with feedback from the shaft encoders. Applying a corrections to the trajectory, while the telescope is moving, is allowed.

3.2. CCD-camera images processing

For accurate determination of the telescope position, CCD-camera images are used. Images from the CCD-camera (see Figure 3) are divided into two regions: the camera region and the sky region.

From the sky region the positions of all sources are extracted using SExtractor software [7]. Then WCS (World Coordinate System) parameters for this region are determined by Astrometry.net software [8], using astronomical catalogue Tycho-2 [9].

The LED positions are extracted from the camera region. The position of an LED is estimated as the center of gravity of its light distribution taking into account pixels that exceeded the established threshold above the background. The position of the camera is calculated as mean offset of LEDs from their reference position plus reference camera position.

For the telescope pointing direction determination the position of the central pixel of the camera is transformed to the sky region. The central pixel coordinates are transformed to the LED coordinate system and then to the sky region. To transform a point from LED coordinate system to the sky region, a linear regression model depending on source position, altitude and camera position is used.

The calculated telescope direction can be used for offline analysis or for on-the-fly corrections of the tracking trajectory. An on-the-fly correction algorithm was used for the TAIGA-IACt telescope operation in 2017-2018 observation season.

4. CCD-camera calibration

All transformation parameters and reference points must be determined for telescope pointing direction calculations. This includes the following measurements:

- (i) reference positions of LEDs and camera;
- (ii) parameters of transformation between focal plane and LED coordinate system;
- (iii) parameters of transformation between LED coordinate system and the sky region.

In order to determine the reference positions and the transformation between focal plane and LED coordinate system, measurements are performed, that are started in twilight with open camera lid and switched-on positioning LEDs, so LEDs and Winston cones can be seen on the images. The positions of the Winston cones can be determined using the convectional template matching (as shown in Figure 4) and are used to determine the parameters of the transformation.

The white screen in the focus of the telescope optical system is installed (see Figure 3) to determine the parameters of the transformation between LED coordinate system and the sky region. To perform these measurements the telescope tracks a number of bright sources at different elevations. For each source several images are taken with different offsets from the camera center to scan the central region of the focal plane.

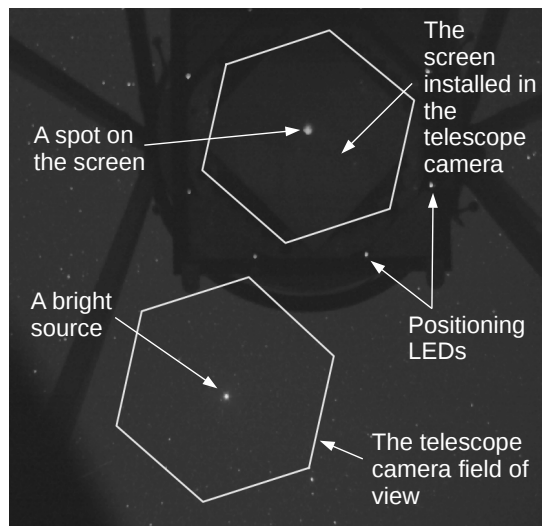


Figure 3. A CCD-camera image during calibration. On the one image we see the telescope camera with positioning LEDs and the tracked source. The white hexagons show the telescope camera PMTs region and field of view.

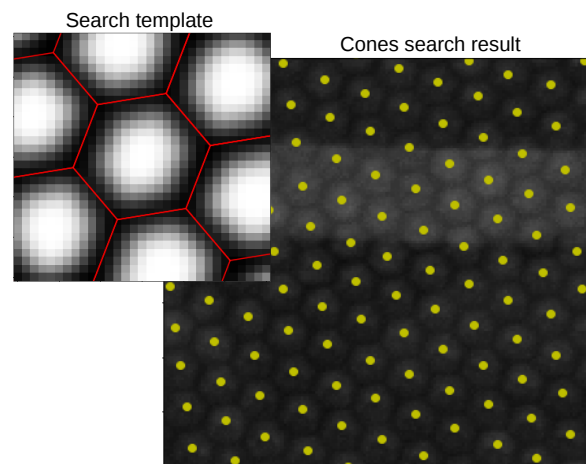


Figure 4. An example of result of the Winston cone detection algorithm. In the left upper corner the search template is shown. Detected positions of the Winston cones with PMTs are shown by dots on the right image. The performance of the algorithm should be better then one CCD-camera pixel.

On the obtained images, the positions of LEDs, of the bright source in the sky region and the spot on the screen are extracted. The parameters of linear regression model for transformation between LED coordinate system and the sky region are fitted using these data. The model also depends on telescope elevation (deformation of the construction caused by gravitation) and camera position on the image (small CCD-camera shifts).

5. The telescope tracking during the season

After the installation of the shaft encoder on the axis in September 2017, the commissioning of the TAIGA-IACT telescope tracking system was started and first source observations in tracking mode were performed in October 2017. This mode is tracking with feedback from the shaft encoders and applying a telescope pointing model. It is the standard approach for IACT

telescope operation in other experiments [10, 11, 12]. Unfortunately, after a month of telescope operation it became clear that due to technical problems related to hardware this approach did not allow to achieve sufficient accuracy for this season.

The solution was to apply telescope trajectory corrections which are calculated on-the-fly using the CCD-camera images. Since January 2018 this approach with double feedback from the shaft encoders and the CCD-camera was in operate. An example of the online tracking errors using this approach is shown in Figure 5. This plot shows that tracking precision can be quite accurate (better then 0.01° , except for some positions, where errors are caused by the backlash of the axis). Also telescope pointing precision is assuming be quite accurate in condition of a correct CCD-camera calibration.

The first model of transformation between the LED coordinate system and the sky region didn't take into account CCD-camera shifts, since the measured offsets of the positioning LEDs didn't exceed 0.02 degrees in the beginning [13]. Further study of the deviations showed the need to take into account the displacement of the CCD-camera. The maximum deviation was observed at extremely low temperatures $< -40^\circ\text{C}$ (see Figure 6).

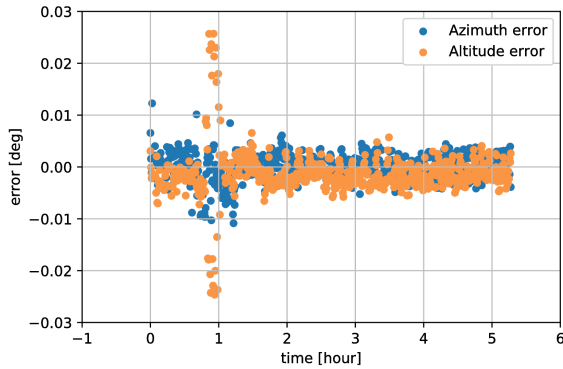


Figure 5. An example of double feedback telescope operation in 13 February 2018. Tracking errors are calculated on-the-fly by the CCD-camera image processing algorithm. The source was tracked for 5 hours. The maximum deviation from target trajectory was during the culmination of the observed source. It is caused by backlash of the drive system.

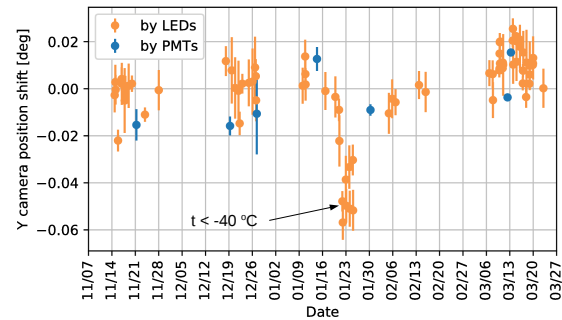


Figure 6. The offsets of telescope camera positions on CCD-camera images from reference position. The maximum deviation was observed at temperature $< -40^\circ\text{C}$. Blue points were measured by Winston cone detection algorithm. Orange points were measured by positioning LEDs.

At the end of February a test was conducted, which showed that the transformation parameters for the CCD-camera are not accurate enough. The test consisted in measuring the anode current on the central PMT that was measured for various offsets of the source. The idea of this experiment is similar to the approach that was used for the HERA telescope calibration [14], but the position of a bright source on the CCD image instead of the encoders was used to test the calibration. The difference of the position of the central pixel for a previous CCD-camera calibration and the current test was up to 0.09° . Using this fact, a correction for the telescope CCD-camera calibration was applied for the March measurements. In April the CCD-camera was calibrated again taking into account these effects and the new calibration was applied also to previous data for offline analysis. The difference between the new CCD-camera calibration and the current test were less then 0.04° . After obtaining the new CCD-calibration in April, all telescope tracking data was reprocessed. The maximal telescope tracking error for the observations in March, corrected by this procedure, was found to be 0.05° .

6. Conclusion

During the 2017-2018 season the TAIGA-IACT telescope operated in tracking mode and a approach with double feedback from the shaft encoders and the CCD-camera was used. Instead of the standard technique this approach was used in cause of technical problems which are taken into account for future operations. The telescope pointing accuracy was better 0.05° in March for the observations (mostly Mrk 421) with corrected calibrations and two times worse for the other observations in the season (Crab Nebula and Mrk 421). The analysis of the telescope camera data is presented in [15]. Pointing accuracy for the upcoming season is expected to be better than 0.05° .

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