MACE TELESCOPE

Imaging Camera: Features & Test Results

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The imaging camera of MACE Telescope is fully custom designed event driven system with state-of-the-art technologies for high speed data acquisition. Camera has been developed within the constraints of space, weight and power in such a way that the entire electronics for analogue signal processing, digitization, triggering and event building is fully integrated into the camera body. Detecting very low intensity signals of very short Cherenkov events (~ 5-10 ns), demands extremely low noise, wideband electronics confined in a small space. Event detection has been implemented in two stage digital trigger generation system which checks for time-space coincidence among nearby pixels. The real time event processing requirement are met using Field Programmable Gate Array (FPGA) based digitization and processing module, which processes the data sampled at 1GSPS.

Features of Mace Data Acquisition System

The MACE data acquisition (DAQ) system is designed to recognize the cosmic event of interest, acquire and compute the charge data for each of the PMT based pixels. The important features of the DAQ systems to meet the above can be summarized as (i) highly efficient trigger generation scheme, (ii) synchronous event acquisition across all the channels, (iii) optimum throughput event building system with data integrity checks, (iv) overall control and monitoring system for the safe operation of MACE camera.

Trigger Generation Scheme

The MACE trigger system is a compact two-stage system to detect and validate the occurrence of an event in real time as a close cluster coincidence, so that the charge and profile data corresponding to the event can be acquired by the MACE DAQ system.The First Level Trigger (FLT) stage is part of the front-end module electronics and detects occurrence of full or partial coincident clusters in a 16-pixel segment of the camera. The Second Level Trigger (SLT) stage analyses all the individual FLT outputs and generate the final camera level trigger which is distributed to the complete DAQ system. The SLT Module also validates the trigger based on full hit-pattern received from the camera to filter out triggers generated from disjoint clusters. The complete trigger generation and distribution process takes 110ns and the validation process takes an additional 400ns. This timing performance is sufficient for read-out of sample data from the channels and processing it. The valid/invalid trigger information is width-encoded in the trigger pulse itself.

DETECTING very low intensity signals of very short Cherenkov events requires use of extremely low noise, wideband electronics, which are confined ergonomically.

The trigger criterion (3-pixel cluster or 4-pixel cluster or 5-pixel cluster) can be selected from the experimental configuration of camera observation. The trigger generation is kept blocked for a programmable time interval following every valid trigger to allow for the event data acquisition. Minimum value (50 μs) of the blocking period, allows for a burst of 50 events at 20k/sec rate, while the average event rate is 1k/sec. The trigger system also generates periodic sky calibration pulse trains to acquire night sky back background during observation and tags LED calibration events as reference events. The event rates, single channel rates and validation rates are acquired periodically from the trigger system as part of telemetry data.

A critical design parameter of the trigger system is the coincidence window for event detection. It dictates the rate of spurious triggers generated by random firings of the channels due to background light and dark current noise. Lowest possible coincidence window is desirable for lower chance rates, but the limit comes from unavoidable skew across different channel propagation delays. The FLT coincidence window has been optimized to average ~4.5 ns and the SLT coincidence window has been optimized to ~8 ns. With these values, chance event rates can be kept below 20 Hz for average 320 kHz singles rate across camera. Theoretical estimate of chance rate is given by the equation:

$$CCR = NC_N\, r^N \tau^{N-1} \qquad (1)$$

Where, N is channel multiplicity
r is average single channel rate
τ is coincidence window

From the above theoretical consideration, we can estimate the prevalent chance rates for MACE Telescope.

Different health parameters of the trigger system are regularly evaluated from MACE telemetry data during observation runs. The most crucial parameter is the coincidence window width (τ), which can be calculated using Equation (1) utilizing Single Channel Rate (SCR) and Chance Coincidence Rate (CCR) values logged in telemetry data for a given Camera Integrated Module (CIM) which houses electronics for 16 pixels. The distribution of FLT coincidence window was estimated from telemetry data of CIM-51 from observation run on October 11, 2021. It can be observed that observed FLT coincidence window is 4.2ns, which conforms to design specifications.

Synchronous Event Acquisition

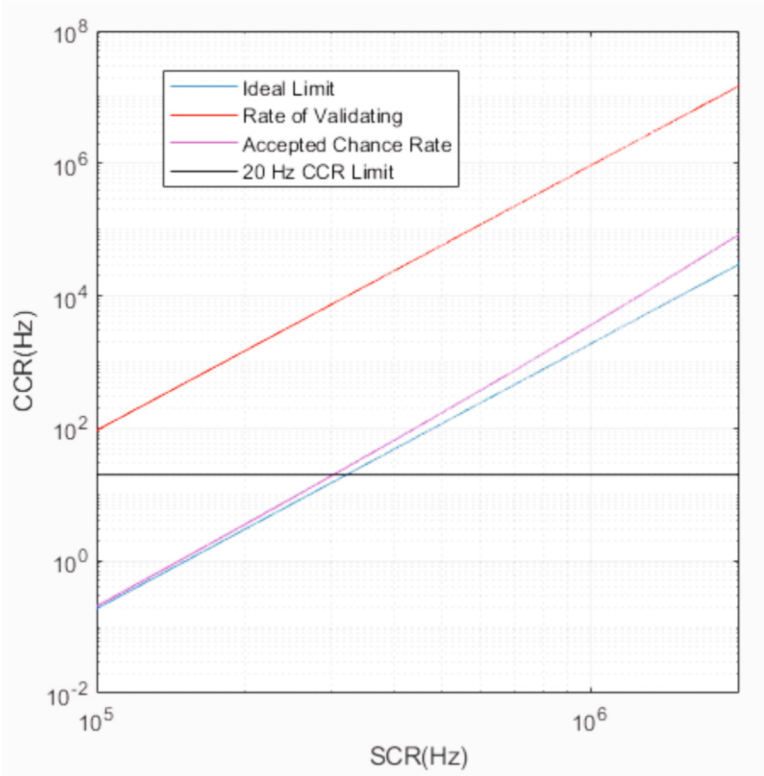
There are 1088 pixels in the imaging camera, each acquiring fast Cherenkov pulses of 5-10 ns. For easy maintenance and online processing of individual pixel data, 16 pixels are grouped in one CIM. Each module acquires, processes and transfers data independently of other modules.

To reduce the data volume, charge accumulated in each pixel is calculated in camera itself. Zero suppressed profile data storage scheme is used, where profile data is sent only for the pixels above set threshold value. Hence, it is very important to align the recorded pulse profile data of 31ns with minimum possible jitter (~2-3ns). Analogue memory ASIC DRS4 is used for sampling at 1 GSPS. Various factors like inherent timing jitters of DRS4 IC, trigger generation jitter and different High Voltage bias (HV) to PMTs add to the uncertainties in the timing of recorded pulses. Data processing algorithms have been implemented in FPGA to correct for these uncertainties in real time and record the incident pulses with reduced jitter. For better timing alignment across modules, 9th Channel of DRS4 is used to sample trigger signal. Event data packet along with CRC is formed in FPGAs of CIM and sent over proprietary point to point Low Voltage Differential Signalling (LVDS) link running at 200 Mbps. The system is designed to have very low dead time of 50µs. To cater to bursts of events, event buffering is also implemented in CIMs. The hit-pattern of a cosmic event acquired by MACE camera indicating the various pixel locations, having pulses whose amplitude is more than the set threshold has been obtained. The profile plot of various Cherenkov pulses acquired by various pixels in the given event has also been obtained. Although events are acquired across various modules, they are recorded with minimum jitter in the profile window of 31 ns. For any incident event on the camera, the pixel profiles are recorded within a jitter of ± 2nS across channels with peak of the Cherenkov pulse around 11-12 cell number. Occurrence of each event is tagged with time stamp synchronized with GPS to the accuracy of 1 µS. The time difference between two events in typical test varies from 50 µs to 100 ms, which conforms to design specification of 50 µS minimum event pair resolution.

Optimum Throughput Event Building System

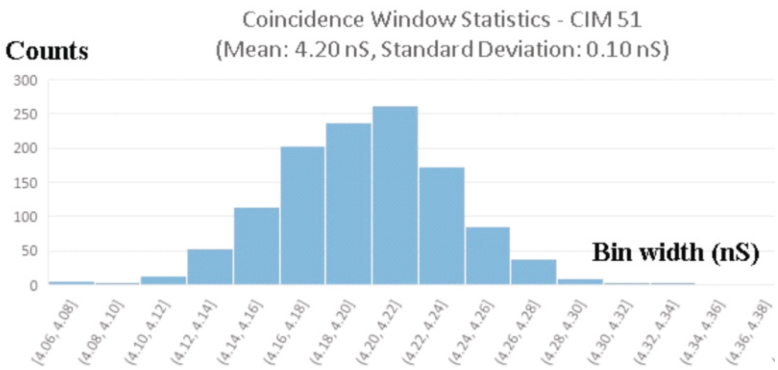
The imaging camera is expected to acquire event at an average rate of about 1k events/sec with low dead time. The information of interest include: charge content in the PMT pulse, the profile of the pulse and instance of occurrence of the event. To cater to burst events, event data buffer management is done at CIM and Data Concentrator (DC) unit. The event data acquired by each CIM is collected in DC. Event collection and data transmission at DC is handled concurrently. DC is custom designed around PC104 plus Single Board Computer (SBC) and has FPGA based event data processing for optimum throughput.

Normally, with less than 5% profiles, the data rate can be as high as 1kHz and an optimum data throughput of around 15 megabytes /sec is achieved. The individual CIM module transfers the processed data to a corresponding hardware

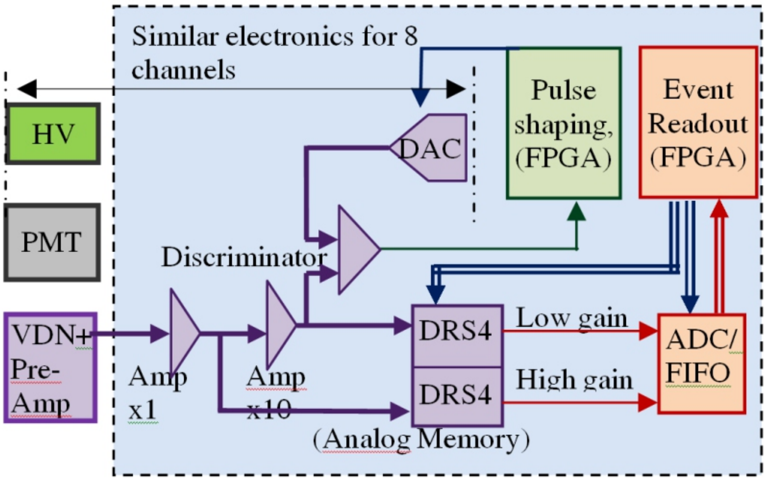


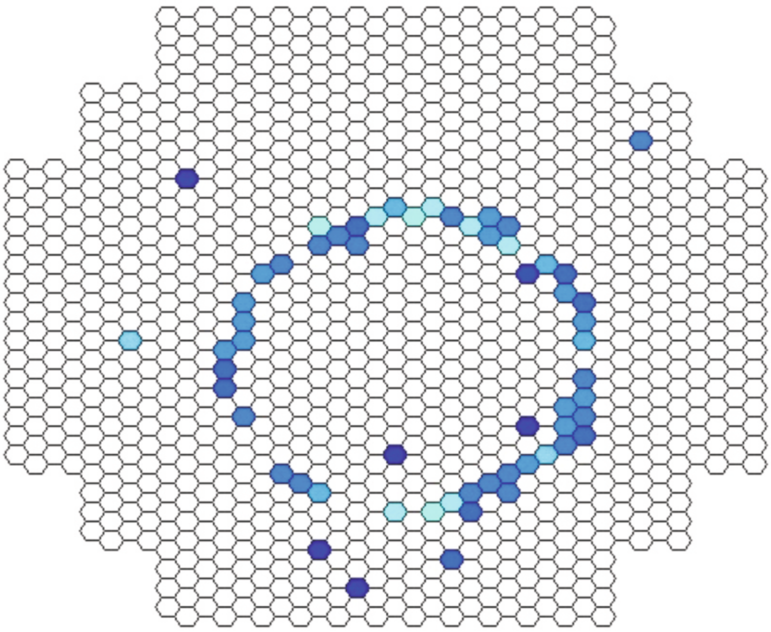
▲ CHANCE TRIGEER RATE Estimation.

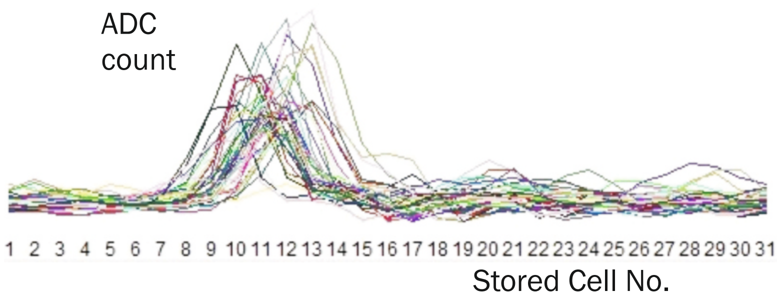
▼ FLT Coincidence window distribution.



THE data acquisition system is designed to recognize the cosmic event of interest. It also allows to acquire and compute charge data for each of the PMT based pixels.







BLOCK DIAGRAM of event acquisition (Top).
COSMIC EVENT acquired by MACE camera (Middle).
PROFILE plot of hit channels in acquired event (Bottom).

FIFO on the DC through a point-to-point LVDS link running at 200 Mbps. The DC compiles data from 68 CIMs into an event data, attaches time stamp and checks the validity of acquired data. For achieving high event throughput, data is transferred over PCI bus to the system memory of the DC under 32 bit DMA transfer. The DC transfers the collected data to the Ground-station based data archive system over gigabit Ethernet link for collation, archiving and analysis. It is essential for data acquisition system to have features to check data integrity at various stages of data collection, data storage and data analysis. Online checks have been implemented in DC for event synchronization across all the front-end modules. The system also has features to automatically recover from any such error with minimum dead time.

Control and Monitoring System

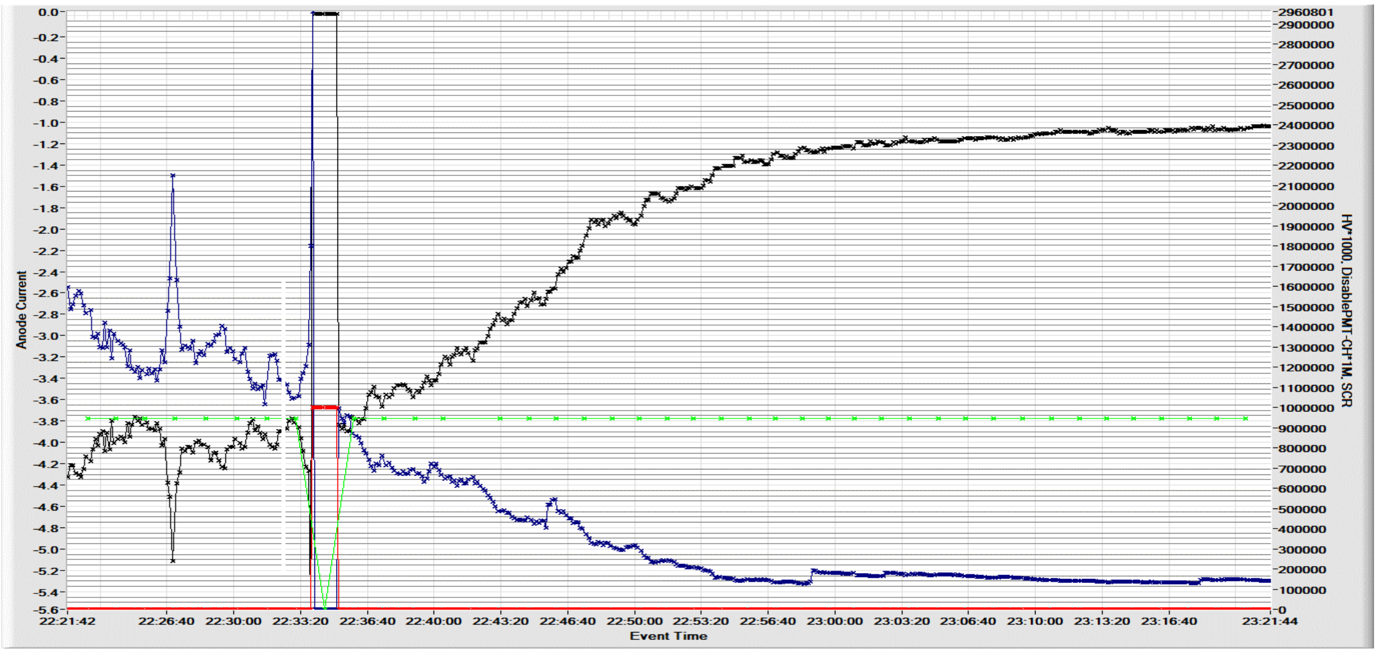
Overall control and monitoring of the camera is ensured by Central Camera Controller (CCC) which is responsible for control and monitoring of all the subsystems of imaging camera as per the command sequence from Operator Console (OC) in ground-station.

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 camera DAQ system adjusts itself to various extreme conditions of external light exposure, very high event rates, event data corruption etc by inbuilt recovery mechanisms. When event rates and data volume were continuously high for few events and the system was not able to handle the data, it momentarily stops generating further triggers. Whenever a pixel anode current exceeds the set threshold value (5 μA for the current case), the pixel gets disabled by reducing its HV value to 0V. In the given graph black trace is anode current when it increases beyond 5 μA, the pixel gets disabled (Red trace) by reducing its HV Value (Green Trace) to 100V. Blue trace is single channel rate for the given pixel.

Various control and monitoring algorithms like self-diagnostics, safety, PMT protection and Telemetry monitoring, recovery from error condition have been established and tested. Stability of various configuration parameters was verified by long trial runs of 4-5 hrs. The camera is performing as per the design specifications and is working reliably in extreme environmental conditions with ambient temperature varying from -25°C to +25°C. Distribution of the light intensity over the camera focal plane shows uniformity. The stability of various experimental parameters of pixels has been demonstrated during the source observation on August 29, 2021. The variation in pixel SCR and Anode Current are correlated, indicating presence of bright star or any other momentary light source. PMT bias voltage is found to be stable throughout the observation period.

Conclusion

MACE camera is fully operational since early 2021. Regular source observations are being carried out. Design values of FLT coincidence window of ~5ns and SLT coincidence of ~8ns has been verified. Compensation of delay variation by non-matched PMTs with digital delay fine tuning across modules is



▲ PLOT of Anode Current, SCR, HV and disabled PMT.

successfully achieved. Profile of the pulse is windowed with an average jitter of ±2 ns by detecting trigger edge and computing delays. Peak event rate of 2500 events per second (eps), average maximum event rate of 678 eps and event burst at 50 μs have been measured.

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