MACE TELESCOPE

Optical System

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The motivation for the optical system of an IACT like MACE is to detect the Cherenkov light from an extensive air shower which is initiated by the primary gamma-ray photon at the top of the atmosphere[2]. The Cherenkov light is emitted from a shower in the form of a cone typically within an opening angle of ~10°. The majority of these Cherenkov photons reach the ground within a light pool of radius ~125m. The detection of faint Cherenkov light against the isotropic background of light of the night sky (LONS) requires an excellent optical system for the collection of these photons[1-3]. IACTs need large reflectors, with multiple spherical mirrors to focus the collected light to a pixelated camera which is placed at the focal plane of the telescope. The light-gathering mechanism for Cherenkov telescopes is simpler compared to the optical telescopes, since the image formation does not require high resolution or a narrow field of view[4]. The main requirement of IACT however, is to provide high light throughput with an imaging quality matching with the PMT resolution, which forms the camera at the focal plane. The requirement of stringent point spread function (PSF) is also relaxed compared to the optical telescopes since a PSF of a few arc-minutes is acceptable for IACTs. The reflector of the telescope is segmented into individual mirror facets. The aberrations are important due to the multi-mirror design with modest focal length to reflector diameter ratios (f/d) of IACTs. The focal length of the telescope is usually selected to keep f/d ratio between 1.1-1.3 to control the aberrations and provide a good quality shower image.

The large reflector telescopes equipped with fine pixel PMTs at the camera plane enables operation of these telescopes at primary energy thresholds of tens of GeVs. Also, it is of prime importance that the mirrors used in the reflectors of IACTs are robust, light weight, and highly reflecting in the wavelength region of interest ~300 - 700nm.

MACE Light Collector Details

The light collector basket of the MACE telescope is a 21m diameter basket consisting of a tessellated structure of 356 mirror panels of size ~984 mm x 984 mm. Each of these mirror panels has 4 square spherical mirror facets of size 488 mm x 488 mm, resulting in a requirement for 1564 (including 140 spares) mirror facets[5]. Each such mirror facet is made up of two thin aluminum plates at the front and back and a sandwich of honeycomb structure, which ensures low weight and high rigidity.

Aluminum mirrors are increasingly being preferred in gamma-ray astronomy over the conventionally employed glass mirrors as the latter being continuously exposed requires regular coating and maintenance. Aluminium mirrors are also preferred due to their inherently superior reflectivity[6].

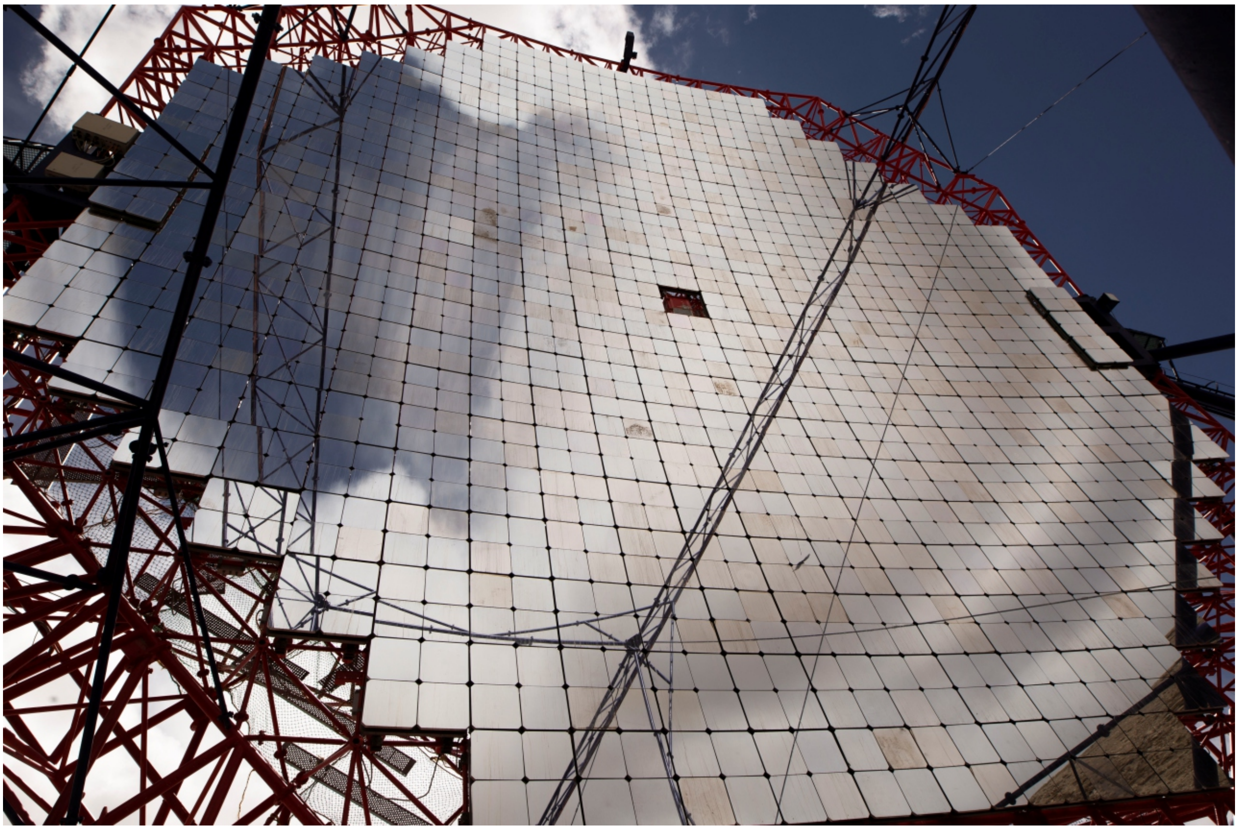
More so, diamond turning technology has made sufficient advances in the past decade or so which allows machining of aluminium alloys to achieve excellent shape accuracy and roughness values of < 0.5nm rms[7], which is quite daunting for the conventional glass mirrors.

The front and the backsides of the mirror facet are 5±0.5 mm and 1±0.5 mm thick Al alloy. The honeycomb structure is made up of HEXEL HexWeb ACG Aluminium honeycomb panel (Hexlite 220) substrate[8], with a cell size of ~ 6± 0.5 mm and thickness of 26±0.2 mm. The front and back plates are glued with honeycomb structures using adhesive epoxy specially made for Al to Al bonding. The total thickness of the mirror facet is ~32±0.5 mm and weighs ~3.5-4.5 kg. It may be pertinent to mention here that a glass mirror of similar dimension weighs ~22-25 kg, thus allowing us to reduce the optical basket weight significantly (~25%). This is particularly important to reduce the weight of large telescopes like MACE where a large number of mirror facets is employed.

The sides and corners of the mirror facet are properly sealed to avoid infiltration of water and dust. Due to its large size, the MACE telescope is not protected by a dome and its mirrors are continuously exposed to the harsh environment[9,10]. To protect the mirror facets the reflecting surface of mirror facets has been coated with SiO_2 for protection.

Fabrication of Mirror Facets

Before production of the mirror facet, the raw mirror Al blanks are cleaned and subjected to dimensionality and water ingress tests. While dimensionality ensures that every raw blank is cut to ensure proper fitting of panels on the telescope basket, the water ingress test is done to ensure that there is no minor crack present in the mirror facet. In this test, mirror facets were immersed in hot water at a temperature of ~80°C for about 30 minutes. The difference in weight of the mirror facet before and after the water ingress test



reveals if any water has seeped inside the mirror. Also, any crack in the raw facet will show in the form of air bubbles during the water ingress test. The mirror facets which qualify the above two tests are subjected to rough machining on a Computer Numerical Control (CNC) lathe machine. The role of the CNC machine is to automate the process of material removal from the front surface of the mirror facet and generate a surface that is at best a few mm away from the desired spherical shape. The Boerringer Goppigen make (model MC-600V-DC) machine was utilized for this purpose. Next, the mirror facets are taken up for the diamond turning process on a Diamond Turning Machine (DTM). Diamond turning is the process of making mirrors using a single tip monocrystalline diamond-turned tool for precise positional feedback.

The rough blank is mounted on the rotating spindle in the DTM, and the diamond tool approaches the mirror blank. The precision quality turning is done by fixing the raw blank onto a rotating spindle and is machined by a diamond tool with movement along the x-axis. The Nanoform 700 Ultra machine (Precitech USA make) employed for this purpose is a large capacity ultra-precision machining system designed for the production of both single point diamond turning and deterministic micro-grinding of optical lenses, optical mould inserts mirrors and precision mechanical components. The machine offers a 700 mm swing capacity with a 350 mm over the optional B-axis. When the Nano form 700 ultra is fitted with optional B/C axes, the lathe can follow 4-axes of continuous path motion. The machine offers ~0.01nm programming resolution and 32 Picometer feedback resolution. The machine is equipped with a highly sophisticated bearing system which enables it to polish the cutting edges in all directions of the diamond tool. During the machining process, the diamond tool very carefully removes the material from the Al blank to generate the pre-programmed surface. In this way, 3 high-quality mirror facets could be fabricated in ~24 hrs. It took about 2 years to fabricate the 1564 mirror facets required for the MACE telescope.

Optical Quality and Other Tests

An exhaustive experimental study was undertaken for in-depth quantification of 1564 mirror facets after their fabrication. Each of the mirrors fabricated has been assigned a Unique Identity Number (UIN-1001 onwards) so as to have a tag on the individual mirrors and maintain a database with regard to the mirror history from the date of fabrication to its installation onto the MACE telescope and maintain a database with regard to the mirror history from the date of fabrication to its installation onto the MACE telescope basket. Section below gives an insight into the testing procedure.

Experimental Setup

Ideally, to test the mirror facets it is desirable to have an experimental setup where the light source is kept at infinity and the image which is reflected back from the mirror facet is captured at the prime focus. However, since it is difficult to have such a measuring arrangement in place, a

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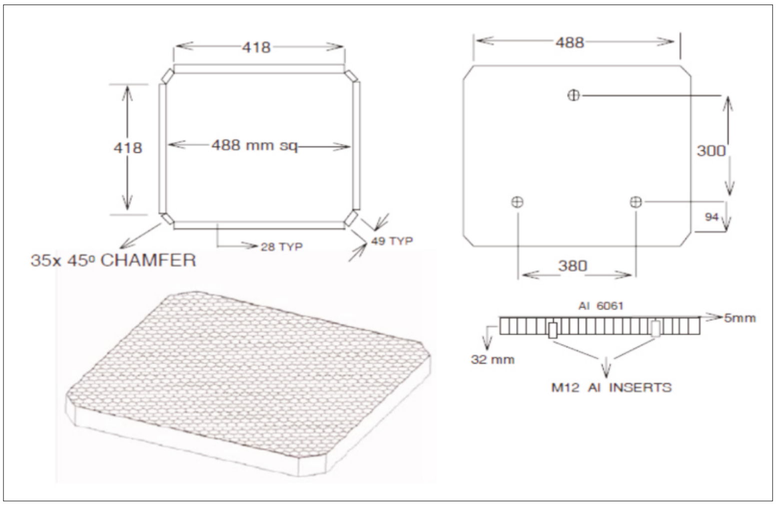
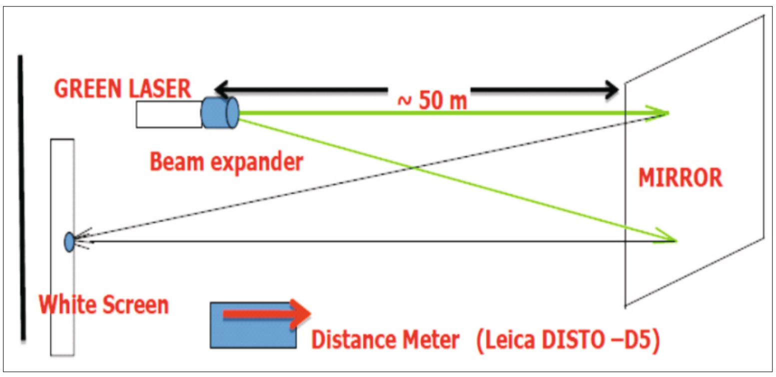


▲ COMPONENTS OF MIRROR facet, a honeycomb sandwich between front and backplates.

▲ NANOFORM 700 ULTRA machine for fabrication of diamond-turned metallic mirrors.

▼ TEST SETUP for measuring ROC.



simpler set up is to place the light source at the Radius of curvature (ROC), i.e., 2x focal length of the mirror, so that the image is also formed close to ROC. Such an experimental set up is referred to as the standard 2f method. For this experimental set up, we have employed a green diode laser 532nm wavelength with a beam diameter of ~2-3mm, the typical divergence of ~1.3mrad, and a power rating of ~ 3mW. This laser is placed at a distance of 50m from the mirror (typical ROC). The mirror is fixed on a mirror holding assembly with a locally provided arrangement and is directly facing the laser beam. A beam expander, which is a short focal length convex lens (~10cm) is fixed in front of the laser beam. The purpose of the beam expander is to expand the highly directional laser beam so that an area of ~1m x 1m is uniformly illuminated.

Once such a set up is in place, the image of the laser light source after being reflected by the mirror facet is formed somewhere close to ROC. This image is brought to a sharp focus on a specially designed white screen, made for this purpose to capture the image. This white screen can slide back and forth so that we can have a sharply focused spot of the reflected image (beam waist).

The distance between the source to the mirror facet and from the mirror facet to the sharply focused image on the white screen is very accurately measured with the help of a distance meter (Leica Disto-D5) which has a high-resolution 2.4-inch digital color point finder display and a 450 tilt sensor, with a measurement range up to 200m and an accuracy of ± 1.5 mm.

Spot Size and ROC Measurements

The mirror facet under test is held in the mirror holder assembly at the three mirror studs specially designed for holding the mirror with the mirror holder assembly. The light from the laser is focussed such that the whole of the mirror is uniformly exposed and the reflected image is captured on the white screen. The screen is adjusted till a sharp and smallest possible spot of the light reflected from the mirror is seen. Once this sharp spot is obtained, we measure the D80 of this image, i.e., the diameter of the circle taken from the center of the spot (bright center), containing nearly 80% of the reflected light. This measurement is made manually by having circles of different diameters between 4mm to 15 mm, beforehand and comparing the image spot with the pre-drawn circle which best fits the spot. Along with this the distance (called V) where this sharp image is obtained and the distance between the light source and the mirror (called U), is also measured accurately with the distance meter. Knowing these two distances the Radius of Curvature (ROC) of the mirror in question can be calculated as:

$$2/R = 1/U + 1/V$$

or

$$R = 2UV/(U+V)$$

Apart from the above measurement, we have also taken photographs of this optimized spot of each of these mirrors tested, using a 10-megapixel digital camera. This image (in jpg format) is converted into a grey-scale image and then digitized by converting the pixel intensity into digital counts. The pixel in the image with the brightest intensity (centroid) is identified and concentric circles are drawn around it with an increase in diameter of the new circle by 1 pixel. The total number of digitized counts in each circle is recorded. Background counts are also recorded from the image frame itself and these are subtracted from the pixel counts. Next, a normalized intensity plot as a function of the number of pixels contained in each circle is obtained. Knowing the conversion scale from the actual measurement of the maximum extent of the image i.e., D100 we can easily calculate the D80 of the image. The measurement of spot size obtained by this method for a particular mirror facet is then compared with the manual measurements done previously (for D80) for the same mirror facet.

Excellent matching of the two schemes (within ~±1mm accuracy) has been obtained. It is important to mention here that since we planned to test all the 1564 mirror facets individually, the measurements carried out via taking photographs and digitizing the images and then obtaining the D80, was quite time-consuming, hence it was used only as a cross-check for a sub-sample. Manual measurements, on the other hand, could be completed quite fast. Results were obtained on frequency distribution of all 1564 mirrors fabricated for this purpose. The mean spot size of (6.77 ± 1.02)mm at ROC translating to a spot size of ~3.4mm at the focus has been obtained. Mirrors with spot sizes of 5mm and 6mm respectively can be considered as representative of the best mirrors, the mirrors which are taken as the worst-case scenario has spot sizes of ~10-12 mm.

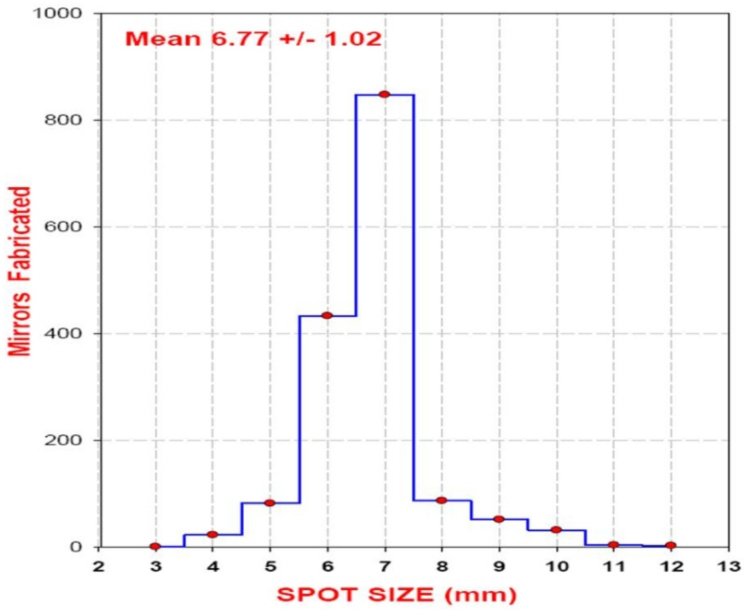
As the MACE telescope uses a very large reflector of ~21m diameter, there is expected to be sufficient variation in spot size if mirrors of the same focal length are deployed from the center of the basket to the periphery. To account for this effect, we have fabricated what is known as "graded focal length" mirrors. The light collector basket of the telescope is divided into 11 different focal length zones and the focal length of each zone is evaluated to fabricate a graded focal length light collector.

In a graded focal length procedure, mirrors of different focal lengths are fabricated depending upon the zone in which they will be placed. It, therefore, puts an additional constraint to fabricating mirrors of different ROCs to be installed in the 11 pre-decided zones of interest.

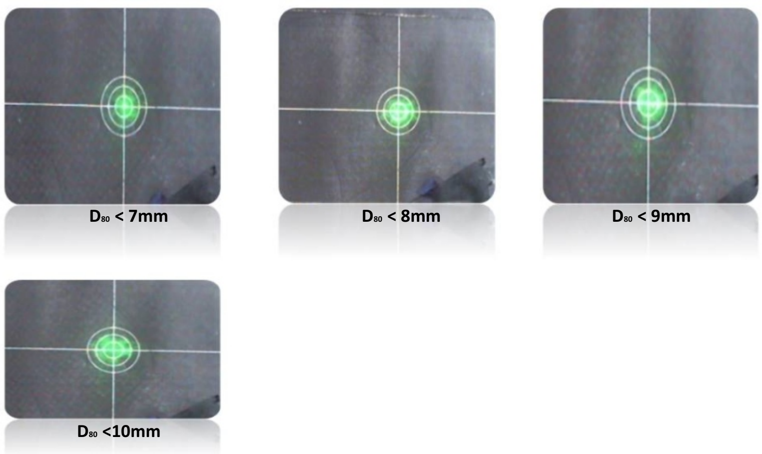
Reflectivity and Surface Measurements

An important requirement of these fabricated facets was to have mirrors of very high reflectivity (~ 85%) in the wavelength region (270-700) nm. Also, it is desirable to have regular check-ups of the reflectivity of mirror facets to investigate the deterioration of reflectivity, if any, under the actual atmospheric conditions.

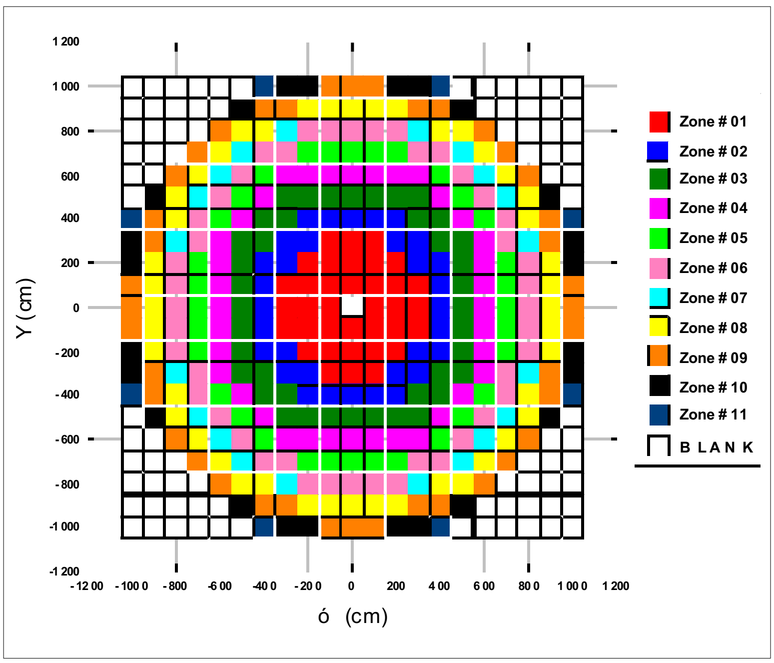
In order to not disturb the mirror panels on the telescope basket, and to monitor the reflectivity degradation, an Al-alloy pipe of the same material as



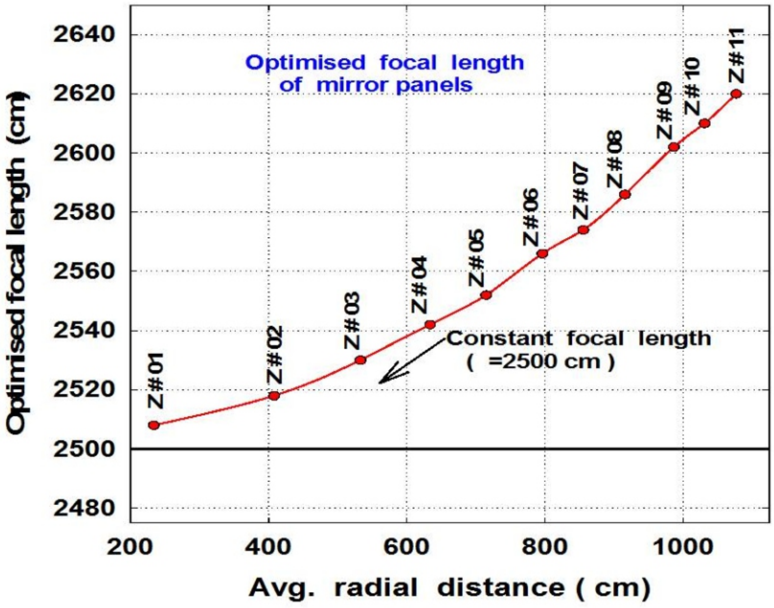
▲ FREQUENCY DISTRIBUTION of mirror as per spot size.



▲ MIRRORS WITH different spot sizes.

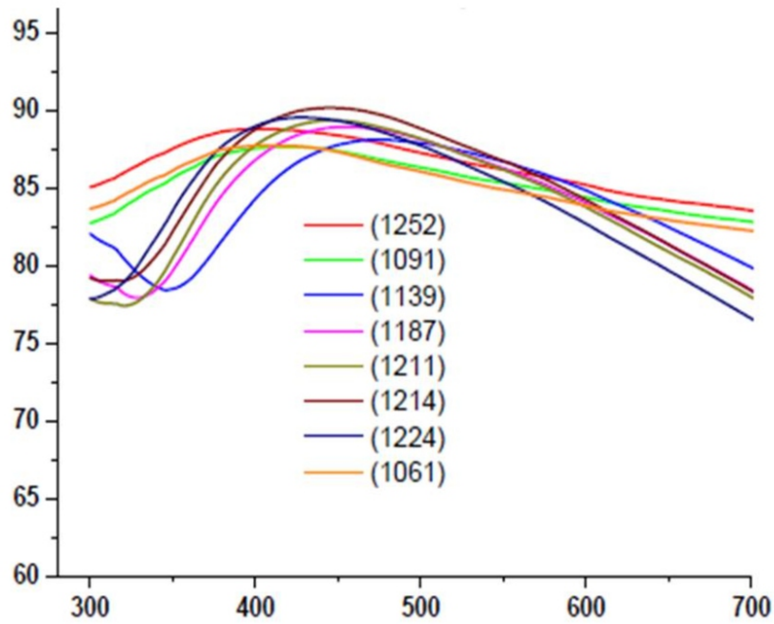


▲ BASKET AREA divided into 11 zones based on ROC variation.



▲ RADIAL distance as a function of focal length.

▼ REFLECTIVITY measurements for various witness samples.



the mirror front plate and about 20mm diameter is cut and small samples of 35mm length are chopped off from this. These samples are then subjected to the matching procedure with the same machining parameters on the DTM as the actual mirror. This small sample is also subjected to a similar SiO_2 coating procedure (discussed in the next section) along with the actual mirror. This new baby mirror, called the witness sample, can therefore be regarded as a section of the original mirror itself.

Thus, some of these 1564 mirrors will have their witness sample which will be assigned the same UIN as the 'mother mirror', and will also be exposed to the actual environmental conditions as the main mirror. Therefore reflectivity measurements of these witness samples can easily be taken in actual settings without disturbing the original mirror assembly. The reflectivity measurements carried out by us, have been done on a UV-1800 Shimadzu UV spectrophotometer. The reflectivity measurements of the eight sample mirrors (best and worst case scenario). have been obtained and it is evident from the obtained results that a mean reflectivity of ~ 85% is achievable.

Silicon Dioxide Coating

The reflection properties of metallic coatings depend on the wavelength, polarization, and angle of incidence. Materials used for metallic coatings are Al, Ag, etc. depending on the wavelength range of interest. The reflectivity level accordingly changes from 85% to 95%. Coatings made of evaporation metals are chemically sensitive and cause oxidation, therefore SiO_2 or MgF_2 is used as a protection layer again depending on the wavelength region of interest. Generally, for ultraviolet/visible, the latter coating is used while for visible region alone the former coating is preferred.

Before the mirrors are subjected to the process of SiO_2 coating, they are cleaned to remove any invisible abrasion, dirt, accidental oil/grease marks, etc., which may have been deposited on the mirror. These marks, though invisible to the eye, can remain on the mirror and cause a dead zone permanently, unless a thorough cleaning process is not adapted. For the purpose of cleaning mirrors, we are using super distilled water which is filtered through a 0.2µm membrane and has a residue of 0.0005% on evaporation.

A standard aluminium coating includes one layer of SiO_2 on top of the aluminium. The basic protective SiO_2 overcoat is only thick enough to seal the aluminium from the elements and provide a hard, scratch-resistant layer, with a little compromise on the reflectivity. It is not intended to enhance the reflectivity in any sense, but only to provide a protective layer and hence prolong the mirror life. The machine used for the coating is Balzers 1250 model which is a batch vacuum coating machine. In the coating process, SiO_2 is loaded in a crucible, the machine generates a vacuum of 2.5x 10^{-5} mbar, the silica melts to vapour form and is gradually deposited to bond with the aluminium. The machine parameters are programmed to deposit a thick gauge of ~(120±20)nm. The machine chamber can accommodate 2 mirrors and their witness samples at a time and the total coating time is ~8 hours. The SiO_2 coating is an amorphous coating with a hardness of 9H and a bonding strength of ~ (7-8) Mpa.

Environmental Testing

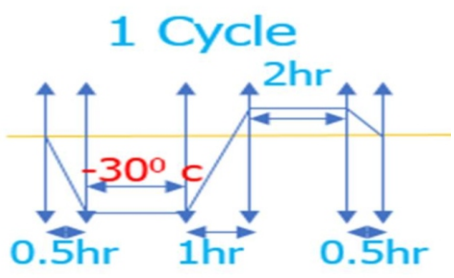
The environmental testing performed on two mirror facets UIN 1019 and UIN 1021 (spot size of 9 mm (D80) at ROC) is done in a two-phase process. This environmental test is classified as "Severity" and was conducted in the following manner. In the first phase, the temperature of the two facets was decreased from the ambient temperature to -30°C within a time span of half an hour. Then the facets were left at that temperature for ~2 hours, a phase called soaking, the temperature was then increased from -30°C to +30°C within one hour and again left in soaking for ~2 hours at that temperature. The temperature was then decreased to the ambient temperature within half an hour.

This process of increase/decrease in temperature constituted one cycle. A total of 76 such cycles were performed on the two mirror facets. In the second phase, the temperature was changed from +30°C to -40°C within a period of one hour and left at this temperature for ~2 hours for soaking. The temperature was then increased from -40°C to +40°C within one hour and then left for soaking at this temperature for ~2 hours and then decreased from +40°C to +30°C within an hour. This again constitutes one cycle. Another 24 such cycles were performed on the two facets. Thus, a total of 100 cycles were performed on the two mirror facets within a period lasting ~30 days. The spot size of these mirror facets was checked before and after the environmental testing. The facets reproduced their earlier spot sizes of 9mm (D80) at the previously measured ROC, reassuring that facets manufactured can withstand the harsh climatic conditions at Hanle, and allow gamma-ray observations for a prolonged period. While it is tough to predict the mirror life as it is the mirror reflectivity which is a major parameter that can change with time. Exposure of similar mirrors employed in the MAGIC telescope at La Palma has shown some degrading after ~5 years of exposure.

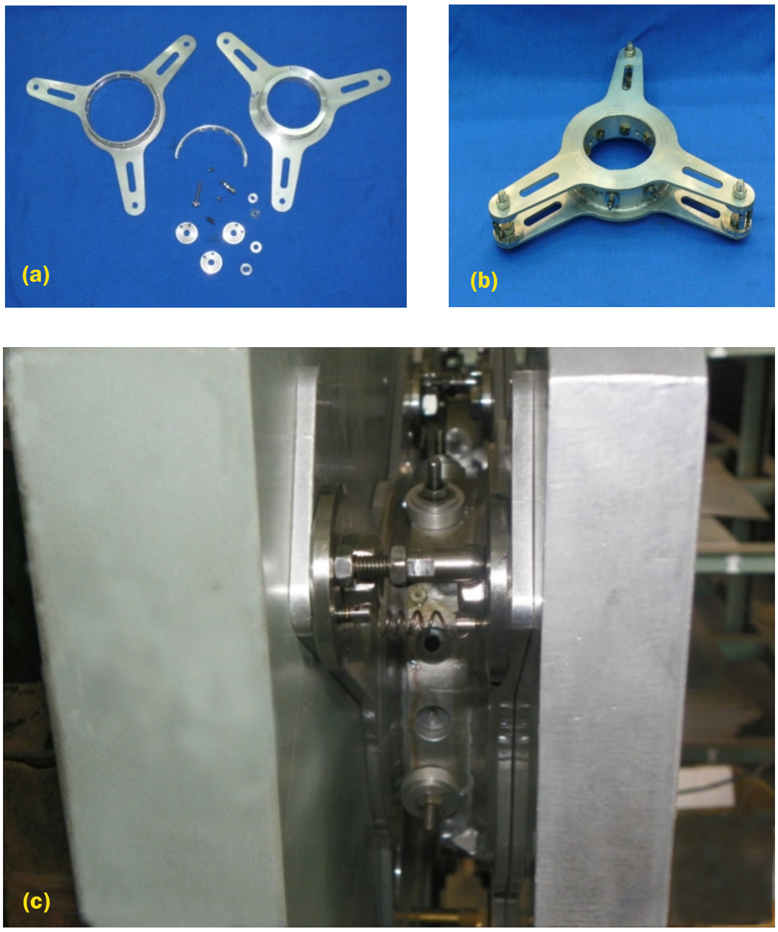
However, since their mirrors are diamond milled and not diamond-turned we expect the lifetime of these mirrors to be superior. It is important to mention here that major factors which enhance the Al mirror life are used in dry climate conditions, low pollution, and operation in non-salt environments. Due to all these favorable factors at the observation site, one expects to be served by these mirrors for a longer duration.

Mirror Alignment on the Ground

Mirror facets are arranged in ascending order of their ROC and 4 closely matched facets in terms of ROC are



▲ ENVIRONMENT cycling test conducted on two mirrors at ECIL. No change in spot size had been observed after multiple levels of testing.



▲ MIRROR FACET MOUNTING adaptor (a) Adapter components (b) Assembled adaptor (c) Assembled adaptor holding mirror facet.

mounted on a single ~1mx1m honeycomb panel. In this way, 356 mirror panels were designed and mounted on the 11 pre-decided focal length zones on the telescope basket. A suitable arrangement in terms of in-house designed ball and socket adapters with suitable fixtures to provide azimuth and elevation movements were die-cast for holding the mirror facets with the 1mx1m back-end panel.

An experimental facility, similar to the one for quantification of single mirror facets with the 2f method, was set up at ECIL Hyderabad and at the telescope site at Hanle, for alignment of the mirror facets. The only difference with the earlier set up is that instead of a single mirror facet now 4 mirror facets, are mounted on a 1m^2 panel and help together in this new experimental setup.

The light source (laser diode) is equipped with a beam expander lens so as to uniformly illuminate the mirror panel at ROC of the panel (~50m away). The image of the laser light source after being reflected by the 4 mirror facet on the panel, is formed on the screen placed at the mean ROC of the panel. This image is brought to a sharp focus on this specially designed white screen, made to capture the images. This white screen can slide back and forth so that we can have a sharply focused spot of the reflected image. When exposed to this green laser source the four mirror facets mounted on each panel, form 4 distinct spots at the

▲ TEST SETUP for alignment of mirror panel (a) Green laser with beam expander (b) 4 mirrors on a 1m x1m panel (c) 4 unaligned spots due to 4 mirrors.

ROC.

The 4 mirror facets are now manually aligned in such a manner so that the reflected spots of 4 mirror facets on-screen overlap at the center of the screen on a pre-designed spot. This manual alignment is done by adjusting the adapters which can be manipulated with ease. This specially designed adapter assembly has been clamped onto the 3 metal inserts of the mirror facets. This adapter assembly can provide for both zenith and azimuthal motions so that distinct reflected spots, captured on the screen, can easily be brought to focus at the desired position. Once this is accomplished, the adapter assembly is locked through various combinations of nuts and locknuts. This procedure is accomplished in such a way so as to form a single spot of diameter (D80) is ⩽15 mm for this purpose. Locktite Grade 290 (thread locker), used for metal to metal bonding, is then applied so that the lock nuts do not slip due to continuous operation on the telescope. This procedure of manually overlapping 4 mirror facet spots to form a single spot, is referred to as alignment on the ground for the whole panel without deteriorating the spots formed by the individual mirrors. The 4 mirror facets are thus assembled in a manner that the resulting reflecting surface behaves like a single spherical reflector.

THE mechanical stability of mirror panels is quite crucial as they are exposed to an open environment where the peak wind speed can go up to 100 km/hr as well as withstand gravitational stress during tracking of gamma-ray sources.

Vibration Test

Mechanical stability of each mirror panel is very important as it will be exposed to an open environment in Hanle, where the peak wind speed can go up to 100 km/hr, and also to withstand the gravitational stress during tracking of gamma-ray sources. To check the robustness of the alignment methodology, each mirror panel is subjected to a vibration test within the standard simulated parameters as the panel will encounter on the telescope basket. For vibration testing the Dickie Hotlz make vibration testing machine has been used. Frequency is varied from 3-350 Hz and value of ‘g’ (acceleration due to gravity) is fixed at 0.1g. Peak to peak displacement of ~6 mm is experienced by the mirror panel. Six such samples, each lasting about 6 minutes are repeated for on the vibration machine. The variation of acceleration as a function of Frequency. The peak value of ‘g’ experience by the mirror panel is ~1.1g, due to resonance. The integrated panel spot before and after the vibration testing is monitored. No change is observed in the panel spot size thereby assuring that the alignment done can withstand the stresses on the basket. The mirror panels are then transported to the site (Hanle), fine-tuned again for alignment due to long journey (ECIL Hyderabad facility to Leh) and then kept ready for mounting on the basket.

Mirror Alignment on Basket

Motorized actuators are used for the alignment of such a large number of mirror panels to obtain the optimal point spread function. Each of the 356 panels is attached to the basket frame at three points by ball joint pivots. Two of these support points are equipped with linearly movable actuators with a travel of 2.5cm. An active mirror alignment control system is used for orienting each panel to achieve the desired optical quality of the reflector. When the telescope points to different zenith angles, the surface reflector may undergo small deformations due to varying gravitation loads. This effect is corrected through the realignment of individual panels by using an active mirror control system. The mirror panel alignment technique for the MACE telescope uses a bright star which can be considered to be a natural point source at infinity.

The telescope is pointed towards the bright star and its image is focused at the focal plane. Before panel alignment, multiple images of the bright star are formed at the focal plane by various mirror panels. The spots corresponding to individual mirror panels are identified and then the panel is aligned in such a way that all the images are focused at the focal point. A CCD camera at the center of the reflector is used to capture the image of the bright star on the focal plane and hence the optical feedback of the telescope.

The optical system of the MACE telescope provides a point spread function less than 0.150 at lower zenith angles. The image of the pole star was measured by the CCD camera on the focal plane after subjecting it to background subtraction and image cleaning. The D80 of the image is seen to be 46.5mm after performing a Gaussian fit to the pole star image.

Conclusion

A total of 1564 diamond-turned metallic mirrors (1424 for 356 panels) and another 140 spare mirror facets have been fabricated. These diamond-turned metallic mirrors with a honeycomb sandwich have been fabricated for the first time in the country. The individual mirror facets have been subjected to rigorous quantification testing. After acceptance, the ROC measurements of facets, alignment on the panel, and vibration tests were conducted. The mirror panels were eventually transported to the MACE telescope site (Hanle, Leh), where some fine-tuning in alignment, were done again to account for misalignment effects due to the ~2000 km journey. Motorized actuators are used for the alignment of a large number of mirror panels to obtain the optimal point spread function. An active mirror alignment control system is used for orienting each mirror panel to achieve the desired optical quality of the reflector.

Acknowledgment

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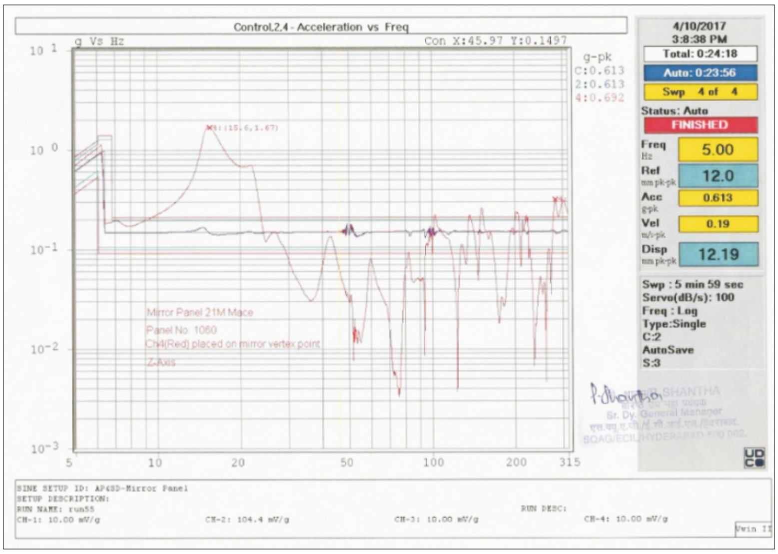
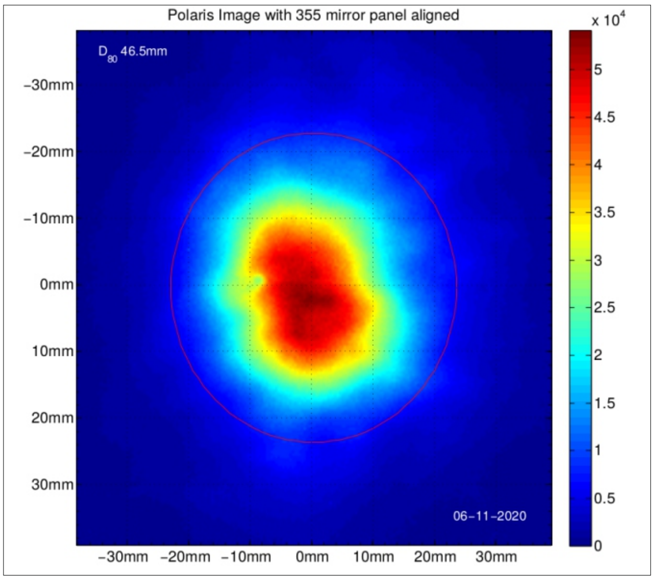
▲ THE VIBRATION TEST machine for testing mirror panels.



▲ ACCELERATION vs Frequency plot of the mirror panels.



▲ POINT spread function of MACE measured for Polaris.