TAIGA: HYBRID METHOD IN VHE GAMMA-RAY ASTRONOMY (FIRST RESULTS AND PERSPECTIVES)

L.G. Sveshnikova (SINP MSU, Moscow) for TAIGA collaboration

TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma-Astronomy)
HiSCORE station:
“Tilting” to South by 25° to cover CRAB

Sub-ns array-wide time synchronization

42 detectors, 106 m distance, 
S~0.5 km2, effective S~0.3 km2

IACT:
S of mirrors = 8.5 m²
Focus 4.75 m²
FOV 9.5°
Accuracy of tracking 0.05°

4 of 8” PMTs with Winston cones light collection 0.5 m² and FoV ~0.6 sr
Non IACT technique was developed in Tunka-25 and 133 array for cosmic rays detection and was optimized for PeV -100 PeV energy. To move to sub TeV region, high sensitive detectors were developed to reach low energy 100 TeV.

What we measure:
1) The arrival direction – by the time delay: accuracy 0.1 - 0.4°
2) The core position by LDF function: With accuracy 5m – 30m
3) Energy by Q at 200m with accuracy 20-40%
3) Type of particles for high energy
METHOD OF IMAGING ATMOSPHERIC CHERENKOV TELESCOPES.

The IACT technique was developed and optimized for energies around 1 TeV. A typical design consists of a system of Cherenkov telescopes with a mirror, a camera with a field of view of the order of 4 degrees. To move to higher energy it requires a larger effective area and a large number of telescopes (CTA).

From image parameters: IACT measures:
1) Arrival direction and core position by stereo systems,
2) Energy by size,
3) Very effective background rejection.

HEGRA
VERITAS
MAGIC
HESS
....CTA
OUTLINES

- Experimental sample of hybrid events 2017-2018 year
- Comparison with full Monte-Carlo simulations obtained with a new TAIGA-Optic program
- Search for gamma excess from Crab in the high energy range
- Outlooks
1 step: Summarize different clusters and subtract pedestals.

2 step: Codes → ph.el., corrections to PMT sensitivity

4 step: Current analysis:
   b) remove bad pixels
   c) remove star tracks

6) Cleaning and visual analysis of images

9) Calculate of Hillass’s parameters

10) Search for joint events in time window of 1.5 µs from the IACT and HiSCORE banks of events.
“Gamma-like”

HiSCORE detectors
E = 50 TeV  Width = 0.19°
tet = 32.9  Fi = 33.58

Information we have about every event from IACT and HiSCORE

Direction to the core

Core position in IACT after introduction of scaling factor Rp’ = Rp/1500

Core position in HiSCORE
PARAMETERS OF IMAGE

1. Size, Npix
2. DIST, Rc
3. WIDTH
4. LENGTH
5. ALFA
6. Asymmetry
7. Concentration
8. Amis
9. Peak(Max) Intensity

From HiSCORE
1. Energy
2. $R_{\text{tel}} = R_{\text{core}} - R_{\text{IACT}}$
3. $\Psi$ - angle between shower direction and source direction

Width, length,
Major axis directed to sources position,
Peak pixel shows the direction to sources
Miss - perpendicular distance from the major axis to the center of the camera, is equivalent to $\Psi$. 
37 days of HiSCORE & 20 days of IACT:

**Crab tracking:** 78 days, 197hr

- $\Theta < 40^\circ$ with HiSCORE: 20 days, 70 hr,
- Good quality of data: 20 days, 25 hours

Without technical problems with camera and good tracking

**Expectation:**
CRAB 130 hr effective time in Hiscore aperture

**IACT only:** 20 days, effective time 25 hr, Size $> 60$, Npix $> 4$:
95000 events

**HiSCORE only** Ndet $> 4$, 50 m from edge:
1.33 mln events

**IACT + HiSCORE** (1 and 2 clusters, all joint showers):
37000 events
**MONTE-CARLO DATA STATISTICS**
**46 HiSCORE STATIONS, 1+2 CLUSTER UP TO R=600M**

<table>
<thead>
<tr>
<th>Primary</th>
<th>Eth</th>
<th>Slope</th>
<th>Ntot</th>
<th>Detected by IACT</th>
<th>By HiSCORE</th>
<th>Joint</th>
<th>Ntot HiScore 50pe</th>
<th>Tm-C hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>70</td>
<td>-2.6</td>
<td>122000</td>
<td>8864</td>
<td>20222</td>
<td>5090</td>
<td>104000</td>
<td></td>
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<tr>
<td>Helium</td>
<td>70</td>
<td>-2.6</td>
<td>110000</td>
<td>8137</td>
<td>10365</td>
<td>2615</td>
<td>86000</td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td>35</td>
<td>-2.6</td>
<td>40000</td>
<td>7396</td>
<td>4135</td>
<td>1216</td>
<td>33018</td>
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</tbody>
</table>

1) Shower development in the air was simulated by CORSIKA;

2) Cherenkov photons of the shower were traced through the optical system of the IACT and optical system of every station of HiSCORE, TAIGA OPTICA,

3) Trigger conditions were included in simulations,

4) The methods of shower arrival direction, energy and core position reconstruction used in experiments were implemented in program.
Primary spectrum and mass composition (Hoerandel, 2001);

Min number of photoelectrons per station, Q_{threshold}~280 ph.el., 70% efficiency provides an agreement with experiment, and gives ~ 100 TeV peak energy.
IMPLEMENTATION OF THE RECONSTRUCTION METHOD (CG & FIT) INTO THE MC SIMULATION

Accuracy of arrival direction reconstruction

Accuracy of energy reconstruction

CG method: only 4 central detectors are used for parameters reconstruction: red stars
Fit method: all hit stations are used for LDF reconstruction: black stars
Assumed primary spectrum
For Pr+HE and Nuclears
Close to spectra of Hoerandel, 200

MC describes experimental spectra: low energy range 2-100 TeV and 70-1000 TeV
In the region near the threshold in both samples we have some discrepancies, requiring the understanding
<table>
<thead>
<tr>
<th>Description</th>
<th>Experiments</th>
<th>M-Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>37500</td>
<td>HAWC</td>
</tr>
<tr>
<td>Rate of HiSCORE 4 stations</td>
<td>20-25 Hz</td>
<td>~24 Hz</td>
</tr>
<tr>
<td>Rate of IACT</td>
<td>13-20 Hz</td>
<td>~20 Hz</td>
</tr>
<tr>
<td>Rate of joint events</td>
<td>0.35 Hz</td>
<td>0.7 Hz</td>
</tr>
<tr>
<td>Rate of joint events</td>
<td>16900</td>
<td></td>
</tr>
<tr>
<td>Rate of joint events</td>
<td>7615</td>
<td></td>
</tr>
</tbody>
</table>
SIZE – DISTANCE FROM IACT TO CORE

Experiment dist <25 cm

Experiment & Monte-Carlo

~7%

Many strange events among this region 7%
PARAMETERS USED FOR GAMMA RAY DISCRIMINATION
Distance from telescope to EAS core

Distance to Weighted center

Suppression of background ~7 times

\[ 1.043x \]
\[ 5.0606Rp \]
ASSYMMETRY

Suppression of background ~2.5 times
Width(Size), Cuts

Suppression ~20 times
A full suppression factor of background (from MC and Experiment)

\[ \varepsilon_{\text{back}} \approx \frac{1}{600} \].

MC gamma-sample decreases by about 2 times,

\[ \varepsilon_{\text{back}} \approx \frac{1}{2} \].
After all cuts we suppress gamma rays by about 65% and expect to detect ~3-4 gamma rays with peak ~ 70 TeV over area 0.3 km² during 25 effective hours.

In 2018-2019 season we try 3 hit stations for selection.
GAMMA-LIKE EVENTS AFTER ALL CUTS

Event #3461815
Ncl = 0, Npix = 23
Size = 2230 p.e.
Width=1.2 cm, α=13.7 deg

Event #20536318
Ncl = 0, Npix = 9
Size = 218 p.e.
Width=0.8 cm, α=7.6 deg

Event #21142697
Ncl = 0, Npix = 10
Size = 257 p.e.
Width=0.9 cm, α=0.3 deg

Event #26855616
Ncl = 0, Npix = 41
Size = 3970 p.e.
Width=1.5 cm, α=2.1 deg

Event #36893196
Ncl = 0, Npix = 34
Size = 3170 p.e.
Width=1.6 cm, α=12.6 deg
OUTLOOK

We’ll put efforts to understand more accurately the hadron background in the threshold region.

In season 2018-2019 ‘wobble’ mode of IACT work is realized

In season 2018-2019 minimum 3 hit stations events are included in processing for decreasing a threshold
CONCLUSIONS.

1. For the first time the hybrid method of EAS registration and gamma/hadron separation in the region around tens-hundred of TeV was realized in the experiment TAIGA. About 37000 events, detected by HiSCORE wide-angle timing array and simultaneously by IACT in the direction to Crab Nebular were detected during 25 effective hours on the area ~ 0.3 km².

2. It was possible to agree spectra, counting rates, Hillas’s parameters, obtained from both installations with MC simulations. Only threshold region requires the additional refinement and understanding. The Qfactor of gamma/hadron separation, estimated from MC simulation is ~ 10.

3. In the first season 2017-2018 of joint operation, the expected peak energy of gamma rays was enough high 70-75 TeV, that allows to expect ~ 3 gamma-like events versus 5-6 particles. In season 2018-2019 due to special efforts we decreased threshold of HiSCORE stations and expect lower threshold of gamma induced showers ~60 TeV.
Event #6281867
Ncl = 0, Npix = 23
Size = 709 p.e.
Width=1.6 cm, α=8.8 deg

"Gamma-like"

E = 50 TeV
Width = 0.19°
tet = 32.9
Fi = 33.58
Gamma-like

$E = 50\,\text{TeV}$
$tet = 37.0$
$Fi = 331.12$

Core position
STATISTICS AND GAMMA-LIKE EVENTS

Gam- angle between direction on Crab and shower direction measured by HiSCORE

Effective Time -
Gam <1 degrees - 255 events
Selection criteria Gam<0.3°, gam <1o, alfa < 18, Rc<27 cm 3 events

Energy ~ 50-70 TeV
Distance ~ 50m, 300m, 270m
WHAT WE CAN EXPECT WITH CURRENT PROTOTYPE?

Current array:

- $S=0.2 \text{ km}^2$, $T\approx120 \text{ hr}$
- Significance = 2.5 sigma

2019: 1 km$^2$ +3 IACT

Integral sensitivity