MACE TELESCOPE

An Overview

S. Godambe, *N. Mankuzhiyil and N. Chouhan

MACE is a very high energy gamma-ray telescope based on the imaging atmospheric Cherenkov technique[1,2,3]. The telescope is operational at the Indian Astronomical Observatory in Hanle, Ladakh since April 2021. The main objective of MACE is observation of VHE gamma-ray photons with energy above 20 GeV which is traditionally considered as the window for space-based instruments. In order to achieve this goal, the telescope has been built with a large light collector of 21m diameter and is commissioned at an altitude of 4270m above sea level. This places MACE in the class of current generation large IACTs around the globe and at the highest altitude in the world. The geographical location of the MACE telescope at Hanle appropriately fills the longitudinal gap among the major IACTs (MAGIC and VERITAS) operating around the globe[4]. At present, MACE is being operated to fine tune its various parameters to attain the expected low energy threshold and integral flux sensitivity to the VHE gamma-ray photons.

The telescope has successfully detected statistically significant gamma-ray photons from the standard candle Crab Nebula at several occasions in the last one year. This reflects the consistency in the telescope performance which is crucial for calibration of the system before its deployment for regular science operations including the discovery potential.

Principle of MACE

VHE gamma-rays cannot be directly detected by ground-based instruments due to their interaction with the Earth's atmosphere. The absorption of gamma-rays in the atmosphere turns into an indirect method of detecting VHE photons of the Galactic and extragalactic origin. A primary VHE gamma-ray is converted into e^+e^- pair due to interaction with atmospheric nuclei. This pair in turn produces further secondary gamma-rays through the Bremsstrahlung process. A combination of these two processes results in the creation of an extensive air shower of thousand of relativistic particles propagating through the atmosphere. This event can be detected by appropriately measuring the Cherenkov light emission by the relativistic particles during the shower development.

A suitable optical system along with photo-detectors can be used to map the shower development through the detection of Cherenkov photons. The information extracted from shape and size of the image of shower leads to the indirect detection primary VHE gamma ray photon from the ground. The MACE telescope makes use of this so called imaging atmospheric Cherenkov technique to observe the astrophysical sources emitting GeV-TeV gamma-rays. A representation of an air shower shower image formation by an IACT is shown in the figure. Measurement of the dim Cherenkov light from an extensive air shower against the isotropic Light Of Night Sky (LONS) requires the collection of as many Cherenkov photons as possible and size of the light collector is governed by the desired gamma-ray detection threshold energy of the telescope. This technique is well established over the last three decades in the field of VHE gamma-ray astronomy [4,5,6].

MACE Subsystems

The main components of an IACT are identified as drive system, optics or mirror dish and detector electronics. The drive and optical system are jointly referred to as the mechanical system. The major subsystems of the MACE telescope are described briefly below.

Drive system

In order to reposition the telescope in any direction in sky, the drive system of the MACE telescope employs an altitude-azimuth mounting. The entire moving weight of the telescope is supported by uniformly spaced 6 wheels with 60cm diameter each and 100mm width on a 27m diameter circular track. Two azimuth drive wheels are coupled to three phase, permanent magnet brushless AC servo motors through multi-stage gearboxes for providing the azimuth motion. The elevation movement is provided through a gearbox coupled to the 13-section bull-gear assembly of 11.6-meter radius. All the drives are provided with counter torque capability to avoid gear backlash error. The positions of the two axes are monitored by a 25-bit absolute optical encoders with 20 arcsecond accuracy. Both the azimuth and elevation gear boxes also have high-speed options to move the telescope at speed of 3° per second to quickly point the telescope in the direction of astrophysical transient events.

The MACE drive system can provide tracking accuracy of better than 1 arcminute in wind speeds of up to 30 km/hr. The telescope is automatically brought to the parking position if sustained wind speed is more than 40 km/hr.

THE FULLY INSTALLED Major Atmospheric Cherenkov Experiment telescope in Ladakh, India.

Light Collector/Reflector

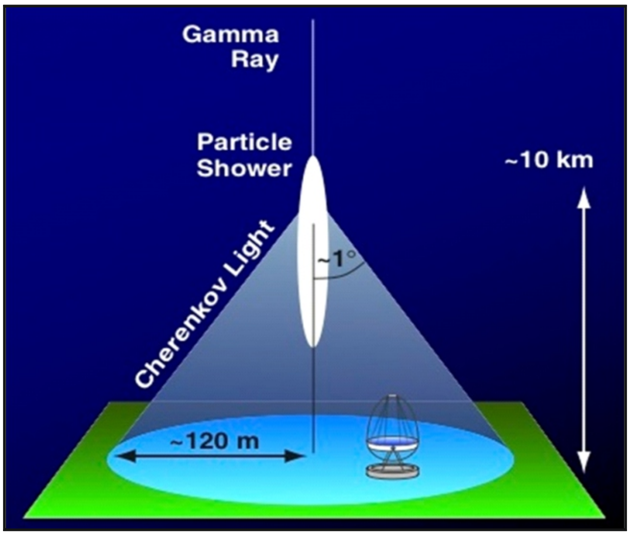
MACE deploys a 21m diameter quasi-parabolic reflector with f-number of 1.2 and covering a total surface area of ~340m^2. The quasi-parabolic design of such a large reflector helps in reducing the optical aberrations of the telescope. The ray tracing simulation studies carried out for various reflector designs suggest that a quasi-parabolic dish with mirror panels of graded focal length in the range 25m to 26.2m yields the best possible focusing and time characteristics for the MACE telescope. The reflector dish is a tessellated structure comprising of 1424 spherical metallic mirror facets of size 0.488m x 0.488m each. These metallic mirror facets have been developed using diamond turning technology for the first time in the country[7]. Four such mirrors with similar focal length are mounted on a single panel of size 0.986m × 0.986m and are manually aligned in such a way that the resulting panel behaves like a single spherical reflecting surface. Thus, the MACE reflector has 356 mirror panels mounted on the telescope basket with focal length gradually increasing from the center of the basket towards the periphery. The reflectance of these mirror facets is more than 85% in the wavelength range of 280nm-600nm. Due to the high altitude, a significant variation in the temperature between day and night as well as rapid temperature drop are frequently expected at the site of the MACE telescope.

Therefore, it is very important that all optical properties of the reflector should be stable within the temperature range -30°C to +30°C and mirrors in the reflector should be able to resist these environmental changes. Also, the MACE telescope is not protected by a dome due to its large size and the mirrors are continuously exposed to the environment. Therefore, reflecting surface of each mirror facet is coated with a thin (100-150 nm) layer of SiO$_2$ for protecting the reflecting surface and ensuring its longevity.

Detector Electronics/Camera

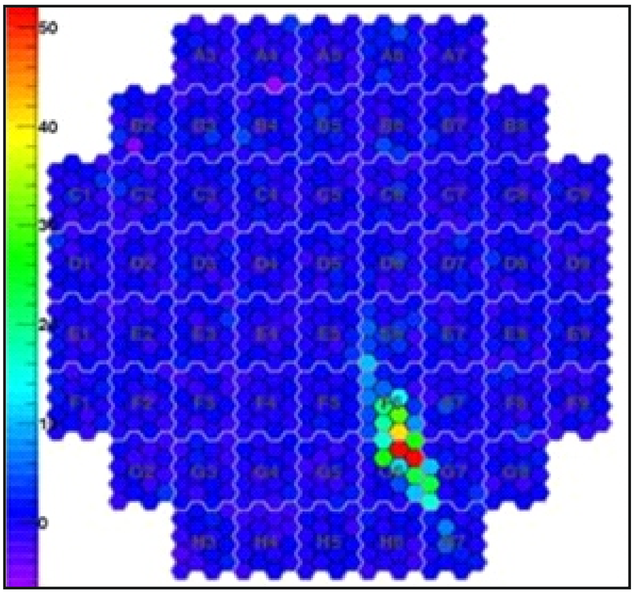
The MACE telescope deploys a 1088-pixel PMT based imaging camera with resolution of 0.125° at its focal plane which covers a field of view of 4.03° × 4.3°. Six stage PMTs with 38mm diameter arranged at a triangular pitch of 55mm are used in the MACE camera for detection of Cherenkov photons. Each PMT is provided with a hexagonal front-coated light concentrator in order to enhance the light collection efficiency by collecting the Cherenkov photons incident in the dead space between adjacent pixels. The light collection efficiency of these compound light concentrators is in the wavelength range of 230nm-600nm. The modular design of MACE-camera consisting of 68 camera integrated modules (CIMs) of 16 PMTs each indicates its uniqueness. Each CIM has its in-house signal processing electronics and data acquisition system. An analogue switched capacitor array Domino Ring Sampler (DRS-4) is used for continuous digitization of the signal at

THE reflecting surface of each mirror facet is coated with a thin (100-150 nm) layer of SiO$_2$ for protecting the surface and also to ensure longevity as the entire telescope is not protected by a dome by virtue of its large size and numerous mirrors.



▲ A REPRESENTATION of imaging atmospheric Cherenkov technique.

▼ IMAGE FORMATION of an extensive air shower by a MACE-like telescope.



THE TELESCOPE is automatically brought to the parking position if the wind speed sustains above 40 km/hr.

a speed of 1GHz from the PMTs. The signal from PMT is simultaneously amplified at low and high gains to ensure a large dynamic range. The discriminator output amplitude of each channel is used for monitoring its single channel rate and also for generating the first-level trigger from an individual CIM. The first-level triggers from all the modules are collated in a second-level trigger generator where proximity of the triggered pixels in adjacent modules is checked. The event trigger in the camera of imaging telescopes is generated by a fast coincidence of few nanoseconds between more than 2-pixels with the condition that the signal from pixels participating in the trigger should exceed certain trigger threshold. In MACE-camera, the innermost 576 pixels (24×24) are used for generating this trigger according to predefined logic for nearest pairs, triplets, quadruplets, etc of the pixels. After the generation of the second-level trigger, the data from all the 68-CIMs are collated by the data concentrator. Approximately, 50GB of data is stored during every hour of observation with the MACE telescope.

Calibration System

As a part of MACE data analysis, estimation of PMT gain is an important step. This is achieved by relative calibration of 1088-PMTs of the imaging camera using a light emitting diode (LED) based calibration system situated at the center of the telescope basket. The main component of the calibration system is an electronic pulsar which provides 5 high speed pulses to drive ultra-fast blue LEDs with variable intensities in order to calibrate the whole dynamic range of the PMT-based camera. The calibration system also provides a sophisticated trigger system which allows pulsing of the LEDs at almost any frequency up to 10 kHz.

Weather Monitoring System

The Weather Monitoring System (WMS) is another important subsystems of the MACE telescope. WMS comprises a weather station data logger which provides the details of the weather conditions at the observation site. WMS parameters are used as an interlock for telescope operation. WMS is integrated with the MACE operator console for the monitoring of weather parameters in real time. The real time data analyzer represents weather parameter visualization and calculates hourly average of weather parameters and stores data in a database for future data analysis.

Expected Performance of MACE

The expected performance of MACE at Hanle site is simulated using CORSIKA (Cosmic Ray SImulation for KAscades) software package assuming US standard atmospheric profile[8,9]. A large database of extensive air showers for very high energy gamma-rays, protons, electrons and alpha particles in the energy range 5GeV to 10TeV over a wide zenith angle range of 0°-60° is generated for studying the performance of MACE telescope. The Cherenkov photons in the wavelength range of 240nm-650nm and intersecting an imaginary sphere containing the MACE reflector at an altitude of 4270m are stored for further analysis.

A simulation code developed for the MACE telescope reads the CORSIKA output and performs the optical ray-tracing, identifies the individual Cherenkov photons detected by the camera, forms the image of each extensive air shower in the camera, adds Poissonian noise due to light of night sky in the PMT and checks for the pixels crossing the discriminator threshold defined from the trigger criterion. Simulation studies indicate that the gamma-ray trigger energy threshold of MACE is ~ 20 GeV in the low zenith angle range of 0°–40° and this value increases to 173 GeV for large zenith angle of 60° with trigger rates varying from ~700 Hz to 305 Hz as the telescope track the sky from lower to large zenith angles.

The 50 hour integral flux sensitivity is estimated to be 2.7% of the Crab Nebula flux at the analysis energy threshold of 38GeV at 5° zenith angle when Random Forest method is used for gamma/hadron segregation[10]. The angular and energy resolutions of the telescope are estimated to be ~0.15° and 25% respectively for zenith angles less than 25°.

Science Motivation

The low energy threshold of the MACE is enables us to observe the distant sources beyond redshift $z>1$ and monitoring of astrophysical transients, in addition to the study of variety of Galactic sources and extragalactic gamma-ray sources. With an analysis energy threshold of ~30GeV, MACE is suitable and likely to play an important role in the study and discovery of gamma-ray pulsars in the Milky-Way Galaxy. It also gives a unique opportunity to discover new sources at higher redshifts. This will help in addressing the open problems related to the propagation of VHE gamma-ray photons over cosmological distances, density of Extragalactic Background Light (EBL) photons, effects of intergalactic magnetic field and photon-Axion Like Particle (ALP) oscillation, and understanding the signature of dark matter candidate especially weakly interacting massive particles (WIMPs) beyond the standard model of particle physics. MACE is also expected to throw light on Galactic sources like supernova remnants.

Bibliography

[1] R. Koul, Current Science, 2017, 113, 691.
[2] K. K. Singh, K. K. Yadav, Universe, 2021, 7, 96.
[3] K. K. Singh, Journal of Astrophysics and Astronomy, 2022, 43, 3.
[4] J. Sitarek, Galaxies, 2022, 10, 21.
[5] T. C. Weekes et al., Astrophysical Journal, 1989, 342, 379.
[6] A. M. Hillas, International Cosmic Ray Conference, 1985, 3, 445.
[7] V. K. Dhar et al., Journal of Astrophysics and Astronomy, 2022, 43, 17.
[8] C. Borwankar et al., Astroparticle Physics, 2016, 84, 97.
[9] C. Borwankar et al., Nuclear Instruments and Methods in Physics A , 2020, 953, 163182.
[10] M. Sharma et al., Nuclear Instruments and Methods in Physics A , 2017, 851, 125.

The authors are from Astrophysical Sciences Division
Bhabha Atomic Research Centre
Trombay, Mumbai- 400085
✉ *nijil@barc.gov.in**