CONCEPTUALIZING THE MACE TELESCOPE

A Brief Historical Account

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The country's first imaging gamma ray telescope TACTIC, operating at a trigger threshold of about 1.2 TeV, was installed at Mount Abu in 1997. During its commissioning trials conducted during April-May 1997 using a 81-pixel imaging camera, it detected gamma-ray emission from the Active Galactic Nuclei, Mrk 501. This was the first time that an extragalactic gamma ray flaring event was detected by 4 different IACTs located around the globe. This first observational result from the TACTIC telescope was well received by the astronomy community in India and abroad and validated the techniques used by us in the hardware, software and data analysis of the telescope. This result also gave us the confidence to look into the possibility of setting up a telescope operating at an energy threshold <100 GeV to explore the Universe in this hitherto unexplored energy range.

Under the leadership of my senior colleague and head of our division, C.L. Bhat, we started looking into the possibility of building a 25m diameter class gamma-ray telescope. It is interesting to note here that TACTIC has a light collection area of about $10m^2$ while the new telescope being proposed would have about 40 times larger light collection area. Various configurations were discussed within the division and a conceptual design was presented at a local instrumentation symposium.

In the absence of a better name we started referring to this bigger telescope as TACTIC+. At the conference we learnt that the drive system for the array of 45m diameter GMRT (Giant Metre-wave Radio Telescope) telescope, installed at Narayangoan near Pune, was designed and developed by BARC. We soon initiated discussions with some members of the design team and found G. Govindarajan, Head, Reactor Control Division and his colleague G.P. Srivastava look positively at our proposal.

In the 19th meeting of the Astronomical Society of India held at Bangalore in February 1999, the team presented the preliminary configuration of a 25m diameter MACE which was estimated to cost around Rs. 40 crore. It was also proposed that the 25m diameter Cherenkov imaging telescope be built along with a piggy-back gamma-ray burst detector.

This telescope would deploy an imaging camera of about 800 PMTs for the imaging of Cherenkov events and a concentric circular ring of 180 PMTs at a distance of 5m from the imaging camera centre for concurrent detection of gamma-ray bursts with fluorescence detectors. This baseline of 10m would give us an accuracy of a few degrees in the detection of a gamma-ray burst direction. We referred to this ring of PMTs as the BEST (Burst Estimation through Scintillation Technique) detector. A notable feature of this hybrid focal-plane instrumentation was that in the event of the fluorescent detectors detecting a gamma-ray burst, the telescope could be reoriented towards the burst arrival direction to search for correlated VHE spectral-tails of these enigmatic cosmic events. This preliminary proposal was discussed in detail and S.S. Kapoor, Director, Physics and Electronics and Instrumentation Group, set up a coordination committee in October 1999 under his chairmanship for the implementation of MACE.

Senior scientists and engineers from Electronics Division, Control Instrumentation Division, Central Workshop and the Nuclear Research Laboratory Division were the members of this committee.

The overall concept of a Cherenkov imaging telescope with a gamma-ray burst detector was appreciated by the astrophysics community at the various conferences where it was presented. However as we went on to the next step of getting an engineering concept evolved we ran into difficulties. Our engineering colleagues were not comfortable with a 10m diameter ring around the imaging camera and cited a host of difficulties they would face with the design. We held on to the concept for a few more months but had to finally yield to their suggestion of building the telescope without the BEST detector as the structural design was getting complex.

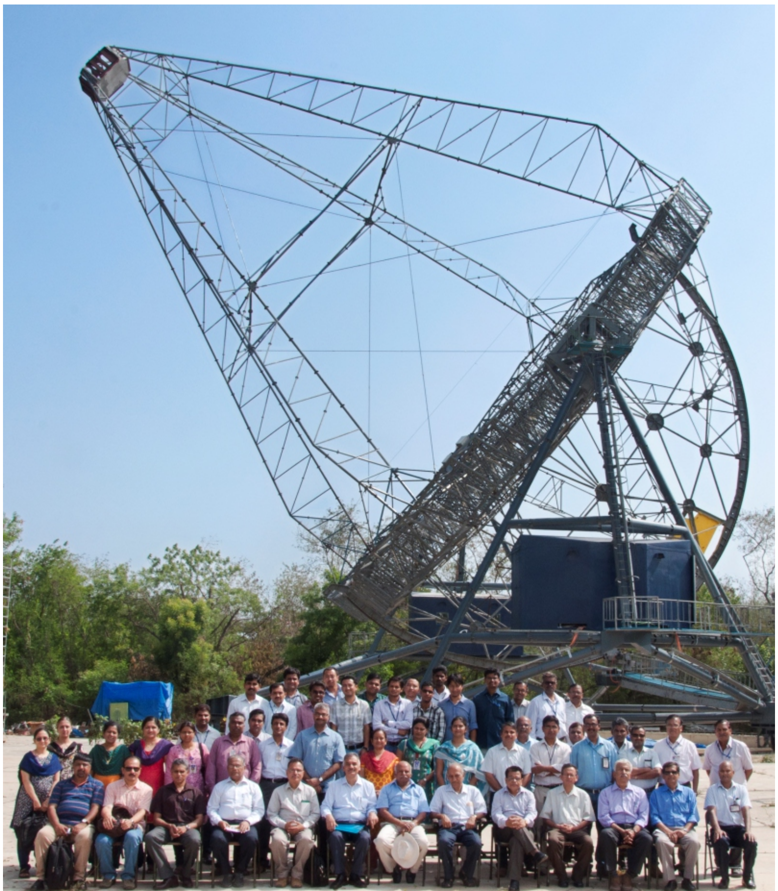
During the intervening period our senior colleagues had a number of interactions with Prof. Eckert Lorentz and Prof. M. Teshima of Max Plank Institute, Munich who were leading the efforts to set up the 17m diameter MAGIC telescope. These interactions led to a consensus of limiting the diameter of the MACE telescope to 17m so that some developments undertaken for the MAGIC telescope can be utilized for the MACE. We presented a paper giving the design details of the 17m diameter MACE telescope at the International Cosmic Ray Conference held in 2001.

Shifting the Location of MACE from Mount Abu to Hanle

The finalization of the site for the MACE was influenced by our experience with the operation of the TACTIC at Mount Abu. The first few years of TACTIC operation were really campaign modes when the telescope was operated with minimal infrastructure support. We had evolved the conceptual design of the mobile dome for protecting the telescope from the monsoon rains and the daytime sunshine but its fabrication got delayed. Every morning after the observations we would cover the 349-pixel camera of the telescope with a specially designed cloth followed by a tarpaulin and tie it with ropes to ensure that the wind would not expose the PMTs to daylight. Though the telescope was pointed towards the North during the day to prevent the sunlight falling directly on the mirrors, we would cover the reflecting surface with a specially designed cloth cover of 5m x 5m size. We finally got the motorized mobile dome fabricated at the site and it was operational in June 1998 just before the onset of the monsoon rains. The dome was good for sheltering the telescope from rain and the sun, however during the first monsoon after its installation we realized that it did not prevent fog and humidity from reaching the telescope. At Mount Abu during the monsoon one can see huge volumes of fog moving close to the ground bringing visibility down to a few feet and at the same time depositing moisture on anything they come in contact with. We installed a dehumidifier inside the dome but it would get saturated during the days with peak fog and keeping it continuously powered on was also an issue due to the irregular power supply conditions prevailing during monsoon. With these experiences with rain and fog at Mount Abu we were not sure how the huge mechanical structure, camera electronics and the mirrors of the MACE telescope could be protected during the monsoon when about 200cm of rainfall is recorded during the months of June to September. As we had also drawn a blank from the Union Ministry of Environment and Forests as far as the allotment of land at Gurushikar was concerned we started looking at alternative locations for setting up the MACE telescope.

The country has to bear the brunt of the annual monsoons, however the northern most areas of Ladakh located across the Karakoram range have scanty rainfall during August-September every year. The total annual precipitation in these areas is < 15cm. Being an arid cold desert the Ladakh region also boasts of less humidity which is ideal for optical telescopes. We were aware about the setting up of a 2m class optical telescope there by the Indian Institute of Astrophysics (IIA), Bangalore. The institute had been allocated a large area in Hanle located about 250km from Leh. Prof. R.N. Cowsik, Director, IIA was keen to set up other astronomical instruments there for better utilization of the site. In fact a few years back he had invited C.L. Bhat to participate in discussions related to this. As our programme was still evolving at that time we did not move ahead on the proposal.

By 2002, the situation at Hanle had changed with the installation and functioning of the 2m Himalayan Chandra Telescope (HCT). The IIA had also set up some



PARTICIPANTS OF THE Critical Design Review Meeting held in June 2014 at ECIL, Hyderabad. The fully assembled mechanical structure of the MACE Telescope (without mirror facets and camera) is in the background.

backup infrastructure both at Hanle and Leh and they were confident that operation at such a high altitude with extreme low temperature conditions during winter is not very difficult. IIA had also signed a memorandum of understanding (MoU) with TIFR, Mumbai for setting up a wave-front sampling gamma-ray telescope array, HAGAR, at Hanle and the scientific infrastructure for gamma-ray astronomy was being setup there. TIFR had been operating a wave-front sampling telescope, PACT (Pachmarhi Array of Cherenkov Telescopes), with a trigger threshold of about 1 TeV, at Pachmarhi since 1996. A similar telescope at Hanle would operate at <200 GeV just because of the high altitude. An additional fact of relatively much darker sky at Hanle compared to Pachmarhi, had also been identified by the TIFR group.

> **THE TELESCOPE** could be reoriented towards the direction of burst arrival to search for correlated Very High Energy spectral tails of enigmatic cosmic events.

The relative merits and difficulties to be faced at Hanle were discussed within the division and the consensus was that in the long term it would be advantageous to set up the MACE at Hanle. We organized a national meeting of experts to deliberate further on this subject on 25th April 2003 at BARC. The meeting was chaired by Dr. Anil Kakodkar, Chairman, Atomic Energy Commission and was attended by senior scientist of BARC, TIFR and IIA. Prof. B.V. Srikantan Former Director, TIFR and H. Razdan, Former Head, NRL-HARL Division also participated in the meeting. The overall feel of the participants was that the setting up of the telescope at

▲ THE ASSEMBLY of the alidade structure with stiffening ring and bull-gear support structure of the telescope was completed at Hanle in November 2015.

Hanle was difficult but doable. Prof. Srikantan opined that this was a chance for us to set up a world class gamma-ray telescope within the country. Dr. Kakodkar also supported the project but cautioned against time and cost overruns.

As a follow-up to this meeting we planned a joint visit of a team of scientists and engineers from TIFR, BARC and IIA to Hanle in September 2003. The team comprised of P.B. Kulkarni, Director, Engineering Services Group, R.K. Kaul, A.K. Tickoo and me from BARC, Prof. B.S. Acharya from TIFR and Prof. P.R. Vishwanath from IIA. After reaching Leh we were advised to stay indoors for at least 48 hours without any physical exertion to ensure that our bodies get acclimatized to the low atmospheric pressure prevailing there. After ensuring that our blood oxygen saturation levels increased to > 90% after 2 days we were allowed to proceed to Hanle. The distance of 250km to Hanle from Leh was covered in about 8 hr. During our 2 days (and 3 nights) stay at Hanle we tried to gauge the sky brightness and the sky transparency based on our experience at Mount Abu, but the cloudy sky did not share its secrets. However our discussions with the local staff revealed that the brightness of the galactic arm at Hanle was seen to be believed.

We also used the 2 days to identify and demarcate the location of the HAGAR and the MACE telescopes, keeping a provision for a 2nd element of the MACE. It was decided to have a 7-element HAGAR with an inter-detector spacing of 50m. The 7 elements were located as the centre and 6 corners of a hexagon of 50m side. 3-elements of the HAGAR were demarcated such that they were on the North–South line. The colleagues from all the 3 institutes were enthusiastic about the decision to set up MACE at Hanle. This was becoming an opportunity for the gamma-ray astronomy community of the country to work together and strengthen a national program. Back in Trombay we prepared a report confirming the decision of the National Committee and circulated it. The die was cast, we had to stay put on this decision and ensure that the MACE is set up at the earliest. We were advised to prepare a new detailed project report wherein the concerns due to the change in location are addressed. We looked at this option as an opportunity to further fine-tune the specifications to give MACE a unique identity. As a follow up of the decision to set up the MACE telescope at Hanle we organized a number of meetings among scientists from IIA, TIFR and BARC to identify common areas of interest in astrophysics. These discussions culminated in the signing of a formal MoU for cooperation in the area of astronomy and astrophysics between BARC, Mumbai and IIA, Bangalore by the directors of the two institutions on 30th December 2004.

This MoU formed the basis of our activities for the next few years which were used for finalizing the over all design concepts to be followed for the MACE telescope. Inputs from Prof. T.P. Prabhu of IIA and his team at Hanle were very useful at this stage. As the scope of activities at Hanle was enhanced, a more detailed MoU was signed by the directors of BARC, IIA and TIFR on 19th February 2009.

Conceptual Design and Implementation Strategy

A small group of engineers and scientists was quickly put together in BARC to start the pre-project activities. Our immediate target was to finalize the specifications and write a detailed project report for seeking funds from DAE (Department of Atomic Energy). During the first meeting of the science group it was emphasized that we should target for a world class facility. In 2003, all the existing gamma-ray telescopes operated at threshold energy of > 100 GeV and the need to explore the Universe in the hitherto unexplored energy range of 10-100 GeV was being discussed extensively. This energy band was becoming more important as the GLAST (Gamma ray Large Area Space Telescope) Space Observatory scheduled for launch in 2007-08 would extend the observation energy range beyond the EGRET (Energetic Gamma Ray Experiment Telescope) range all the way to about 10 GeV though with limited sensitivity. The 17m diameter MAGIC telescope was at an advanced stage of development and a proposal for the ECO-1000 (European Cherenkov Observatory), a 30m diameter Cherenkov telescope had been prepared by the Max Planck Institute, Munich. The HESS group had also started conceiving the 28m diameter HESS-II telescope. The emphasis of these experimental facilities was on lowering the energy threshold.

The experience of setting up TACTIC had given us the appreciation of the technical and administrative difficulties associated with a large project which has to rely on the technical inputs from experts in various fields. We concentrated on the physics aspects first and drew a wish list of our requirements in the light of ECO-1000 and HESS-II proposals. This was followed up with the broad specifications of the 4 major subsystems of the telescope which we identified as mechanical structure, drive system, optics and detector electronics.

Having targeted the trigger threshold energy of the telescope to be <30 GeV we were constrained to have a large light collector area of the order of 300m^2. Our experience with TACTIC had also sensitized us about the importance of the F-number of the light collector and we set this to 1.2 for the new telescope. These 2 parameters were required for the overall conceptual design of the mechanical structure of the telescope. A team of mechanical engineers under the leadership of R.L. Suthar, was constituted to evolve the conceptual design. The team visited the 45m diameter GMRT near Pune and had extensive discussions with S.C. Tapde, Engineer-in-charge of the facility and his team. The first version of the conceptual design which was available in the summer of 2004 had a strong bias towards the TACTIC and GMRT designs and it really looked like their scaled hybrid version. This first version was discussed at various scientific meetings in the country. The decadal vision document on astronomy produced by the Indian Academy of Sciences in 2004 listed the proposed MACE telescope as an important Indian initiative in astronomy. The conceptual design was also discussed extensively within the centre and a number of suggestions were received from various experts. During these discussions it was decided that the track and wheel design for azimuthal movement should be finalized. Considering the large structure and the solid mirrors to be used in comparison to the wire-mesh collector of the GMRT the track and wheel design turns out to be much more stable. After a number of iterations the light collector evolved as a 21m diameter space-frame suspended from a 1m wide stiffening ring which is held over the two elevation axis support structures. The 3-layer space frame has a grid structure over which the mirror panels can be fixed.

In view of the large size of the light collector the telescope optics has to be based on a tessellated mirror concept. Considering the off-axis spot size the optimized size of a mirror tile is about 1m x 1m. The square shape of the mirror tile gives a better fill factor for the light collector compared to a circular shape and also simplifies the backup grid design. As the design process was evolving we also had discussions for the manufacture of these mirror tiles with various institutions within the country. Manufacture of glass mirrors for the telescope was discussed with experts at the IIA, LEOS (Laboratory for Electro Optics Systems), Bengaluru and Central Glass Research Institute, Kolkata. It was realized that a 1m x1m glass mirror tile will take about 50 days for grinding and polishing to the required finish. We also looked into the possibility of using metallic mirrors like the MAGIC telescope. Detailed discussions over telephone and email were held with M/s. Eltec, Germany and 10 mirror tiles of 50cm x 50cm were procured from them for the purpose of evaluation of the concept.

During the course of discussions within the centre, a colleague from the Precision Engineering Division talked about the possibility of manufacture of metal optics using the diamond turning process. We were also told that a few vendors with diamond turning facilities required for some other programmes of the centre, had been developed within the country. As a first step we sought 50mm and 100mm diameter aluminium mirror samples from these vendors. The reflectivity characteristics of these samples were very good. On further discussions with the vendors it turned out that the maximum diameter that their machines can handle is 300mm. We toyed with the idea of using 9 mirror tiles of 30cm x 30cm size on a 1m x 1m panel, but operationally it seemed to be a difficult proposition as 9 tiles per panel had to be pre-aligned. After a few more rounds of discussion, one of the vendors was enthusiastic to set up a facility for our requirement. In view of his strong financial background and experience with diamond turning we decided to work with him and have the first facility of this kind set up in the country.

While the mechanical structure and the mirror design seemed to be on a firmer ground the camera electronics team took a little longer to come to terms with the fact that the signal processing and data acquisition electronics has to work reliably over a temperature range of -30°C to +30°C. The other constraint we had put was that the entire instrumentation has to be housed within the camera structure and only data communication optical cables and power supply cables are connected to it from outside. Miniaturization was the key and our electronics team looked at state-of-the-art solutions for the camera electronics.

In the earliest version of the imaging camera we had started with 800-pixels which subsequently went up to 1536-pixels and we finally settled for 1088-pixels with a triangular pitch of 55mm which corresponds to a pixel size of 0.125°. Though we were targeting a pixel size of 45mm which corresponds to 0.1° the final pixel size was dictated by the dimensions of the smallest signal processing and data acquisition printed circuit boards which we could design in-house. The documented first version of the conceptual design of the telescope was available in the summer of 2005 and was discussed in the "Workshop on New Generation Cherenkov Telescopes" held at BARC, Mumbai during 1st-2nd August 2005. This workshop was planned as a pre-event for the 29th International Cosmic Ray Conference held in Pune. Organizing this workshop turned out to be a challenge as Mumbai was hit by a record rainfall of ~90cm on 26th July 2005 disrupting normal life in the city. However, the workshop went of well and it was attended by 65 scientists including 36 from abroad.

All the 4 gamma-ray telescope collaborations, namely MAGIC, HESS, VERITAS and CANGAROO were well represented in the workshop and it gave us an opportunity to discuss the details of all the subsystems proposed for the MACE telescope. The reassuring comments of the experts helped us move ahead. The discussions were continued during the International Cosmic Ray Conference meeting at Pune during August 3-9, 2005. During one of these discussions Prof. M. Tashima suggested that we may look into the possibility of setting up the MACE telescope at La Palma, where it could become a prototype for the large size telescope of the proposed international collaboration project CTA (Cherenkov Telescope Array). We did not discuss this proposal further as MACE was being looked as an important scientific infrastructure project in the country.

A six member Project Implementation Committee (PIC) under the chairmanship of G.P. Srivastava, Director, Electronics & Instrumentation Group, BARC was constituted on 19th July 2006, to devise a strategy for the implementation of the project. The other members of the Committee were Head, Center for Design and Manufacture, Head, Electronics Division and Internal Finance Advisor, BARC. I was nominated as the Member–secretary of the PIC with the task of ensuring regular meetings. In its first meeting held on 31st July 2006 the PIC concluded that the project was too big for in-house implementation and deliberated about the need to interact with various

▲ THE FULLY ASSEMBLED MECHANICAL STRUCTURE of the MACE telescope along with the camera structure at Hanle in July 2017.

mechanical fabrication agencies in the country. It was decided to have preliminary discussions with a M/s. Larsen and Toubro (L&T), M/s. Godrej, M/s. Walchandnagar Industries and M/s. Tata Consulting Engineers (TCE).

In the following weeks a number of discussions were held with these vendors. M/s. TCE who were associated with the setting up of GMRT, Pune had the domain specific knowledge however they were interested only in the detailed design work related to the telescope structure. M/s. L&T expressed their willingness to take up the project on a turn-key basis, however they did not have the specific domain expertise. The other manufacturers contacted were not enthusiastic about the one of a kind project that the telescope represented. During one of the PIC meetings, it was suggested that M/s. Electronics Corporation of India (ECIL) should be contacted as they had recently got an order from the Department of Space for the manufacture of a 32m diameter Deep Space Network (DSN) antenna. A series of meetings was held and M/s. ECIL expressed their willingness to take up the project on a turnkey basis. As ECIL is a public sector undertaking of the DAE, the PIC members felt that it will be easier to manage a developmental project like MACE with ECIL. It was decided to seek an in-principle approval from DAE for working out the details of the contract with ECIL. The proposal was approved by DAE on 8th Dec 2006. In the mean time, all the details about pricing and implementation had been worked out with ECIL and we were ready with the final tender enquiry to be issued on a single tender basis. A budgetary quote was sought from ECIL a few months earlier and a series of discussions for price negotiations were held. In order to speed up the detailed design process we issued a Letter of Intent (LoI) to ECIL so that pre-project activities including identification of design consultants could be initiated before the release of the final work order.

MINIATURISATION was considered to be the key aspect and the electronics team of BARC had pursued state-of-art solutions for equipping the camera electronics.

In view of the uncertainty in the pricing of various items being manufactured in the country for the first time a strategy of fixed-cost items and cost-plus items was followed. Metallic mirror facets and the imaging camera electronics were the two items included in the cost-plus category as their design and manufacturing procedures were still being worked out. Project management, including logistics and contingencies and transportation costs were also defined separately. After a number of rounds of discussions which included finance experts from ECIL and BARC a work order for the detailed design, development, supply, installation and commissioning of the MACE telescope at Hanle was issued to ECIL on 3rd March 2008. The work order was handed over to Rajshekhar Rao, CMD, ECIL by V.C. Sahni, Director, Physics Group, BARC in the presence of Anil Kakodkar, Secretary, DAE, in his office at OYC, Mumbai. As per the work order the telescope was to be commissioned at Hanle within 33 months. While accepting the work order Rajshekhar Rao, CMD, ECIL enthusiastically remarked that with the expertise available with ECIL the telescope will be commissioned well within its allocated time. Despite the optimism displayed by ECIL my conservative estimate was that the telescope would surely see first light towards the end of 2012 with observations on the Crab Nebula.

Epilogue

The detailed design of the mechanical structure, which was outsourced, got delayed by about 2 years and technical difficulties faced in the manufacture of some critical components like the large size bull-gear segments, mirror actuators and gear-boxes, added another 2 years to the delay. The production of the metallic mirror facets, which were being manufactured indigenously for the first time, also got delayed, however, as the mirrors were required at the last stage of installation, the delay in their manufacture did not stretch the schedule any further. The camera electronics was installed in the camera structure and tested at ECIL, Hyderabad in June 2016.

The trial installation of the telescope mechanical structure was done in ECIL, Hyderabad in June 2014. Subsequently, the structure was dismantled and shipped to Hanle for installation. At Hanle, the installation work was started in September and by the end of the working season in November 2014, the 27m track and the first layer of the adelade structure with 6 wheels was installed. As the installation work proceeded three major retro-fitting works had to be undertaken for the 4-boom structure, the bull-gear support structure and the camera housing, leading to a cumulative delay of about 2 years.

The fully wired 1088-pixel camera was exposed to the night sky for the first time on 10th October 2018 and Cherenkov images were recorded with the central 50 mirror panels aligned. As the number of mirror panels was increased to 225 some structural deformations were noticed which led to the major retro-fitting of the bull-gear support structure. Subsequently, all the 356 mirror panels and their actuators were installed. After elaborate testing of all the telescope sub-systems, on-source data was collected from the Crab Nebula for a few hours during February 20-26, 2020 with the central 120 mirror panels exposed. The gamma ray signal from the Crab Nebula was picked up with a statistical significance of 6.2σ from an on-source data spell of 5.6 hrs. Subsequently all the mirrors were aligned and the Crab Nebula was observed at large zenith angles during April 1-3, 2021 when a 6.4σ gamma ray signal was picked up in 75 mins of on-source observation. In October-November 2021, a 20.5σ signal was observed in about 17 hrs of on-source observations.

The telescope and the data analysis chain has been optimized to a level where the steady emission of gamma rays from the Crab Nebula can be detected at a 5σ statistical significance in about 60 minutes of on-source observations, however efforts are on to improve the sensitivity to its design value where the Crab Nebula steady gamma-ray signal can be detected in about 10 minutes of on-source observation.

 # The article is dedicated to the memory of my former colleagues Dr. H. Razdan, Dr. C. L. Bhat and Dr. A. K. Tickoo, who contributed substantially towards the development of ground based Gamma-Ray Astronomy in India.

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