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MACE CAMERA ELECTRONICS: CONTROL, MONITORING & SAFETY MECHANISMS

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Abstract

MACE Telescope installed in Ladakh Region of India comprises of many functionally diverse subsystems, Camera being the most important one. Mounted at the focal plane of 21 m diameter parabolic reflector dish, event driven Camera system comprises of 1088 PMTs, with 16 PMTs constituting one Camera Integrated Module (CIM). Central Camera Controller (CCC), located in Camera housing, manages and coordinates all the actions of these 68 Modules and other camera subsystems as per the command sequence received from Operator Console. In addition to control and monitoring of subsystems, various mechanisms have been implemented in hardware as well as embedded firmware of CCC and CIM to provide safety of PMTs against exposure to ambient bright light, bright star masking and detection and recovery from loss of event synchronization at runtime. An adequate command response protocol with fault tolerant behaviour has also been designed to meet performance requirements. The paper presents the overall architecture and flow of camera control mechanisms with a focus on software and hardware challenges involved. Various experimental performance parameters and results will be presented.

INTRODUCTION

The MACE Telescope is a 21m diameter gamma ray telescope installed at Hanle in Ladakh, India at an altitude of 4270m above sea level, the highest for any Imaging Atmospheric Cherenkov Telescopes (IACT) based telescope. Primary objective of such IACT's is to detect High energy cosmic gamma rays emanating from various galactic and extragalactic sources. MACE Telescope detects very faint and narrow (5-10 nS) Cherenkov light generated by Extensive Air Shower when High Energy Gamma rays (20 GeV – 10 TeV) interact in the earth's atmosphere. The Imaging Camera is an essential subsystem of the Huge Telescope system and has been designed with state-of-the-art technologies for High Speed Data acquisition within the constraints of space, weight and power in such a way that the entire electronics for analog signal processing, digitization, triggering and event building is fully integrated into the camera body. Only Power supply and Network cables are connected between Ground station and Camera. Control and monitoring aspects of highly compact camera electronics is discussed in the current paper. Figure 1 presents the latest photograph of MACE Telescope during observation.

Figure 2 describes the block diagram of various subsystems of Camera Electronics. Second level trigger Generator (SLTG) detects time-space coincidence across nearby pixels in trigger regions based on the first level Trigger information from various CIMs and generates system-wide Trigger signal. After receiving the Trigger signal, CIMs start acquisition and send event data to the Data Concentrator (DC). Efficient data processing algorithms [1] have been implemented in CIM and accumulated charge data for each pixel along with profile of hit pixels is formed in the CIM data packets. DC collects these data packets from all the CIMs and prepares camera event packets. Event data from camera is sent via 1 Gbps Ethernet link to the Ground station. The co-ordination, control and monitoring of various subsystems in a reliably deterministic manner is a challenging task.

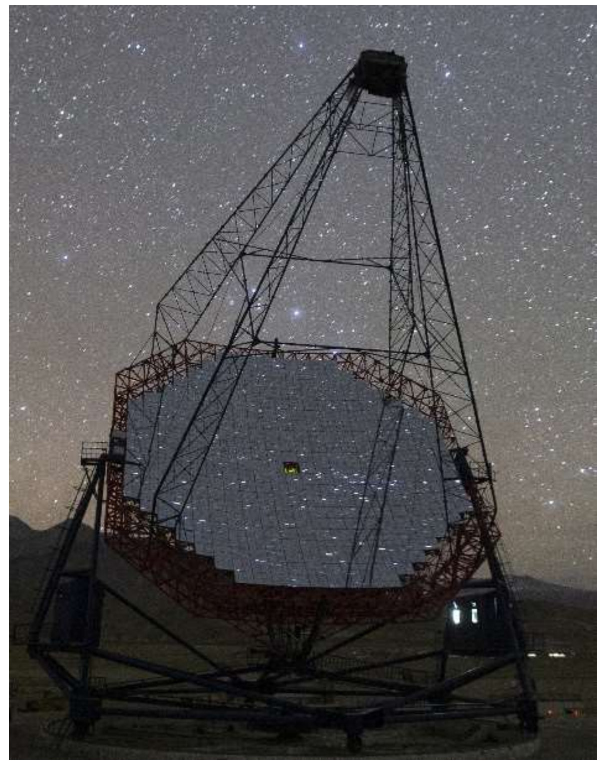

Figure 1: MACE Telescope during observation.

Other subsystems which are part of the camera electronics are Lid Controller, Temperature monitoring system and LED/Sky Calibration system.

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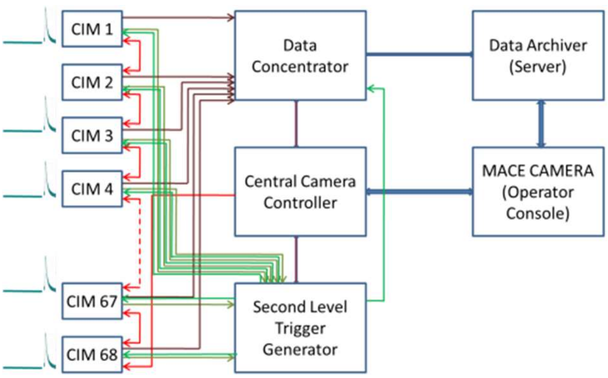

Figure 2: MACE Camera block diagram.

MACE CAMERA CONTROL SYSTEM ARCHITECTURE

Requirements of the System

The main requirements of MACE Camera Control system is to set system configuration, monitor operating parameters, coordinate all functions through command/ response protocol and take corrective / recovery action to ensure safe and stable operating conditions during a sky observation.

The settable configuration parameters include pixel related settings like Bias voltage, Discrimination Threshold etc. within CIM. For STLG the configuration includes Trigger Configuration, Trigger mode etc. and for DC it includes Acquisition mode, Active data modules etc. The operating parameters such as Anode Current (AC), Single Channel Rate (SCR) etc. that indicate light seen by the PMTs are monitored at higher rate of 5sec to ensure corrective action to limit exposure of PMTs to excessive light. Set parameters such as PMT Bias Voltage (HV), Temperature, Power Supply Status etc. are monitored at 1min to ensure stable operating conditions.

Other operation involves Lid controller to safe and reliable shutter open/close based on the command from ground station and Temperature monitoring to monitor temperature at different locations inside the camera.

Hardware Implementation of the System

Each Camera Integrated Module (CIM) contains programmable HV generation module, Pre-Amplifiers, Amplifiers, Pulse discriminators, Scalar counters for individual channels [2]. Each module also houses First Level Trigger generators, scalar counters and Digitization circuits. Extensive Data acquisition, Control and monitoring analysis has been carried out on CIM modules [3]. All these 68 Modules and other subsystems are controlled by Central Camera Controller (CCC) [4]. CCC receives control commands from ground station over Ethernet and accordingly controls various subsystems of Camera Electronics and transmits regular Health monitoring information to the ground station.

Camera Shutter open/close mechanism is also implemented in CCC embedded software as well as FPGA firmware. Two shutters (2m x 1m each) are moved by DC Brushless motors, which are controlled by CCC FPGA firmware in Voltage control mode. It regularly checks for various limit switches and varies the speed of motor to optimize the time to open/close. Various failsafe mechanisms are implemented in firmware to avoid deadlock condition. There is also a mode to operate shutters manually during maintenance schedule. Figure 3 shows the rear view of MACE Camera Electronics.

There are two control links between CCC and CIM modules, which are connected in multi-drop topology. First control link, based on RS485 standard, is used to sense the status of Input power supplies to CIM and accordingly

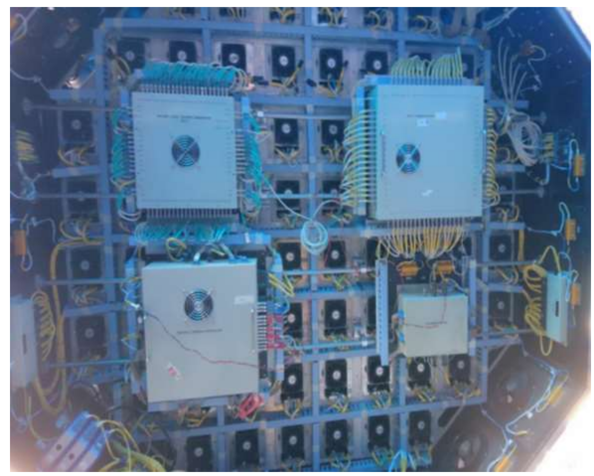

Figure 3: Rear view of MACE Camera Electronics.

Switch ON/OFF of CIMs can be performed. CIMs can be reset using this link. This link is used for sequential powering of CIMs, which reduces sudden power surge associated with powering of all CIMs together. Second control link is based on I2C protocol and it is used to control overall functioning of CIM module including individual channel HV values, Discrimination threshold for each channel, First level Trigger logic modes, Digitization modes etc. This link is also used to collect and send health parameters of the CIM including HV read back value, Anode current, Discrimination Threshold read back, Scalars of various input channels, readings of 5 temperature sensors inside CIM etc. I2C bus operates at 100 kbps speed. Local microcontroller firmware controls various functions of the CIM. Detailed description of the firmware is given in the next section. The control link between CCC and Data Concentrator is RS-232, operating at 115200-baud rate; through this link, DC is set into proper mode of operation and various status flags are read at regular interval. Control link between CCC and SLTG is based on SPI Interface operating at 1 MHz clock; through which SLTG is set into particular operation mode and various status flags are read at regular interval. Figure 4 describes the block diagram of various control links.

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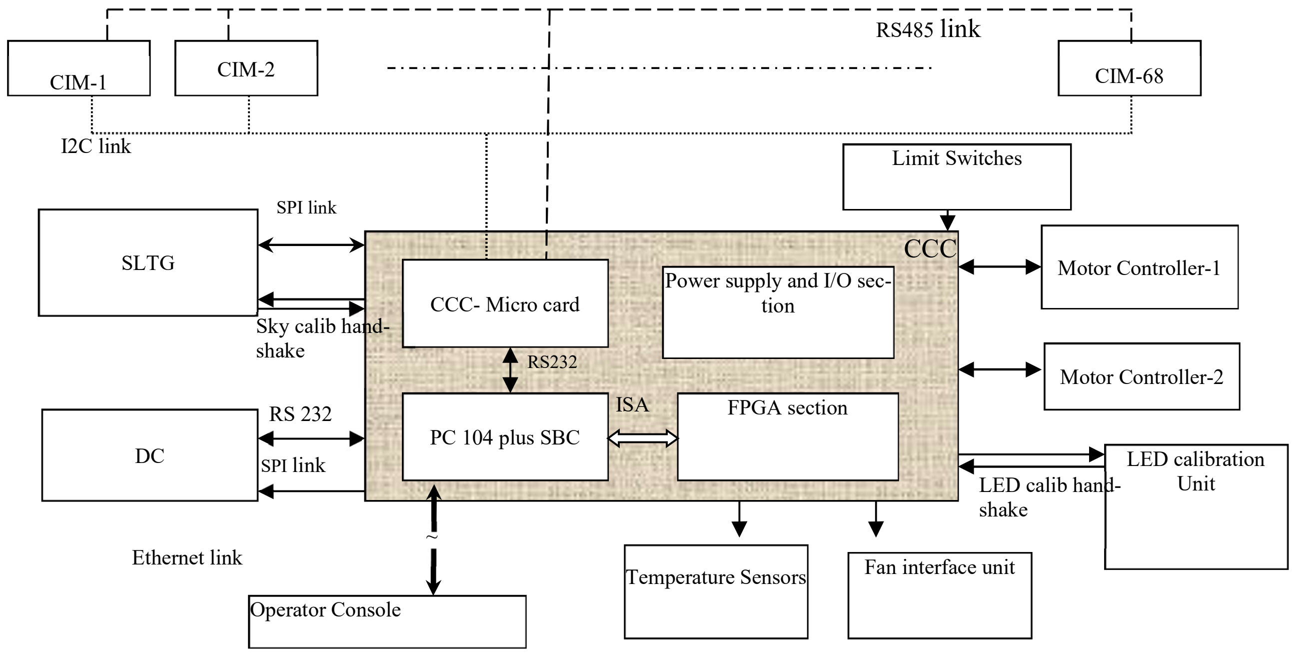

Figure 4: Control and monitoring system of MACE Camera.

Software Implementation

For control and monitoring of various subsystems and to provide overall safety of MACE Camera, embedded firmware of CCC and CIM plays an important role.

Each CIM has a controller card, referred to as LTC Micro board, which controls various functions of CIMs. It monitors telemetry parameters of the CIM like Anode Current, SCR, HV, DT, board temperature etc. Additional functions of control of PMT HV bias and LVDS link for event data transmission to data concentrator and sequential powering up of camera electronics are also performed. The LTC Micro module communicates with CCC on a multi-drop, differential I2C network with CCC acting as master and CIM as slave. System and experimental configuration settings are received upon initialization of the CIM. Post configuration, different telemetry parameters are acquired from the CIM at regular intervals on request- response basis.

The Microcontroller firmware is designed to be multitasking in order to effectively monitor the critical parameters of CIM and to service asynchronous telemetry data requests and other commands from the CCC. Periodically, CIM parameters of HV, DT, AC and SCR are acquired from the respective hardware modules. A correction algorithm is run on the acquired data, which analyses the current data with set limits for each parameter from the pre-loaded configuration. The algorithm iteratively evaluates and sets each pixel's state based on the current value of monitored parameter. Based on the algorithm, a pixel identified to be persistently in an abnormal state for a set duration is permanently disabled to safeguard the PMT. Concurrently, a dedicated task responds to commands from CCC.

ISR for controlling I2C operations has been designed and exhaustively tested to handle all conditions of the bus state [5]. However, in situations where the CIM becomes unresponsive over the I2C network, a RESET command from CCC can be sent over an auxiliary link to reset the microcontroller to its initial state.

Central Camera Controller (CCC) is the central entity that manages and coordinates all the actions of the camera. The CCC interfaces with the subsystems for control, configuration, monitoring, error handling, and recovery to ensure that fault tolerant and reliable observations are obtained. CCC software has a layered architecture consisting of Managers dedicated for specific functionality at each level, which interact among themselves through event notifications. The top layer consists of important modules like Command Parser, Telemetry Manager, Sky Calibration Manager and Sync Loss Manager for carrying out dedicated functionalities like managing actions on Camera subsystems by parsing the command received from MACE OC, and serializing the final response to MACE OC after execution; periodic health monitoring of CIMs, collection of diagnostics information from all the subsystems and sending them to OC; facilitating the sky calibration cycles during data acquisition; and error handling and recovery of Camera during event data acquisition from synchronization errors. Managers at top layer uses the lower level Communication Managers for interaction with different subsystems involved.

Apart from basic functionalities of control and monitoring, CCC software also provides fault tolerance, error handling and recovery of Camera at runtime [6]. To ensure high availability of the entire telescope, CCC allows failures of certain number of CIMs, within acceptable limits that is user configurable. On error response from CIMs, on

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timeout or incorrect response, after 3 retrials of the command, it disables and power off the faulty module. The scheme allows the telescope to continue to operate with useful data collection making the system fault tolerant in nature. It provides error handling mechanism by categorizing different types of errors for each of the sub-actions involved for Commands from OC including timeout and communication error. Some of the errors are handled and recovered by retrials of command, while others are reported at OC.

An adequate command response protocol between CCC and CIM has been established to meet the stringent performance requirement of acquiring periodic telemetry requests from 68 CIMs every 5 seconds. CCC sends some of the commands for CIMs over I2C link in a Broadcast mode for parallel execution of the commands, wherein one of the active CIMs, set as an acknowledgement module, responds with the result of the command. This broadcast scheme highly increased the responsiveness of the system by reducing the effective system response time for overall observation run.

CONTROL AND MONITORING FEATURES

Bright Star Masking

In the field of view of certain Gamma ray sources, various bright stars are also visible. These bright stars emit light, which create very high Single Channel Rates (SCR) in few of the nearby pixels, resulting in generation of spurious triggers from the Trigger Generator and compromising the recording of actual gamma ray events. In order to avoid such spurious triggers, a Bright star masking Algorithm has been implemented in the firmware of CIM. This algorithm monitors SCRs of each pixel every second, and if the value crosses a set Threshold limit, the particular pixel is disabled from participating in generation of First Level Triggers. This way the pixel remains active and collects charge information during actual gamma ray event caused by other pixels without generating spurious triggers. Hysteresis of 70 % has been implemented in the Algorithm itself, due to this the pixel starts participating in trigger generation when the SCR values reduces to 70% of set Threshold value. The following graph shows the pattern of Bright start masking in the case of pixel no. 855 during the observation of source MrK501 on 29/08/2021. For the day's experiment, Threshold for Bright star masking was kept as 1 MHz. During the observation period, the algorithm got activated for few of the pixels. For the sake of simplicity pattern of only one pixel is presented in Fig. 5.

PMT Light Exposure Protection

Photo multiplier Tubes are an indispensable part of Camera electronics and it is of paramount importance to preserve them from overexposure to unwanted light, which may reduce their productive life. During the source observation, various vehicular movements or bright stars cause drastic increase in Anode currents of individual PMT based pixels. In order to protect PMTs from exposure to unwanted light sources, an algorithm has been implemented in the firmware of CIM which continuously monitors Anode current (AC) and SCRs of individual pixel every second. If any pixel crosses the set value of AC for a particular number of times called UCT, the algorithm temporarily disables the particular pixel by reducing the bias voltage to a safe value. The algorithm re-enables the pixel after a set time interval called Reactivation Time (RT) and checks for AC again for UCT and accordingly takes a decision to keep it enabled or temporarily disabled. Few such attempts are carried out which are set by Maximum Retrial Count (MRC), after that the pixel is permanently disabled for the day's observation. Graph in Fig. 6 describes the behaviour of the pixel protection algorithm. Here, the y-axis describes the PMT Anode current and x-axis describes the Telemetry sample number. The threshold for Anode current is set at -5 μA. Value of UCT and RT is set as 4 and 30 seconds respectively.

Event Data Synchronization Loss Detection and Recovery

After receipt of Master Trigger signal from SLTG, all the CIMs acquire event data independently and transfer the event data in a predefined packet format through unidirectional point to point LVDS links to DC. DC Firmware then reads the event data from individual channel buffers and builds the Event data packet. It is of paramount importance that DC event packet shall have all the event packets from CIM, which are due to the same cosmic event and the corresponding event numbers across all CIMs are synchronized. To ensure that there is no event misalignment due to any data corruption during transmission or processing, Event synch-loss detection and recovery mechanism has been implemented in DC and CCC. Data Concentrator checks for event marker at every DC event in order to detect any data processing error. Additionally, DC regularly checks for CIM Event packet nos. for all the CIM event packets in a DC event packet. If there is any mismatch in the CIM event nos., then DC informs Loss of Data Synchronisation to CCC. On receipt of Synch loss info from DC, CCC stops the ongoing data acquisition and restarts a fresh data acquisition after resetting all event counters. This automatic recovery of Synch loss takes approx. 5 seconds and it is a very rare phenomenon in actual observations. Even if it occurs, it gives advance indication to some hardware related issue like data cable malfunction or other hardware issues that can be sorted out with pro-active fault diagnosis.

Regular System Calibration

During the course of the observation, there is huge variation in night sky background light due to various factors. For better resolution of acquired charge on the PMT during source observation, effect of this background light on pixel accumulated charge has to be considered. Regular system calibration runs are carried out during the source observation every 5-15 min interval so as to assess the extent of

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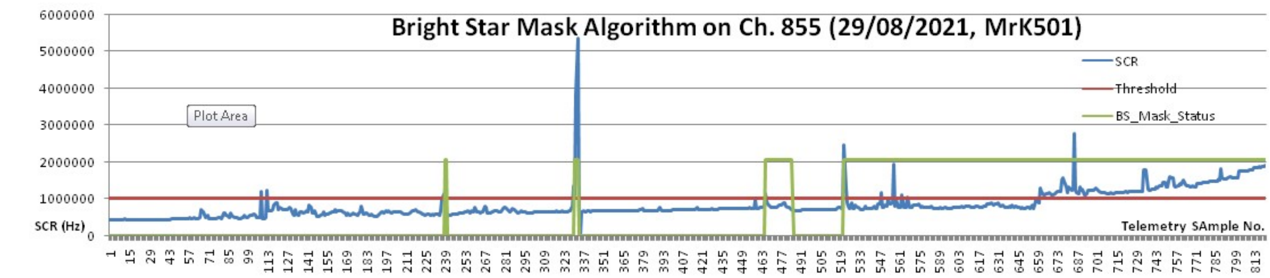


Figure 5: Bright Star Mask algorithm trend on pixel number 855.

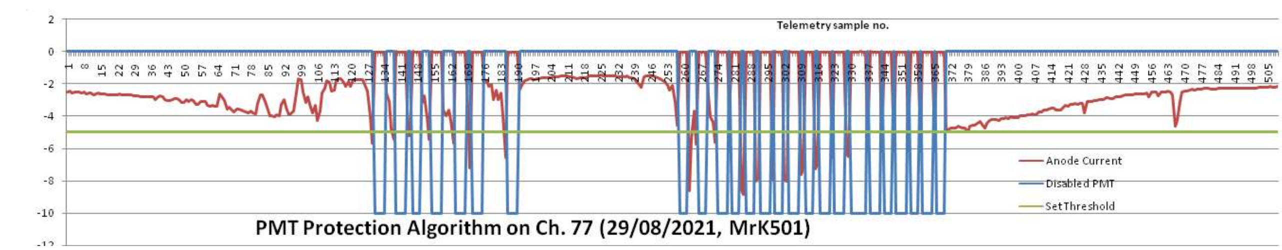
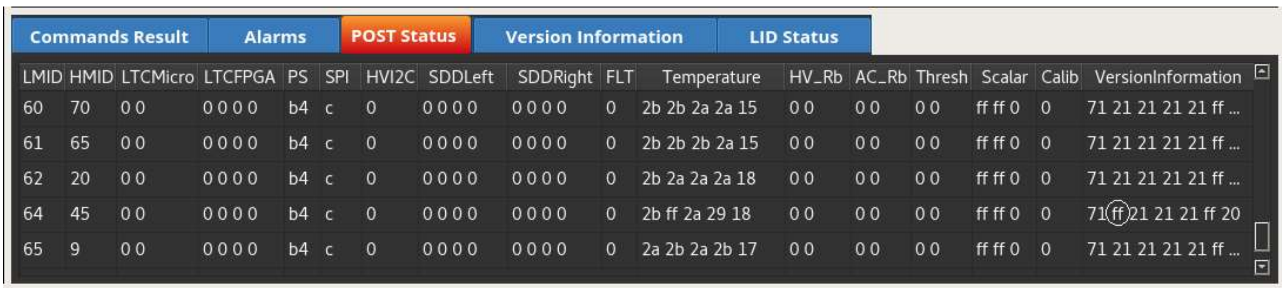


Figure 6: PMT Protection algorithm pixel number 77.



LMID	HMID	LTCMicro	LTCFPGA	PS	SPI	HVI2C	SDDLeft	SDDRight	FLT	Temperature	HV_Rb	AC_Rb	Thresh	Scalar	Calib	VersionInformation
60	70	0 0	0 0 0 0	b4	c	0	0 0 0 0	0 0 0 0	0	2b 2b 2a 2a 15	0 0	0 0	0 0	ff ff 0	0	71 21 21 21 21 ff ...
61	65	0 0	0 0 0 0	b4	c	0	0 0 0 0	0 0 0 0	0	2b 2b 2b 2a 15	0 0	0 0	0 0	ff ff 0	0	71 21 21 21 21 ff ...
62	20	0 0	0 0 0 0	b4	c	0	0 0 0 0	0 0 0 0	0	2b 2a 2a 2a 18	0 0	0 0	0 0	ff ff 0	0	71 21 21 21 21 ff ...
64	45	0 0	0 0 0 0	b4	c	0	0 0 0 0	0 0 0 0	0	2b ff 2a 29 18	0 0	0 0	0 0	ff ff 0	0	71 ff 21 21 21 ff 20
65	9	0 0	0 0 0 0	b4	c	0	0 0 0 0	0 0 0 0	0	2a 2b 2a 2b 17	0 0	0 0	0 0	ff ff 0	0	71 21 21 21 21 ff ...

Figure 7: POST Status on operator console of MACE Telescope (08/07/2021).

variation of night sky background light. At the set Interval, CCC gives commands to SLTG, which in turns generates fix number of self-triggers at a set frequency due to which all the pixels record charge collected due to background light and such events are tagged as SKY calibration events in DC Event data packet. Similarly, PMT gain calibration is also carried out at a regular interval just after the SKY Calibration cycle, during this CCC instructs LED driver (mounted at the centre of reflector dish) to generate fix number of LED pulses at a set frequency. All the PMTs collect charge due to LED pulses fired from the centre of reflector dish. Gain of all the PMTs is calibrated with respect to the charge calculated in the Reference PMT.

Safety & Diagnostics Features of the System

Due to harsh weather conditions in Hanle, Temperature in winters can go up to -30 degrees Celsius. CCC is designed to operate in such harsh environments and initially only CCC is powered on. It acquires the temperature from 8 Temperature sensors mounted inside the camera body and 2 mounted on the outer body of Camera. Temperature reading from all these is taken into consideration before powering ON of other subsystems of the camera in winter season. Passive heaters are provided inside the Camera to bring Camera Temperature to an operating range. Only after attaining the operating temperature, various subsystems of camera are switched ON. At the time of powering ON of Camera electronics, each subsystem performs its own Power on Self-Test (POST). After power ON CIM checks for various memory locations, setting and read back of discrimination voltages, ADC baseline read back, firmware version mismatch, Temperatures etc. If there is any error in POST STATUS from CIM, the particular CIM is switched OFF and does not participate in observation. One such scenario is presented in Fig. 7 where one of the board firmware version information of CIM 64 was not recorded correctly at the time of POST so CIM 64 was switched OFF for the particular experiment. The system also performs various link tests like Auxiliary Link Test, I2C link test and Data link test etc. and takes corrective actions before proceeding to the observation schedule. Regular health parameters of CIM are recorded and sent to the ground station. There are 5 Temperature sensors inside each CIM. CCC monitors each of them at regular intervals, if the temperature of any CIM crosses the set value, CCC can take corrective actions.

CONCLUSION

MACE Telescope is operational since early 2021 and regular trial source observations are being carried out. Initially stability of various configuration parameters was verified by long trial runs in close lid conditions and parameters were found to be stable over a long period of time e.g. 4-5 Hrs. various control and monitoring features of Camera

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Electronics have been rigorously tested in real source observation condition. Implemented algorithms like self-diagnostics, safety, PMT protection and Telemetry monitoring etc. are performing as per the design specifications.

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