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DATA ANALYSIS METHOD FOR THE SEARCH OF POINT SOURCES OF GAMMA RAYS WITH THE HAGAR TELESCOPE ARRAY

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Abstract. The High Altitude GAmma-Ray (HAGAR) experiment is the highest altitude atmospheric Cherenkov sampling array, set up at 4300 m amsl in the Himalayas (Northern India). It constitutes 7 telescopes, each one with seven 90 cm-diameter mirrors, a field of view of 3 degrees, and was designed to reach a relatively low threshold (currently around 200 GeV) with quite a low total mirror area (31 m^2). In order to remove the strong isotropic background of charged cosmic rays, data are collected by tracking separately ON-source followed by OFF-source regions, or vice-versa. Typical observations period is about 30-40 min. ON-OFF data pairs are then selected according to quality parameters such as stability of the trigger rate and the comparison of average trigger rates between ON and OFF-source data sets. Signal extraction from point sources is done by performing analysis cuts on the count rate excess, rejecting off-axis events. Validation of method and systematics are evaluated through the analysis of fake sources (OFF-OFF pairs) located at similar declination as the observed point sources. Spurious signal, if any, would show up in this study.

Keywords: gamma rays: atmospheric Cherenkov technique, methods: data analysis, telescopes: HAGAR

1 Introduction

When a cosmic gamma-ray photon enters the Earth atmosphere, it causes a shower of relativistic particles. These particles initiate a spherical wavefront of blue-UV Cherenkov light which originates mostly from the shower maximum region (at about 10 km a.s.l. at 100 GeV). This wavefront has a width of few nanosecondes and forms on the ground a pool of light with a diameter of about 200 metres. Sampling the Cherenkov light using fast PMTs and recording precise relative arrival time between the detectors are the key for the detection of gamma rays at GeV energies, using wavefront sampling detectors. 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 HAGAR experiment is a Cherenkov 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 (Fig. 1a).

Other characteristics are: f/D $\sim$ 1; fast Photonis UV sensitive photomultipliers (PMTs) XP 2268B at the focus of each mirror and 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; absolute event arrival time accurate to μs. For trigger generation, the 7 pulses of PMTs of a given telescope are linearly added to form one 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. 2009).

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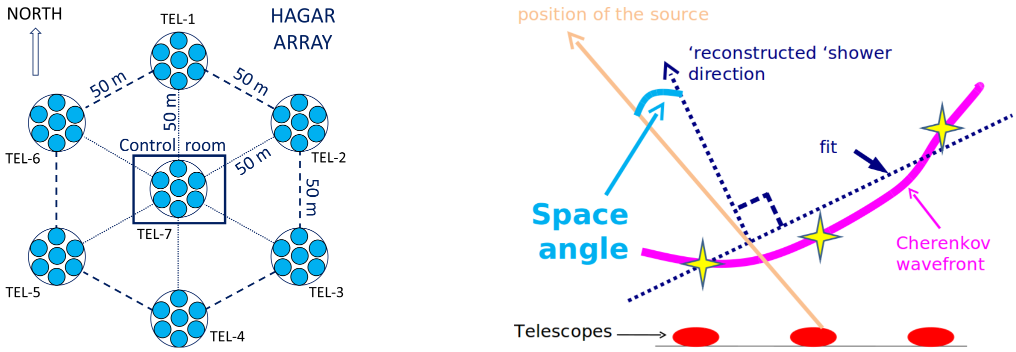

Fig. 1. (a) The HAGAR telescope array. (b) Illustration of the space angle fitting procedure.

Several sources are observed with HAGAR (Chitnis et al. 2011). We give in brackets the duration in hours of the ON-source observations up to June 2011: Galactic sources: Crab Nebula and pulsar (117), Geminga pulsar (76), X-ray binary LSI +61 303 (26), MGRO 2019+37 (15); and extragalactic sources—blazars: Markarian 421 (86) and 501 (49), 1es2344+514 (80), and 3C454.3 (15). Also we have started to regularly observe some Fermi pulsars.

2 Signal extraction procedure

The analysis of HAGAR data is based on the estimation of the arrival angle 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 shower at each telescope. This allows us to fit the arriving spherical Cherenkov wavefront, using plane front approximation. The normal to this plane gives the reconstructed shower direction (Fig. 1b). Precise time calibration of the optoelectronic chain is then required, as well as an accurate pointing of telescopes (Chitnis et al. 2009). Time calibration is achieved first by computing TDC differences between pairs of telescopes from fix angle runs (*i.e.* using real cosmic-ray events) where the time-offsets are calculated, 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 each telescope. These offsets are 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. As we require a timing precision of 1 ns, the accuracy of the calculation of T_0's is fundamental. We have found that the computation of a set of T_0's is dependent on the nature of trigger. We require that at least 4 telescopes out of 7 get a signal above a preset threshold, which leads to 64 possible combinations for the trigger: events which trigger Tel. 1,2,3,4, events which trigger Tel. 1,2,3,5, etc. (Britto et al. 2011a).

Space angle (Ψ) 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 NTT=4, NTT=5, NTT=6 and NTT=7.

Events with $\chi^2 \geq$ (mean + 1 σ) are rejected, where χ^2 is the parameter of plane front fit. Further we reject events with space angle greater than 7°, as these are mostly due to bad fits (noise, chance triggers, etc.). Space angle distribution is plotted for each pair and each event type.

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 mins). However, 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 large space angles, where no significant gamma-ray signal is expected. This yield a ratio, called *normalisation constant* "C". The normalisation region (NR) of Ψ is defined as the range from the FWHM cut (say Ψ_{cut}) to 7 deg (Fig. 2a). The ON-OFF excess is then computed as the normalised excess below Ψ_{cut}. However, two difficulties arise in the use of C. First, we assume that no signal at all is present in the NR. The second difficulty is that the number

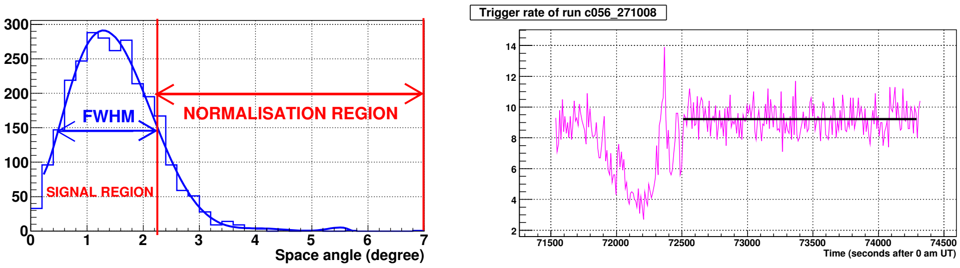

Fig. 2. (a) Illustration of the cuts we perform to define the normalisation region on the space angle distribution of OFF-source data sets. Cut is shown for NTT=7. (b) Raw trigger rate versus time for a run with a rate stable after 72500 seconds: only the stable part of the run was kept. Each bin corresponds to a duration of 10 seconds.

of events in the NR is small, which induces some statistical error on C. Therefore, our results are given through two ways of computing C. The first method is the basic ratio:

$$C1 = \frac{N_{ON}^{(NR)}}{N_{OFF}^{(NR)}}. \tag{2.1}$$

The second method is a χ^2 minimisation of the bin per bin $N_{ON}^{(NR)} - C2 \times N_{OFF}^{(NR)}$ expression:

$$\chi_k^2 = \sum_{i=\Psi_{cut}}^{7} (N_{ON}^{(NR)} - C2_k \times N_{OFF}^{(NR)})^2 \tag{2.2}$$

where $C2_k$ varies from 0.5 to 2.0 with a step (k) of 0.001. The size of the i bin is 0.1 deg.

3 Data selection

Data selection is done using some parameters which characterize good quality data, in order to reduce systematics as much as possible. Our selection is done both run-wise and pair-wise. Runs with high value of the trigger rate are laid aside for future analysis, as they were taken under different conditions. We first reject acquisitions whose trigger rate is non stable and whose defaults in timing information are identified. We show in Fig. 2b an example of a trigger rate plot as a function of time of a run, where only the stable part of the plot can be selected. The stability of the trigger rate of each run is quantified using one variable, called R_{stab}, defined as the RMS of the rate on the square root of its mean. For perfect poissonian fluctuations, this variable is expected to be equal to 1. Run rejection is done for $R_{stab} \geq 1.5$. Also, stability of the mean rates of events remaining after analysis cut is verified by $R_{stab} \leq 1.2$.

Pair selection is then done by constraining several parameters. One of our selection parameters is the relative difference of the *One Fold* rate (rate of triggers due to one or more telescopes which is recorded as monitoring information) between ON and OFF source runs. This parameter is related to the night sky background rate. Its value is imposed to be less than 15 %, otherwise the pair is rejected. Due to changes in the HAGAR hardware, the *One Fold* rate was not monitored for most of the dark region acquisitions presented in next section. An other criterion for selection is on the ON/OFF absolute difference of the average trigger rate. This difference is imposed to be less than 2.5 Hz. These previous criteria are designed to control dramatic changes in atmospheric conditions, night sky brightness, acquisition threshold, etc., within a pair. During the pair processing, ratio of events for each telescope are computed and constrained to be between 0.75 and 1.25 for at least 6 telescopes, for the analysis of data from dark regions. A cut on the value of C is required in the same range. Then, a cut is imposed to reject data sets with a hour angle greater than 2.5 hours (39 deg. of zenith angle).

4 Analysis and results of data from sky dark regions

Crab nebula, standard candle of the γ-ray astronomy, is used to calibrate the instrument and optimize hadronic rejection. As previously mentioned, our current analysis method is built upon the estimation of the space angle of both the ON and OFF data sets, and on a proper evaluation of the normalisation constant C (computed to

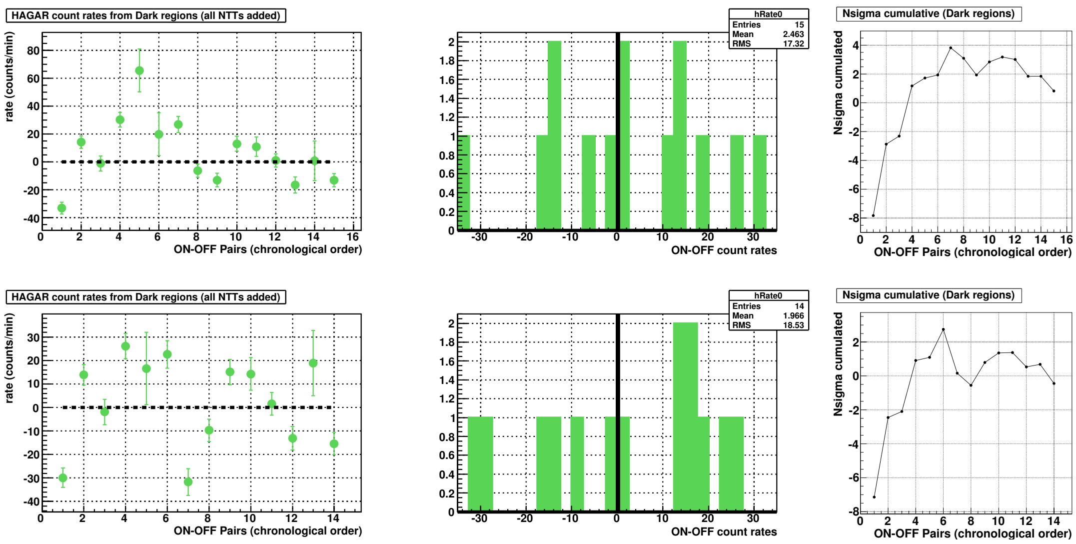

Fig. 3. Pair by pair count rates for the selected dark region data set, computed using C1 (top), and C2 (bottom).

Data sets	C	no. of pairs sel./ini.	duration	N_σ
Dark	1	15*/26	6.5 h	0.8
	2	14*/26	6.4 h	-0.4

Table 1. Summary of results obtained from the 3 data sets. (*) indicates that two pairs share a common "OFF 1" run respectively in two occurrences.

balance differences in comic-ray triggers between ON and OFF data sets). 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* or *fake sources)*, located at a similar declination as of Crab nebula ($\simeq 22°$). Out of the initial 26 pairs, we have selected up to 15 pairs, corresponding to 6.5 hours of data. An excess with a significance of 0.82 and -0.44 σ (for excess computed with C1 and C2 respectively) is seen, which is compatible with zero (Fig. 3 & Tab. 1). This indicates that systematic effects due to sky and time differences during observations are not dominant in our data/analysis.

5 Conclusions

Observations with the HAGAR telescope array are regular since September 2008. Several Galactic and extra-galactic sources are observed. Analysis of dark regions and regions containing a bright blue star show us that, under appropriated data selection and analysis cuts, we can perform the analysis of gamma-ray point sources (Britto et al. 2011b).

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