

Stereo imaging of the VHE γ -rays with HEGRA & H.E.S.S.

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Abstract. At present, the ground-based astronomy of very high energy (VHE) ($E > 100$ GeV) γ -rays experiences the challenging transition phase caused by the substantial upgrading of its observational instrumentation. Recently the HEGRA collaboration has evidently demonstrated the power of arrays of imaging atmospheric Čerenkov telescopes and initiated a number of complementary projects, such as H.E.S.S., CANGAROO IV, VERITAS. The common philosophy of those projects is based on the stereoscopic observations of air showers with a number of imaging telescopes simultaneously. Such observations allow to reduce substantially the effective energy threshold of detected γ -ray showers; to improve the angular and energy resolution for individual γ -rays; to gain in suppression of the cosmic ray background. In my talk I have summarized the general advantages and achieved sensitivity of the stereoscopic observations using the HEGRA data taken with an array of 5 imaging telescopes having the energy threshold of 500 GeV. These results completed with the relevant simulations may be extrapolated on a firm ground towards the future H.E.S.S. (phase I) array of four 12 m imaging telescopes with the estimated energy threshold below 100 GeV. Here I discuss in short the anticipated performance of such an array.

NEW PHYSICS FRONTIERS

The recent achievements of the VHE γ -ray astronomy offer a great number of diverse and fundamental physics results which make further developments in the field highly physically motivated. Future γ -ray observations will deliver exhaustive knowledge to understanding the origin of the cosmic rays by observing the supernovae remnants (SNRs) and the physics of the relativistic jets in the active galactic nuclei (AGN), the measurements of the infrared (IR) absorption of γ -rays propagating in the interstellar medium, the necessary data to prove the mechanisms of a particle acceleration in the pulsars and plerions, clues to the enigma of the gamma-ray bursts *etc.* At the same time the significant advancement towards the new physics frontiers will be only possible after a significant improvement of the observational instrumentation. The efficient search and detailed study of the

sites of the particle acceleration up to multi-TeV energies, which may brighten up in γ -rays, need lowering farther the energy threshold of the instruments down to 50-100 GeV, ability to localize the γ -ray emission with accuracy better than 1 arcmin, large telescopes' field of view for the comprehensive studies of the extended γ -ray emission, large dynamic energy range (50 GeV - 50 TeV) and good energy resolution ($\leq 10\%$) for precise measurements of the γ -ray energy spectra, larger γ -ray statistics at the time scale less than 1 hr for efficient search for the episodic or highly variable sources *etc.* The forthcoming *stereoscopic* arrays of the imaging air Čerenkov telescopes, like H.E.S.S. (High Energy Stereoscopic System), will exactly meet all those requirements. One can reach this conclusion using both the observational experience with the currently operating HEGRA (High Energy Gamma Ray Astronomy) instrument (hereafter by HEGRA I denote the system of 5 IACTs operated by the HEGRA collaboration) as well as the specific Monte Carlo simulations. All that allows to predict reliably the performance of the H.E.S.S. which is briefly summarized below with the emphasize on the further advancements in the physics analysis of the observational data.

HARDWARE PARAMETERS OF IACTS ARRAYS

Although a good number of hardware parameters is different for H.E.S.S. as compared with HEGRA one can pick out several of those which are of the utmost importance. They are – *(i)* the larger diameter of the reflector; *(ii)* better optics making use of a stable dish and better mirrors alignment; *(iii)* smaller angular size of the pixels.

TABLE 1. The hardware parameters of HEGRA and H.E.S.S.

	HEGRA	H.E.S.S.
• Reflector diameter	3 m	13 m
• Davies-Cotton design	Yes	Yes
• Focal length	5 m	15 m
• Number of channels	271	960
• Ang. pixel size, deg	0.25	0.15
• Field of view, deg	4.3	5.0
• Signal sampling	120 MHz FADCs	1 GHz ARS
• Dynamic range	1-500 ph.e.	LG: 1-100 ph.e./HG:16-1600 ph.e.
• Trigger	2NN/271	4/960(sect.)

Due to the large reflector and better efficiency of the photon-to-photoelectron conversion the H.E.S.S. telescopes will detect by a factor of $\simeq 10$ more Čerenkov light from the same shower comparing with HEGRA. Such an advantage in the effective reflecting area of the telescopes enables to reduce the energy threshold of the observed air showers from 500 GeV, as for the HEGRA, to the energy threshold within 50-100 GeV for H.E.S.S. For such low energy threshold the observed air showers will place effectively at the higher height above the observation level and in

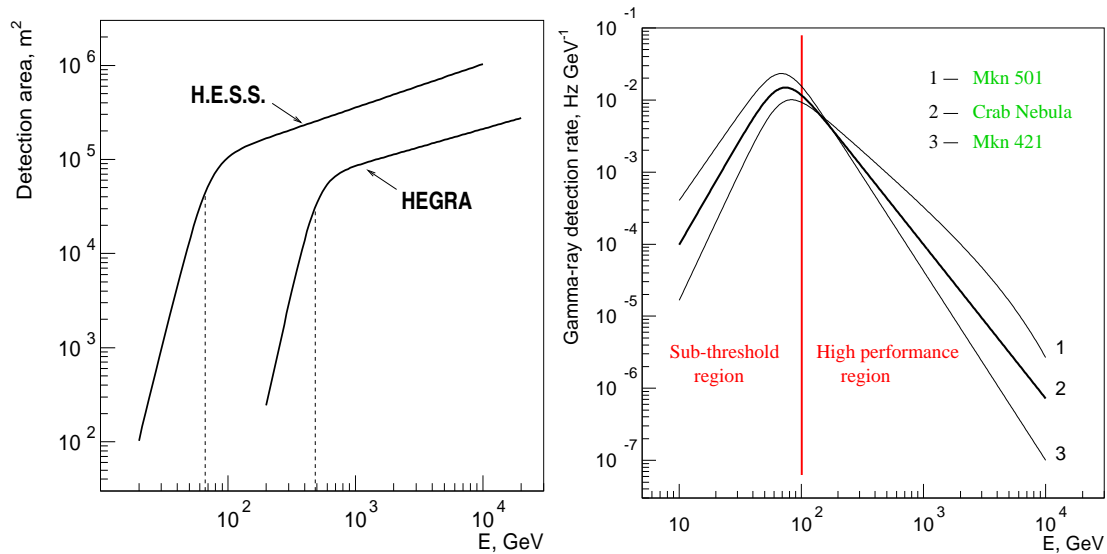


FIGURE 1. The effective detection areas for HEGRA (Trigger: 2/5, 2NN/271>8 ph.e.) and H.E.S.S. (phase I: 4 CTs) (Trigger: 2/4, 4/960(sect.)>4 ph.e.) (left panel). The differential detection rate for H.E.S.S. assuming the initial γ -ray energy spectrum as for Crab Nebula, Mkn 421, Mkn 501, measured with HEGRA IACTs system (right panel).

addition will have more narrow lateral divergence of the charges particles emitting Čerenkov light. All that gives effect to the angular size of the Čerenkov light images which become relatively small. In order to measure effectively the angular shape of such images the future telescopes need to have a better optics and fainter camera pixellation. Note that the high quality stereoscopic observations with the arrays like H.E.S.S. need relatively large separation of the telescopes of about $\simeq 120$ m.

ENERGY THRESHOLD & RATES

The effective collection areas of the γ -ray air showers for the arrays of IACTs may be well represented by the following fit:

$$A(E) = a_0 E^{a_1} / (1 + (E/a_2)^{a_3}) \quad (1)$$

where a_2 -parameter defines the energy threshold, which is of 500 GeV for HEGRA and $\simeq 80$ GeV for H.E.S.S. (see Figure 1). HEGRA counts of about 120 γ -ray events per one hr of the Crab Nebula observations close to the zenith and before applying the analysis cuts. Assuming the energy spectrum of the Crab Nebula as measured by HEGRA

$$dJ_\gamma(E)/dE = 2.8 \cdot 10^{-11} E^{-2.6} [\text{photon m}^{-2}\text{s}^{-1}\text{TeV}^{-1}] \quad (2)$$

one can calculate the corresponding rate for H.E.S.S. which could be about 150

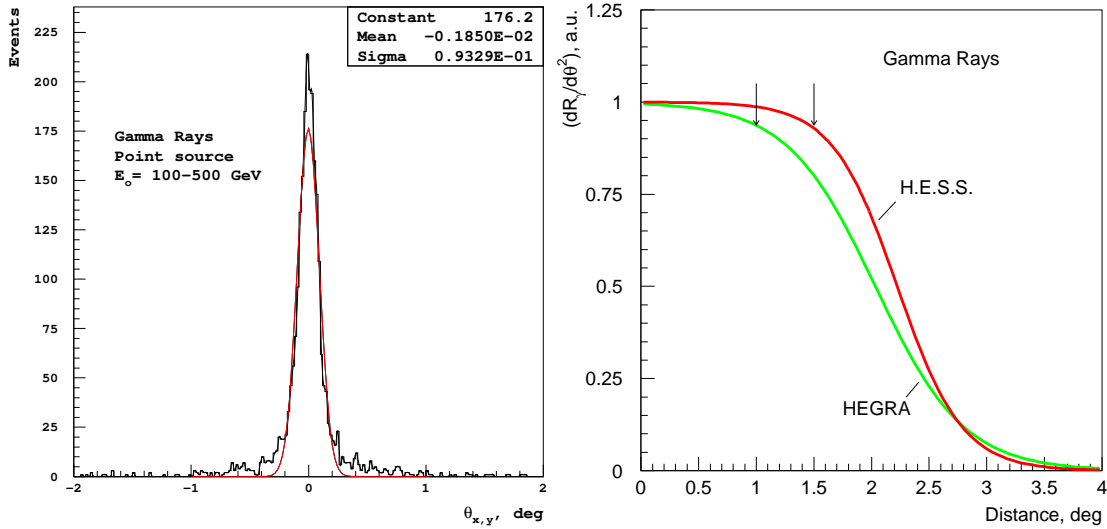


FIGURE 2. Distribution of the error in the reconstructed shower core for H.E.S.S. (left panel). The efficiency of the OFF-axis γ -ray observations with the HEGRA & H.E.S.S. (right panel).

TABLE 2. Accuracies in the stereo reconstruction.

	HEGRA	H.E.S.S.
• Angular resolution, [deg]	0.07°	0.1°
• Source localization, arcsec	40	10
• Error in impact distance, [m]	7	10
• Energy resolution, $\delta E/E$	12%	20%
• Error in shower maximum, [km]	0.5	1
• Cosmic Ray rejection	$0.01 \div 0.06$	$0.01 \div 0.1$

γ -rays per min ! Such enormous statistics will allow the measurements of the spectral shape for the Crab like γ -ray sources after less than 1 hr of observations. The maximum γ -ray detection rate for H.E.S.S. corresponds to the γ -ray energy within $\simeq 50-100$ GeV (see Figure 1). The uncertainty in the position of the peak is caused by the current uncertainties of the efficiencies along the over-all photon-to-photoelectron propagation chain. One can break the entire dynamic energy range (extending up to $\simeq 10$ TeV and $\simeq 50$ TeV for the observations at high and low elevations, respectively) into two parts (see Figure 1). As for the *high performance region* (above 100 GeV) H.E.S.S. will enable the high quality stereoscopic observations with the ability of high precision spectroscopy based on the images of a large size as well as high trigger multiplicity. At such energies the conventional data analysis developed for HEGRA could be of general use. It is important to note that the effective collection area of H.E.S.S. is larger than HEGRA, by a factor of $\simeq 5$, above 1 TeV. It provides very high sensitivity of the H.E.S.S. in the multi-TeV energy region. In the *sub-threshold region* (see Figure 1) the Čerenkov light images are substantially affected by the telescope's trigger, have rather small

angular size and poorly defined shape due to the large fluctuations. In addition for these images the night sky light contamination might be a severe problem. Nevertheless, the search for the periodic γ -ray signals (e.g., from the Pulsars) in the energy range below 50 GeV could well be physically expedient, eventhough it may need to develop a specific analysis algorithms in particular for these observations.

STEREO IMAGING

For a system of IACTs the *stereoscopic* (geometrical) *reconstruction* of the air showers means the direct measurement of the orientation of the shower axis in space; determination of the position of the shower core in the observation plane; measurement of the angular dimensions of a shower, and height of its maximum (the details of such reconstruction could be found elsewhere). The major parameters of the H.E.S.S. performance (phase I), comprising 4 IACTs in a system, are summarized in Table 2.

The important issue of the H.E.S.S. performance is a sensitivity to the diffuse γ -rays over the field of view (FoV) (see Figure 2). The analysis of the Monte Carlo events for H.E.S.S. doesn't show a significant decrease in the angular resolution for the OFF-axis events whereas the detection rate drops down rather fast beyond 2° (see Figure 2).

Although a numerous attempts have been undertaken in past in order to improve the conventional stereoscopic algorithms, neither of those could gain much. The HEGRA, with its ability of the individual event time sampling, did not reveal a dominant use of the time profiles of the Čerenkov light flashes from the air shower (at least for the minimum time bins of 8 ns). On the contrary, applied after imaging analysis, the timing technique does not help at all. However, one could hope for a $0.5\div 1$ GHz signal processing devices the advantage of the event time sampling might be of great importance (e.g., for the night sky noise reduction etc).

H.E.S.S. SENSITIVITY

Provided with a 50 hrs observational time looking at a point source, H.E.S.S. could see the γ -rays of the flux as low as

$$F_{\gamma}^{\text{p.s.}}(> 100 \text{ GeV}) \simeq 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \quad (3)$$

at the 5σ confidence level with the γ -ray statistics exceeding 10 γ 's. The minimum detectable flux for an extended γ -ray source was estimated as

$$F_{\gamma \text{ ext}} \simeq (\Theta_0 / 0.1 \text{ deg}) \cdot F_{\gamma}^{\text{p.s.}} \quad (4)$$

No doubt such impressive sensitivity of future advanced ground based γ -ray instrument allow to explore very effectively the sources of “non-thermal emission in the Universe”.