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Observations with the High Altitude GAmma-Ray (HAGAR) telescope array in the Indian Himalayas

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Abstract. The High Altitude GAmma-Ray (HAGAR) array is a wavefront sampling array of 7 telescopes, set-up at Hanle, at 4270 m amsl, in the Ladakh region of the Himalayas (Northern India). It constitutes the first phase of the HImalayan Gamma-Ray Observatory (HIGRO) project. HAGAR is the first array of atmospheric Cherenkov telescopes established at a so high altitude, and was designed to reach a relatively low threshold (currently around 200 GeV) with quite a low mirror area (31 m^2). Regular source observations are running since September 2008. Estimation of the sensitivity of the experiment is undergoing using several hours of data from the direction of Crab nebula, the standard candle source of TeV gamma-ray astronomy, and from dark regions. Data were acquired using the On-source/Off-source tracking mode, and by comparing these sky regions the strength of the gamma-ray signal could be estimated. Gamma-ray events arrive close to telescope axis direction while the cosmic-ray background events arrive from the whole field of view. We discuss our analysis procedures for the estimate of arrival direction, estimate of gamma ray flux from Crab nebula, and the sensitivity of the HAGAR system, in this paper.

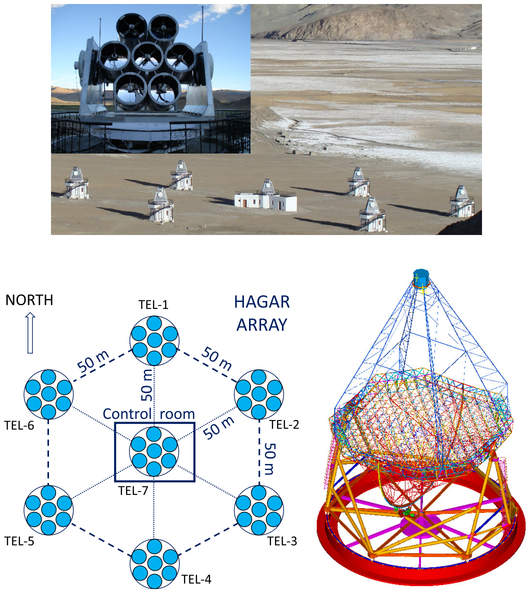

Fig. 1. **(a), (b)** The HAGAR telescope array. **(c)** MACE design.

1 The HImalayan Gamma-Ray Observatory (HIGRO)

Located at 4270 m amsl in the Ladakh region of the Himalayas, in Northern India (Latitude: 32°46'45" N, Longitude: 78°58'36" E), the HImalayan Gamma-Ray Observatory (HIGRO) was designed to conduct experiments using the Atmospheric Cherenkov Technique (Koul et al. (2005) and Fig. 1).

Operating with the full array of telescopes since 2008, the HAGAR experiment is the first phase of HIGRO. It is a sampling array of 7 telescopes, each one built with 7 para-axially mounted 0.9 m-diameter mirrors, giving a total reflective area of $\sim 31\,m^2$. Other characteristics are: f/D ~ 1; fast Photonis UV sensitive PMTs XP 2268B at the focus of each mirror and

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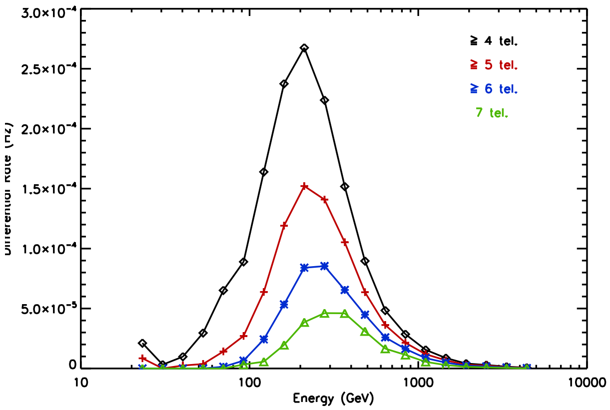

Fig. 2. Differential gamma-ray count rates from a simulated source with a flux equal to the Crab one, as estimated from simulated showers at vertical incidence. The four curves correspond to the four combinations of the number of triggered telescopes. For each combinations, the energy threshold corresponds to the peak of the distribution.

with a field of view of 3°17′; data recorded for each event: relative arrival time of shower front at each PMT accurate to 0.25 ns using TDCs; total charge at each mirror recorded using 12 bit QDCs (ADCs); absolute event arrival time accurate to μs; for trigger generation, the 7 pulses of PMTs of a given telescope are linearly added to form telescope pulse, called royal sum pulse. HAGAR operates with a trigger logic designed to significantly reject random triggers due to night sky background (NSB), as well as some of the cosmic ray events. Thus, a coincidence of any 4 telescope pulses above a preset threshold out of 7 royal sum pulses within a resolving time of 150 to 300 ns generates a trigger pulse (Chitnis et al., 2009a).

The phase 2 of HIGRO will be the installation of an imaging 21 m-diameter telescope, MACE (Major Atmosperic Cherenkov Experiment), whose first light is expected in 2012 (Yadav et al., 2009). This telescope was designed to reach an energy threshold as low as ~20 GeV, which is good for the studies of pulsars and high redshift AGNs where spectral energy distribution cutoffs are expected. Other charasteristics of this new instrument are a total reflective area of $\sim 330\,\mathrm{m}^2$ from 356 mirror panels, f/1.2 m, FOV of $4° \times 4°$, a 1088 pixel camera. The location in longitude of HIGRO will allow uninterupted observations along with other major gamma-ray observatories of the Northern Hemisphere: MAGIC in Canary Islands and VERITAS in the USA. This is particularly convenient to monitor sources such as AGNs, with flux variabilities in sub-hour time scales.

2 Monte Carlo simulations and energy threshold

Extensive Monte Carlo simulations are been carried out in order to understand performance of HAGAR experimental setup. Extensive air showers due to protons, alpha particles, electrons, and gamma primaries impinging on the atmosphere are simulated using the CORSIKA software package (Knapp and Heck, 1998; Heck et al., 1998), following appropriate energy spectrum. Cherenkov light distribution from these showers was then passed through detector simulation program specific to HAGAR, developed in-house. This program takes into account various site and instrument related parameters. Preliminary outputs of our simulations yield an estimation of the HAGAR energy threshold to be around 200 GeV, for vertical showers, before performing analysis cuts on data, for a total experimental trigger rate around 14 Hz (Fig. 2). Further simulations and analysis of simulation samples are going on to improve the precision of these values, to reproduce accurately the analysis variables, and defining analysis cuts. More on the performance parameters of HAGAR can be found in Chitnis et al. (2009a).

3 Signal extraction procedure

The analysis of HAGAR data is based on the arrival angle estimation of the incident atmospheric shower w.r.t. the source direction. This angle – called space angle – is obtained for each event by measuring relative arrival times of the showers at each telescope. Precise time calibration of the optoelectronic chain is then required, as well as an accurate pointing of telescopes (Chitnis et al., 2009a). The former is achieved first by computing TDC differences between pairs of telescopes from fix angle runs where the theoretical time-offsets are computed, using information on the pointing direction, coordinates of telescopes, and on the transit time of each channel through the electronic chain. The TDC differences between pairs of telescopes from fix angle runs yield the calculation of what we call "T_0's" (say "t-zeros"), which are the relative time offsets for all telescopes to be used in the analysis to ensure a valid estimation of the relative timing differences in the arrival of the Cherenkov signal on the telescopes. Space angle is then computed by fitting the arriving spherical Cherenkov wavefront, using plane front approximation. For each event, the value of the χ^2 of the fit and other fit parameters are given, and the number of telescopes with valid TDC information, i.e. participating in the trigger, is written. Thus are defined four types of events, based on the Number of Triggered Telescopes (NTT), viz. events with $\mathrm{NTT} = 4$, $\mathrm{NTT} = 5$, $\mathrm{NTT} = 6$ and $\mathrm{NTT} = 7$.

In order to remove isotropic emission due to cosmic rays, source observation region (ON) is compared with OFF-source region at same local coordinates on the sky, but at a different time (before or after tracking the source region for about 30 – 50 min). Atmospheric conditions change during observation time, reflected by variations on the trigger rate readings. This add systematics in our analysis. Normalisation of background events of both the ON and OFF source data sets is done by comparing number of events at

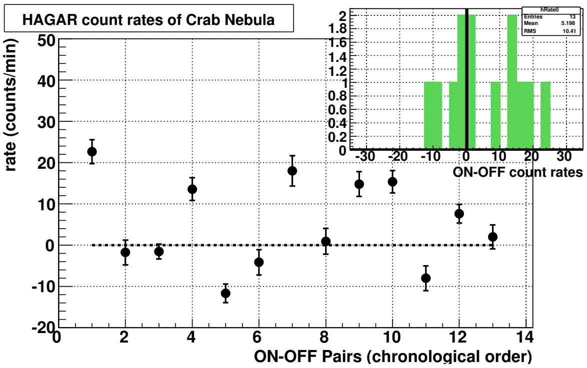

Fig. 3. Count rates of the selected pairs on Crab nebula in chronological order. Enclosed is the distributions of these counts.

large space angles, where no gamma-ray signal is expected. This yield a ratio, called normalisation constant, which allows to calculate the ON-OFF excess below one specific cut on the space angle distribution. More on the descrition of the analysis method and data selection can be found in Britto et al. (2009b).

4 Preliminary analysis of HAGAR data

Crab nebula, standard candle of the γ-ray astronomy, is used to calibrate the instrument and optimize hadronic rejection. However, signal extraction can be confirmed if background fluctuation between ON and OFF-axis source is not dominant, so an important step in the validation of the analysis method is to observe and analyse data by comparing two sets of OFF-source regions (called dark regions), located at a similar declination as of Crab nebula ($\simeq 22°$). A statistical significance less than 3σ was obtained from 6.6 h of dark region data (13 pairs) in our preliminary analysis, which indicates that systematic effects due to sky and time differences during observations are not dominant in our data/analysis. The analysis of 9.1 h of Crab nebula data (13 pairs) from the period September-December 2008 gives about 6.0σ, corresponding to 4.1 ± 0.7 counts min^{-1} above ~ 250 GeV (Fig. 3 and Britto et al., 2009a,b). The sensitivity of HAGAR to gamma rays from Crab nebula is similar to the results obtained with the CELESTE experiment in the first phase (3.8 ± 0.5 counts min^{-1} at 7.5σ significance for 12.1 hrs of data after analysis cut for an analysis energy threshold above 60 GeV (De Naurois et al., 2002)), and with the HEGRA experiment (6.1σ significance for 15 hrs of data after analysis cut for an analysis energy threshold of 350 GeV (Lucarelli et al., 2003)).

In our earlier analysis, T_0's were computed by using all triggering events, i.e. events with NTT ≥ 4. However, the more telescopes we used in reconstructing the Cherenkov wavefront, the more accurate should be the space angle estimation, as the impact parameter of the shower will be smaller. In the same way, estimation of T_0's is expected to be more accurate when we keep only events with NTT $= 7$ to compute TDC differences (the impact parameter is smaller, so the plane front approximation of the spherical front whose impact parameter is unknown will be more accurate). We show in Fig. 4 the count rates of dark regions using T_0's computed with all events versus T_0's computed using only 7 fold events. We notice less fluctuation in the count rates while using the new set of T_0's: the standard deviation of the pair by pair count rate distribution is equal to 3.8 in the latter case, but 6.7 in the former one.

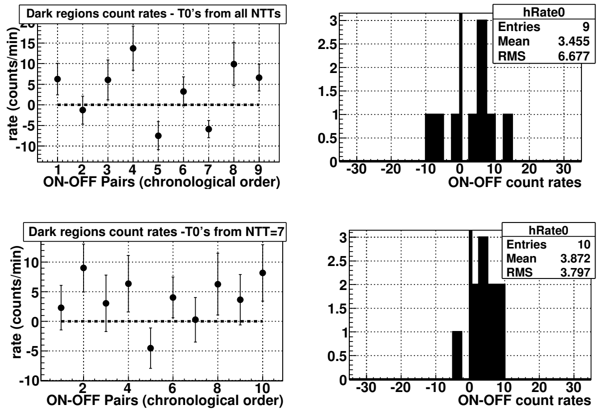

Fig. 4. Count rates from dark regions and distribution of these count rates. Left: Analysis with T_0's computed using all events. Right: Analysis with T_0's computed using events with NTT $= 7$ only.

Several other sources are observed with HAGAR (Chitnis et al., 2009b; Acharya et al., 2009). We give in brackets the duration in hours of the ON-source observations up to September 2010: Galactic sources: Crab Nebula and pulsar (83), Geminga pulsar (59), X-ray binary LSI +61 303 (8), MGRO 2019+37 (13); and extragalactic sources (blazars): Markarian 421 (75) and 501 (49), 1es2344+514 (52), and 3C454.3 (13).

5 Development of a new analysis for HAGAR

Recent developments in our analysis as well as the upgrade of our hardware setup provide us with additional tools to improve our signal extraction methods.

5.1 Improvement of the timing analysis using T_0's

As we require a timing precision of 1 ns, the accuracy of the calculation of T_0's is fundamental. In the process of establishing an accurate analysis method, we have investigated several ways of computing T_0's. As a dedicated calibration system which would flash same amount of light simultaneously at each PMT is not yet implemented, we compute T_0's using real cosmic-ray events from fix angle runs, as already mentioned above. We need to perform fix angle runs

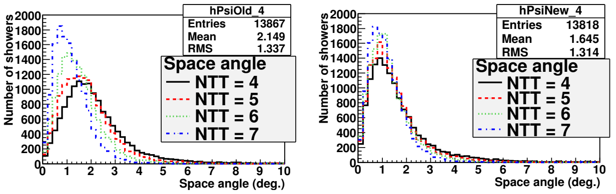

Fig. 5. Space angles for the four NTTs of a fix angle run. left: a single value of T_0 per telescope; right: 64 sets of T_0's. In each panel, distributions are normalised w.r.t. the one with $NTT = 4$.

for a long enough duration (typically 40 to 60 min), so that our statistics is relevant to fit the mean values of the TDC differences.

We have recently found out that the result of the computation of a set of T_0's is dependent of the geometry of the telescope location in the array. As we require that at least 4 telescopes out of 7 get a signal above a preset threshold, we have 64 possible combinations: events which trigger Tel. 1,2,3,4, events which trigger Tel. 1,2,3,5, etc., until events which trigger the combination 1,2,3,4,5,6,7. Through every 64 trigger combination, HAGAR samples the Cherenkov front with a bias which is inherent to the geometric combination of telescopes. The 7-Fold configuration will sample a larger part of the Cherenkov wavefront (which corresponds in average to a smaller impact parameter of the shower, as described above), the combination 1,2,6,7 will sample a smaller part, the combination 1,5,6,7 will sample another smaller part of the wavefront (Fig. 1**(b)**). Preliminary tests showed us relevance of analysing source data using the 64 combinations of T_0's. We show in Fig. 5 the comparison of space angle distributions displayed for each NTT, when computed by two different methods. The left figure contains the space angle distributions computed by applying only one value of T_0 per telescope (computed with 7 fold events only). The right figure is after application of the 64 sets of T_0 values (one set per trigger combination). A sharper shape, as well as a smaller mean value of the space angle of $NTT = 4, 5$ and 6, is observed. We expect this new method to allow a more accurate hadronic rejection through the space angle analysis cut.

5.2 Flash ADCs

Since April 2009, we collect data using a parallel acquisition system of Flash ADCs in addition to the regular CAMAC-based data acquisition system (TDCs and QDCs). We use two 4-channel modules of Acqiris flash ADC (FADC) digitizer model DC271A. This is a 8 bit compact PCI digitizer with 1 GHz bandwidth with 50 Ω resistance and sampling rate of 1 GS/s. Seven telescope pulses are input to this module. This will enable us to study pulse shape, use gamma-hadron separation parameters based on pulse shape, reduce night sky background contribution by restricting window around Cherenkov pulse and also incorporate a technique for a software padding, as applied for the CELESTE experiment (De Naurois et al., 2002). We show in Fig. 6 a typical saturated FADC event, with a typical pulse fit by a log-normal function (enclosed). The first 40 ns of each FADC window are used to plot the pedestal of the NSB light for each telescope. By comparing NSB in the ON versus OFF data acquisition, we can evaluate the NSB difference and we can expect to balance this difference by an offline addition of noise on the channel with less noise, through the procedure of software padding.

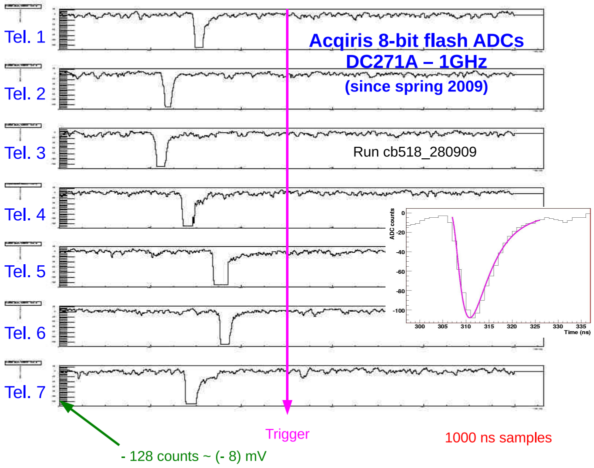

Fig. 6. One FADC event (saturated for the seven telescope pulses). Enclosed is a typical event fit with a log-normal function. The 8^{th} channel is not connected to any telescope.

5.3 Hardware upgrade

In July 2010 several upgrades have been implemented in our hardware setup: a meter for monitoring the night sky brightness, and a home made programmable discriminator unit where threshold level could be remotely controled. Also, the trigger circuit was modified and upgraded in order to reduce the width of the coincidence window (to reduce chance triggers). Further upgradation is also planned to linearly add all telescope pulses through what we call "Grand Sum pulse", which could reduce the HAGAR energy threshold. This Grand Sum logic will demand the installation of programmable analog delays. Lastly, a new data format for additional house keeping information has been implemented.

6 Summary

Observation with the HAGAR telescope array are regular since September 2008. Several Galactic and extragalactic sources are observed. After reporting preliminary results on the Crab nebula and dark regions, we have implemented new developments in our analysis method. Improvement of the method and development of new analysis softwares are still undergoing. Upgrade of the hardware also gives us good expectation in controlling more systematics and decreasing the energy threshold.

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References

Acharya, B. S., Britto, R. J., Chitnis, V. R., et al.: Observation of Geminga and Crab pulsars using HAGAR telescope systems, in: Proc. 31^{st} ICRC, OG 2.2, 669, 2009.

Britto, R. J., Acharya, B. S., Chitnis, V. R., et al.: Gamma-Ray Source Observations with the HAGAR telescope system at Hanle in the Himalayas, in: Proc. Ann. meeting of the French Society of Astron. Astrophys., edited by: M. Heydari-Malayeri, C. Reylé, and R. Samadi, 131, 2009a.

Britto, R. J., Acharya, B. S., Chitnis, V. R., et al.: Observation of Crab Nebula with the HAGAR telescope system at Hanle in the Himalayas, in: Proc. 31^{st} ICRC, OG 2.7, 958, 2009b.

Chitnis, V. R., Acharya, B. S., Cowsik, R., et al.: Status of HAGAR telescope array at Hanle in the Himalayas, in: Proc. 31^{st} ICRC, OG 2.7, 696, 2009a.

Chitnis, V. R., Acharya, B. S., Britto, R. J., et al.: Observations of Blazars Mkn421 and 1ES2344+514 using the PACT and HAGAR telescope systems, in: Proc. 31^{st} ICRC, OG 2.3, 697, 2009b.

De Naurois, M., Holder, J., Bazer-Bachi, R., et al.: Measurement of the Crab Flux above 60 GeV with the CELESTE Cerenkov Telescope, Astrophys. J., 566, 343–357, 2002.

Heck, D., Knapp, J., Capdevielle, J. N., Schatz, G., and Thouw, T.: CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers, Forschungszentrum Karlsruhe Rep. FZKA 6019, 1998.

Knapp, J. and Heck, D.: EAS Simulation with CORSIKA, V5.60: A User Guide, 1998.

Koul, R., Kaul, R. K., Mitra, A.'K., et al.: The Himalayan Gamma-Ray Observatory at Hanle, in: Proc. 29^{st} ICRC, 5, 243–246, 2005.

Lucarelli, F., Konopelko, A., Aharonian, F., Hofmann, W., Kohnle, A., Lampeitl, H., and Fonseca., V.: Observations of the Crab nebula with the HEGRA system of IACTS in convergent mode using a topological trigger, Astropart. Phys., 19, 339–350, 2003.

Yadav, K. K. (for the HIGRO collaboration): TACTIC and MACE gamma-ray telescopes, in: Proc. 44^{th} Rencontres de Moriond, 2009.