Status of Himalayan Gamma Ray Observatory (HiGRO) at Hanle

B S Acharya
Tata Institute of Fundamental Research, Mumbai, INDIA
(for the HiGRO collaboration)

5th Workshop on Detection of Air Showers at High Altitudes, APC, Paris, May 26-28, 2014
Himalayan Gamma Ray Observatory, HiGRO @ Hanle

- Hanle: a high altitude location in Himalayas
- Cost effective way of reducing energy threshold of atmospheric Cherenkov telescope

Higher Cherenkov photon density and less atmospheric attenuation of Cherenkov photons at higher altitudes
Himalayan Gamma Ray Observatory (HiGRO)

- Lower energy threshold using high altitude location
- Collaboration between BARC, IIA, TIFR and SINP

Located at Hanle in Himalayas
Latitude : $32^\circ 46' 46''$ N
Longitude : $78^\circ 57' 51''$ E
Altitude : 4270 m

- Located at the base camp of Indian Astronomical Observatory of IIA
- 260 spectroscopic nights/year

Phase 1 : HAGAR
(array of 7 small telescopes)
Phase 2 : MACE
(21m diameter single telescope)
High Altitude GAamma Ray (HAGAR) Telescope Array

- An array of 7 telescopes based on wavefront sampling technique
- Arrival time of Cherenkov shower front recorded at various locations in Cherenkov pool using distributed array of telescopes

- 7 telescopes consisting of 7 para-axially mounted parabolic mirrors of diameter 0.9 m
- f/D ~ 1
- Photonis UV sensitive phototube (XP2268B) at the focus of each mirror
- Field of view : 30° FWHM
HAGAR Telescope Array

Installation during 2005-2008
IIA & TIFR
Fabricated at Bangalore by IIA
Optical system + DAQ by TIFR
**Tracking System**

- Alt-azimuth mount, each axis driven by separate stepper motor
- Telescope movement control system consists of two 17 bit rotary encoders, two stepper motors with drivers and micro-controller based Motion Control Interface Unit (MCIU)
  - Maximum zenith angle coverage upto $85^\circ$
  - Steady state pointing accuracy of servo is $\pm 10$ arc sec
  - Maximum slew rate: $30^\circ$/min

**MCIU**

**Pointing offsets for 49 mirrors**

**Pointing accuracy of a mirror:**
12.5 arcmin (SD=6.95 arcmin)

---

*K. S. Gothe et al., Experimental Astronomy, Vol. 35, p. 489-506, 2013*
Data Acquisition System

- High voltages given to individual PMTs are controlled through CAEN controller model (SY1527)
- PMT pulses are brought to control room through coaxial cables of type LMR-ultraflex-400 and RG213
- Data acquisition through CAMAC based instrumentation
- Event interrupt generated on coincidence of at least 4 telescope pulses
- Data recorded for each event:
  - relative arrival time of shower front at each mirror accurate to 0.25 ns using TDCs
  - pulse height at each telescope using 12 bit ADC
  - absolute event arrival time accurate to \( s \)
- Various count rates recorded every second for monitoring purpose
- Cherenkov pulses from telescopes recorded using Acqiris waveform digitizer with sampling rate of 1GS/s
Data Acquisition and Telescope Control System

CAMAC based => VME based + 8 ch Acqiris Digitiser
Modules Developed In-House

- CAMAC controller
- 16 ch. CAMAC Latch
- 16 ch. CAMAC Scaler
- CAMAC Real Time Clock
- NIM to ECL Converter
- ECL Delay Generator
- Programmable Delay Generator
- HAGAR Trigger Logic
- Programmable Discriminator
Simulations for HAGAR

CORSIKA + Detector simulation program developed in-house

CORSIKA v. 6.720:

VENUS, GHEISHA, EGS4, US standard atmospheric profile
Cherenkov photon wavelength range: 200-650 nm
Impact parameter range: 0-300 m
Viewcone: 0-4° for cosmic rays
HAGAR geometry, geomagnetic field at Hanle
Mirror reflectivity (80%), PMT quantum efficiency

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy range</th>
<th># of showers generated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma rays</td>
<td>20-5000</td>
<td>1 x 10^6</td>
</tr>
<tr>
<td>Protons</td>
<td>50-5000</td>
<td>3 x 10^6</td>
</tr>
<tr>
<td>Alpha particles</td>
<td>100-10000</td>
<td>6 x 10^6</td>
</tr>
<tr>
<td>Electrons</td>
<td>20-5000</td>
<td>3 x 10^6</td>
</tr>
</tbody>
</table>

Detector simulation program:

NSB generation:
2x10^8 ph/cm²/s/sr

PMT response:
gain=6.8x10^6, Gaussian 3 ns rise time

Attenuation in coaxial cables:
LMR-ultraflex-400 + RG213

Trigger formation:
4 fold trigger with 150 ns coincidence window
Comparison of Simulations with Observations

Variation of trigger rate with zenith angle →

Space angle distributions from plane front fitting of Cherenkov shower front ←

L. Saha et al., Astroparticle Physics
Performance Parameters of HAGAR

1. Trigger threshold : 17.5 photo-electrons/telescope

2. Trigger rate : Protons 9.2 Hz, α particles 3.7 Hz, Electrons 0.11 Hz
   Total trigger rate ~ 13.0 Hz

3. Energy threshold :
   208 GeV for vertical showers
   For ≥4 telescopes triggering

4. Expected gamma ray rate from Crab like sources = 6.3/min

5. Collection area = 3.2 × 10^4 m²

6. Sensitivity :
   1.2σ/√(hour) for Crab like sources

L. Saha et al., Astroparticle Physics
Comparison of Simulations with Observations

Rate-bias curve

Cherenkov pulse: width and amplitude

Charge in pulse

E. Kundu et al., NSGRA-2013
**HAGAR Observation Summary**

- Regular observational runs commenced in September, 2008

<table>
<thead>
<tr>
<th>Galactic sources</th>
<th>ON (Hours)</th>
<th>OFF (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>202.4</td>
<td>189.3</td>
</tr>
<tr>
<td>Geminga</td>
<td>126.3</td>
<td>76.1</td>
</tr>
<tr>
<td>Fermi pulsars</td>
<td>179.6</td>
<td>70.4</td>
</tr>
<tr>
<td>LSI+61 303</td>
<td>44.9</td>
<td>47.7</td>
</tr>
<tr>
<td>MGRO J2019+37</td>
<td>30.2</td>
<td>29.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extragalactic sources</th>
<th>ON (Hours)</th>
<th>OFF (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrk 421</td>
<td>196.1</td>
<td>227.1</td>
</tr>
<tr>
<td>1ES2344+514</td>
<td>114.0</td>
<td>131.0</td>
</tr>
<tr>
<td>Mrk 501</td>
<td>121.5</td>
<td>127.1</td>
</tr>
<tr>
<td>1ES1218+304</td>
<td>47.7</td>
<td>56.2</td>
</tr>
<tr>
<td>BL Lac</td>
<td>40.3</td>
<td>40.3</td>
</tr>
<tr>
<td>3C454.3</td>
<td>15.3</td>
<td>15.3</td>
</tr>
<tr>
<td>1ES1959+650</td>
<td>6.9</td>
<td>9.5</td>
</tr>
<tr>
<td>H1426+428</td>
<td>22.3</td>
<td>23.3</td>
</tr>
<tr>
<td>M87</td>
<td>2.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Calibration runs : 448.22 Hours

Total observation duration (during September, 2008 – September, 2013) : 2706.62 Hours
HAGAR Observation Summary

Seasonal variation of observation duration in Oct 2012 – Sept 2013
Data Analysis

(II) Event arrival direction profiles

(a) Source Positions
Shower Directions
NTT = All

(b) Source Positions
Shower Directions
NTT = All

(c) Number of Showers
Space Angle (deg.)

(d) Distribution
$\Delta \theta$ (exp-obs)
FWHM = 2.46
Mean = -0.20 $\pm$ 0.06

(e) Distribution
$\Delta \phi$ (exp-obs)
FWHM = 14.69
Mean = 0.08 $\pm$ 0.15

(f) Right Ascension (degree)
Declination (degree)
Analysis Method

- Observations carried out in ON-OFF pairs of 40 minutes duration each
- Selection cuts applied based on data quality, stability of rates etc
- Arrival direction of a shower is determined by reconstructing the shower front using arrival time of Cherenkov shower front at each telescope
- Cherenkov shower front approximated by plane front
- Space angle: angle between normal to the plane front and source direction

- Background space angle distributions are normalized w.r.t. source distributions by comparing shapes in LL to UL window

\[ \gamma \text{ ray signal} = \text{excess events} \]

\[ \text{no. of } \gamma\text{-rays} = \sum (S-cB) \]

C: normalization constant

B. B. Singh et al., NSGRA-2013
Observations & Data

- ON-OFF pairs of 40 minutes duration
- Calibration runs for systematic checks

<table>
<thead>
<tr>
<th>Source</th>
<th>Observation duration (hours)</th>
<th>Number of Run pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>110</td>
<td>171</td>
</tr>
<tr>
<td>Dark region</td>
<td>35</td>
<td>53</td>
</tr>
<tr>
<td>Delta leo (star m=2.7)</td>
<td>23</td>
<td>34</td>
</tr>
<tr>
<td>Milky way</td>
<td>18</td>
<td>32</td>
</tr>
</tbody>
</table>

Yearly Timeline:
- 2008 (Nov–Dec)
- 2009-2010 (Nov–Feb)
- 2010-2011 (Nov–Feb)
- 2011-2013 (Nov–Feb)
- 2012-2013 (Nov–Feb)
Data Analysis

Crab region:

RA  # 05:34:32
DEC # 22:00:52
Epoch # 2000

FoV of HAGAR: 3 degree

Crab nebula

Milkyway

Zeta tauri star, m=3

RA  # 05:37:38
DEC # 21:08:33
Epoch # 2000

Dark region
Data Analysis

Result – 1: Crab region vs Dark region

![Graph showing significance vs observation time for Crab region with NTT ≥ 4.]

<table>
<thead>
<tr>
<th>Crab region</th>
<th>Dark region</th>
<th>Milkyway</th>
<th>Star (δ-leo)</th>
<th>Crab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Runs</td>
<td>108/171</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total duration (hours)</td>
<td>67.3/109</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTT</td>
<td>Rate (min⁻¹)</td>
<td>σ</td>
<td>Rate (min⁻¹)</td>
<td></td>
</tr>
<tr>
<td>≥ 4</td>
<td>15.4 ± 0.4</td>
<td>38.6</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>≥ 5</td>
<td>9.7 ± 0.3</td>
<td>30.1</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>≥ 6</td>
<td>5.9 ± 0.3</td>
<td>23.5</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>≥ 7</td>
<td>2.5 ± 0.2</td>
<td>14.6</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>
Data Analysis

Result – 2 : Dark vs Dark region

<table>
<thead>
<tr>
<th>Crab region</th>
<th>Dark region</th>
<th>Milkyway</th>
<th>Star (δ-tau)</th>
<th>Crab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Runs</td>
<td>108/167</td>
<td>Monte-Carlo simulation*</td>
<td>40/53</td>
<td></td>
</tr>
<tr>
<td>Total duration (hours)</td>
<td>67.3/109</td>
<td>26.1/34.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTT</td>
<td>Rate (min⁻¹)</td>
<td>σ</td>
<td>Rate (min⁻¹)</td>
<td>Rate (min⁻¹)</td>
</tr>
<tr>
<td>≥ 4</td>
<td>15.4 ± 0.4</td>
<td>38.6</td>
<td>6.3</td>
<td>0.3 ± 0.8</td>
</tr>
<tr>
<td>≥ 5</td>
<td>9.7 ± 0.3</td>
<td>30.1</td>
<td>3.9</td>
<td>-0.5 ± 0.7</td>
</tr>
<tr>
<td>≥ 6</td>
<td>5.9 ± 0.3</td>
<td>23.5</td>
<td>2.4</td>
<td>-0.4 ± 0.5</td>
</tr>
<tr>
<td>≥ 7</td>
<td>2.5 ± 0.2</td>
<td>14.5</td>
<td>1.5</td>
<td>0.4 ± 0.4</td>
</tr>
</tbody>
</table>

Conclusion: No artificial signal is added if the sky brightness around ON-source and OFF regions are almost same.
Data Analysis

Result – 3: Milky-way vs Dark region

<table>
<thead>
<tr>
<th>Crab region</th>
<th>Dark region</th>
<th>Milkyway</th>
<th>Star (δ-leo)</th>
<th>Crab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Runs</td>
<td>108/167</td>
<td>40/53</td>
<td>20/32</td>
<td></td>
</tr>
<tr>
<td>Total duration (hours)</td>
<td>67.3/109</td>
<td>26.1/34.6</td>
<td>11.5/17.6</td>
<td></td>
</tr>
<tr>
<td>NTT</td>
<td>Rate (min⁻¹)</td>
<td>σ</td>
<td>Rate (min⁻¹)</td>
<td>Rate (min⁻¹)</td>
</tr>
<tr>
<td>≥ 4</td>
<td>15.4 ± 0.4</td>
<td>38.6</td>
<td>6.3</td>
<td>0.3 ± 0.8</td>
</tr>
<tr>
<td>≥ 5</td>
<td>9.7 ± 0.3</td>
<td>30.1</td>
<td>3.9</td>
<td>-0.5 ± 0.7</td>
</tr>
<tr>
<td>≥ 6</td>
<td>5.9 ± 0.3</td>
<td>23.5</td>
<td>2.4</td>
<td>-0.4 ± 0.5</td>
</tr>
<tr>
<td>≥ 7</td>
<td>2.5 ± 0.2</td>
<td>14.6</td>
<td>1.5</td>
<td>0.4 ± 0.4</td>
</tr>
</tbody>
</table>

Conclusion: No systematic/artificial signal is added due to brightness of the milky-way.
Data Analysis

Result – 4 : Star vs Dark region

On-source : δ-léo
Off-source : dark region

<table>
<thead>
<tr>
<th></th>
<th>Crab region</th>
<th>Dark region</th>
<th>Milkyway</th>
<th>Star (δ-léo)</th>
<th>Crab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Runs</td>
<td>108/167</td>
<td>40/53</td>
<td>20/32</td>
<td>24/34</td>
<td></td>
</tr>
<tr>
<td>Total duration (hours)</td>
<td>67.3/109</td>
<td>26.1/34.6</td>
<td>11.5/17.6</td>
<td>17.3/22.7</td>
<td></td>
</tr>
<tr>
<td>NTT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 4</td>
<td>15.4 ± 0.4</td>
<td>38.6</td>
<td>6.3</td>
<td>0.3 ± 0.8</td>
<td>9.2  ±0.8</td>
</tr>
<tr>
<td>≥ 5</td>
<td>9.7 ± 0.3</td>
<td>30.1</td>
<td>3.9</td>
<td>-0.5 ± 0.7</td>
<td>-0.1 ±0.9</td>
</tr>
<tr>
<td>≥ 6</td>
<td>5.9 ± 0.3</td>
<td>23.5</td>
<td>2.4</td>
<td>-0.4 ± 0.5</td>
<td>3.3  ±0.5</td>
</tr>
<tr>
<td>≥ 7</td>
<td>2.5 ± 0.2</td>
<td>14.6</td>
<td>1.5</td>
<td>0.4 ± 0.4</td>
<td>0.9  ±0.4</td>
</tr>
</tbody>
</table>

Conclusion: A star of magnitude 3 located at distance of 1 degree from a γ-ray source adds substantial systematic/artificial signal.
### Data Analysis

**Result – 4: Crab vs Dark region**

<table>
<thead>
<tr>
<th></th>
<th>Crab region</th>
<th>Dark region</th>
<th>Milkyway</th>
<th>Star (δ-leo)</th>
<th>Crab</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Runs</strong></td>
<td>108/167</td>
<td>40/53</td>
<td>20/32</td>
<td>24/34</td>
<td></td>
</tr>
<tr>
<td><strong>Total duration (hours)</strong></td>
<td>67.3/109</td>
<td>26.1/34.6</td>
<td>11.5/17.6</td>
<td>17.3/22.7</td>
<td></td>
</tr>
<tr>
<td><strong>NTT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rate (min⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 4</td>
<td>15.4 ± 0.4</td>
<td>6.3</td>
<td>0.3 ± 0.8</td>
<td>0.6 ± 1.1</td>
<td>9.2 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>38.6</td>
<td>30.1</td>
<td>-0.5 ± 0.7</td>
<td>-0.1 ± 0.9</td>
<td>5.8 ± 0.7</td>
</tr>
<tr>
<td>≥ 6</td>
<td>5.9 ± 0.3</td>
<td>2.4</td>
<td>-0.4 ± 0.5</td>
<td>-0.4 ± 0.7</td>
<td>3.3 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>23.5</td>
<td>20.1</td>
<td>1.5</td>
<td>0.4 ± 0.4</td>
<td>0.9 ± 0.4</td>
</tr>
<tr>
<td>≥ 7</td>
<td>2.5 ± 0.2</td>
<td>1.5</td>
<td>0.4 ± 0.4</td>
<td>0.1 ± 0.5</td>
<td>1.6 ± 0.2</td>
</tr>
</tbody>
</table>

*Monte-Carlo simulation*
**HAGAR Results : Crab Nebula**

- Only runs near transit of the source selected
- Observation duration after applying data quality cuts for data collected in 2008-2013 = 67.3 hours

### Significance

<table>
<thead>
<tr>
<th>#triggering telescopes</th>
<th>γ-ray rate (per minute)</th>
<th>Significance σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥4</td>
<td>6.18±0.40</td>
<td>15.5</td>
</tr>
<tr>
<td>≥5</td>
<td>3.90±0.32</td>
<td>12.1</td>
</tr>
<tr>
<td>≥6</td>
<td>2.61±0.25</td>
<td>10.4</td>
</tr>
<tr>
<td>=7</td>
<td>1.67±0.17</td>
<td>8.96</td>
</tr>
</tbody>
</table>

Crab flux = \((2.07 \pm 0.13) \times 10^{-10}\) ph/cm\(^2\)/s for threshold of 218 GeV

*B. B. Singh et al. NSGRA-2013*
Figure 4.6: Orbital geometry of LSI 61-303. The phases for Inferior conjunction (INFC), Superior conjunction (SUPC), periastron (P), and apastron (A) are shown following Ref. [101] and they occur at orbital phases 0.313, 0.081, 0.275 and 0.775, respectively.

Figure 4.7: Location of LSI 61-303 (red circle with size 3 degrees; ON-source region) in the sky along with the two background regions (green circles with size 3 degrees; OFF-source regions).

Figure 4.8: Distribution of orbital phase vs exposure time for the observation of LSI 61-303.

Figure 4.9: Upper: Distribution of gamma-ray rates for 14 pairs of LSI 61-303 for NTT > 4. Lower: Light curve of LSI 61-303 for different trigger conditions.

Figure 4.10: Gamma-ray rates of LSI 61-303 as a function of orbital phase for different telescope trigger conditions.
Status at Hanle site

240 KWp Solar Power Plant for MACE
Subsystems of the MACE telescope

- Mechanical Structure (150T)
- Mirror Panels (1564/4)
- Mirror Alignment System
- Bull Gear & Drive System
- Modular Camera Electronics
- Instrumentation Shelters
- Data Connectivity
- Data Archive

R. Koul et al. NSGRA-2013
Assembly status in Jan, March & May 2013

# Transportation requirements (size < 5mx3m)
TDU At Site

TDU RACK

Motorized AZ Axis Wheel

Shelter mounted on Structure
Mirror Assembly

# 1310 out of 1564 quality Diamond turned Al alloy mirror facets ready.

# 30 panels assembled & ready for deployment

# On-axis spot size of assembled panels measured < 5mm diameter

# Storage and transportation boxes for panels

# 9-panel mirror alignment system assembled

# Manufacture of Actuators
Spot-size distribution status after (1310 mirrors)

\[ \mu = 6.87 \pm 1.02 \text{ mm (ROC)} \]

\[ \mu = 0.45 \pm 0.06 \text{ arc min} \]

Spot size for \( D_{80} \) at ROC.
Alignment at mirror and at panel side procedure

- Aligning 2 panels in a day, to be speedup
- Torque behind the mirror facets and behind the panel
MACE Camera

- 1088 PMTs (ETE 9117 WSB) with a uniform pixel resolution 0.125 deg.
- 16 PMTs are arranged in a Camera Integrated Module (CIM).
- PMTs are powered by Voltage Divider Network (VDN).
- The socket, VDN and a pre-amplifier assembly is housed in a metallic enclosure.
- Programmable HV required for PMT gain matching is mounted close to PMT tubes.

Picture courtesy: ED
Status: Integration of fully assembled 4 CIM modules with DC, CCC, SLTG, Console, Data Archive, Master Clock is completed. Performance evaluation in progress.
64 channel prototype camera housing
Overall architecture - Block diagram of camera electronics

Entire electronics on camera, only power and communication cables to camera from ground station
Trigger generation, **MACE telescope** – two stage, two phase pattern based coincidence

First Level Trigger -
- effective coincidence window ~ 5-6 ns
- pe threshold ~ 3-5 photo-electrons
- Selectable tight cluster pattern of 3 to 6 pixels
- Nearest neighbour FULL trigger and partial border triggers,
- Border strength - STRONG, MEDIUM, WEAK

*Lower power, lower volume. Allows to compensate for PMT transit time variation with respect to high voltage bias*
Camera Electronics

# One 16 channel CIM tested extensively
# Assembly of three additional modules
# Integrated testing of 64 channels to start soon
# Bulk production to start after 64 ch. testing
# Data Archive – specifications finalised & procurement initiated
# Data connectivity – Anunet link
Revised time-line

# Review of Telescope Structure
    assembly: June 11-12, 2014

# Alignment & Drive tests : from 15 June 2014

# Dismantling of structure : 1 July 2014

# Transportation to Hanle : 1 Aug 2014

# start Installation at Hanle: 1 Sept 2014

# finish Installation by mid 2015
Mkn421
Figure 4.11: Location of the MGRO J1919+37 (3 degree red circle; ON-source region) in the sky along with the two background regions (0 degree green circles; OFF-source regions).

Figure 4.12: Upper. Distribution of gamma-ray rates for all 9 pairs for NTT > 4. Lower. Light curve for MGRO J1919+37 for all 9 pairs for different telescope triggering conditions.