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Capability of MAGIC to make scans. Critical evaluation of the proposal "A scan of the Cygnus region with the MAGIC telescope"

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1 WHAT IS OUR CAPACITY FOR SCANS?

1.1 Data and analysis

For the present study we have analized data from a set of Crab Nebula observations at low zenith angle ($< 30°$) at 0, 0.3 and 0.4 degrees off-axis angles, respectively. The observations were performed during September 2004 and January 2005. In order to fully characterize the sensitivity up to 1 degree off-axis angle, we have also analized a sample of MC simulated γ-ray events at 0, 0.25, 0.5 0.75 and 1 degrees, and compared the results with those obtained with Crab Nebula observations.

Data are processed using a standard Hillas analysis. In the present work we do not assume the knowledge of the source position (which is the case e.g. during a sky-scan), and therefore we parametrize the shower images using exclusively the set of variables describing the image shape. Gamma/hadron separation is performed by means of a Random Forest classification algorithm. The direction of arrival of the individual showers is estimated using the DISP method.

For off-axis observations, the background recorded in a given camera position at an angular distance r from the camera center can be computed from the n symmetric positions in the camera, provided that $r\sin(\pi/(n+1)) > 2\sigma$, where σ is the angular resolution. Regions suspected to contain signal must be removed during background estimation. The 2-σ level ensures that 85% of the signal from a point-like source is removed so that the remaining 20% does not affect background estimation. For an hexagonal camera as that of MAGIC, $n = 1$, 2 or 5. The error on the background estimation is proportional to $n^{-1/2}$, so for each camera position the maximum number of symmetric positions is used. For the region ($r < 2\sigma$) the background is estimated from the observations of an empty field in the sky, where only background events are expected.

1.2 Off-axis sensitivity

We have computed the sensitivity of MAGIC above 200phe for off-axis observations as a function of the off-axis angle (r), using both MC γ-ray and real observation data samples.

MC simulated γ-rays are used to compute the gamma detection efficiency. For this, about 5×10^5 gamma-initiated atmospheric showers with a fixed incoming direction were simulated with standard MAGIC mc programs for the different considered observation angles (0, 0.25, 0.5, 0.75 and 1 degrees). The γ-ray detection efficiency above 200 phe was compared to that obtained for on-axis observations. The results are shown in figure 1.

Background efficiency was computed using data from observations of an empty FOV at low zenith angle. For the different considered angular distances, the number of background events were compared with that obtained at the camera center. The obtained values were combined with those of the gamma efficiencies to compute the sensitivity degradation: $s_0/s = \frac{N_\gamma/N_\gamma^0}{\sqrt{N_h/N_h^0}}$, where N_γ is the gamma event rate for a given off-axis angle, N_γ^0 the gamma event rate at angle $r = 0$, and similarly for the rate of hadrons (N_h). The values of the hadron efficiency and sensitivity degradation are shown in figure 1.

In order to check the results obtained with the MC simulation, we have analized a set of Crab Nebula observations at 0, 0.3 and 0.4 degrees off-axis angle. We have applied these data the same analysis as for the MC samples and compared both results (see figure 1). There is a good agreement between the results obtained for MC and data samples. Note that this result depends on whether one optimizes the cuts for different off-axis distances or not. In our case we do not perform such an optimizaction. Results from other studies (E. Aliu PhD thesis in preparation, A. Moralejo private communication)

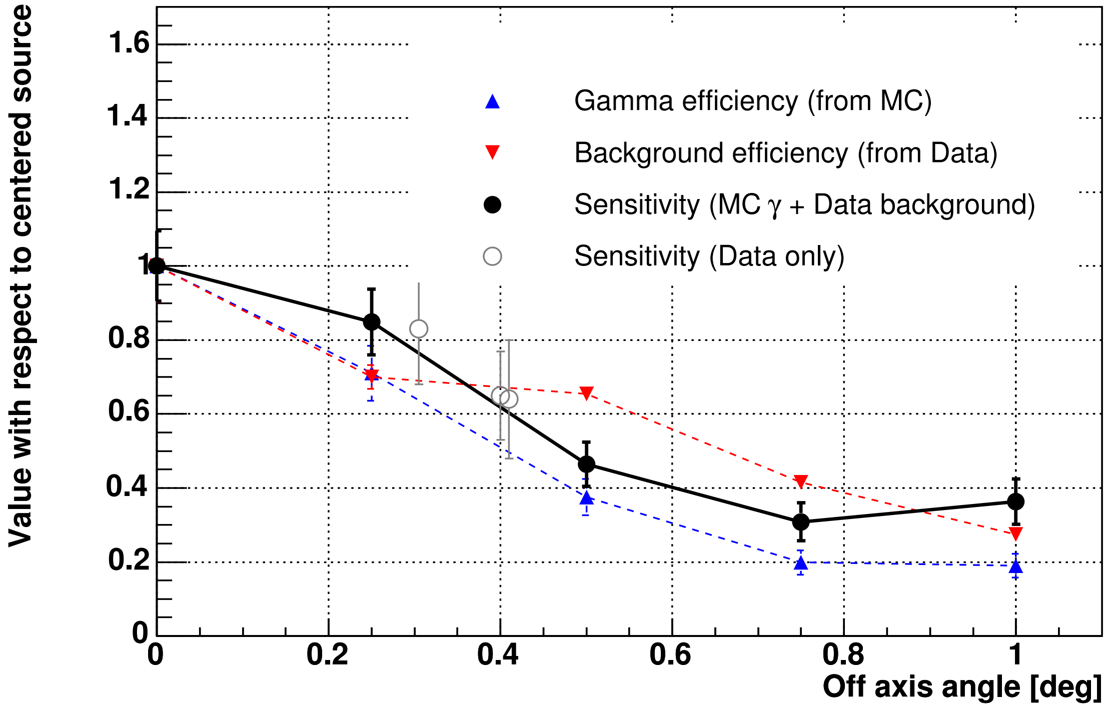

Figure 1: Degradation of the sensitivity above 200 phe together with signal and background efficiencies as a function of the off-axis angle computed both from MC and Crab-Nebula off-axis observations.

yield a somewhat more optimistic result. However, the level of the discrepancies have no effect on the conclusions drawn in this note.

1.3 Performance for a sky-scan

From previous result we can estimate MAGIC performance for sky-scans. Let us consider a sky-scan in one direction (e.g. Galactic Longitude). We point at zero Galactic Latitude at a given Galactic Longitude, observe for a given time, and move the telescope only in Galactic Longitude. The absolute sensitivity is determined by:

- T = total observation time
- L = total covered Galactic Longitude range
- d = step (distance between 2 adjacent observation points)
- The off-axis sensitivity curve shown in Figure 1

From them we can obtain the following relevant quantities:

- Radius of sensitive area: R
- Number of observation points: $n = (L - 2R + d)/d$

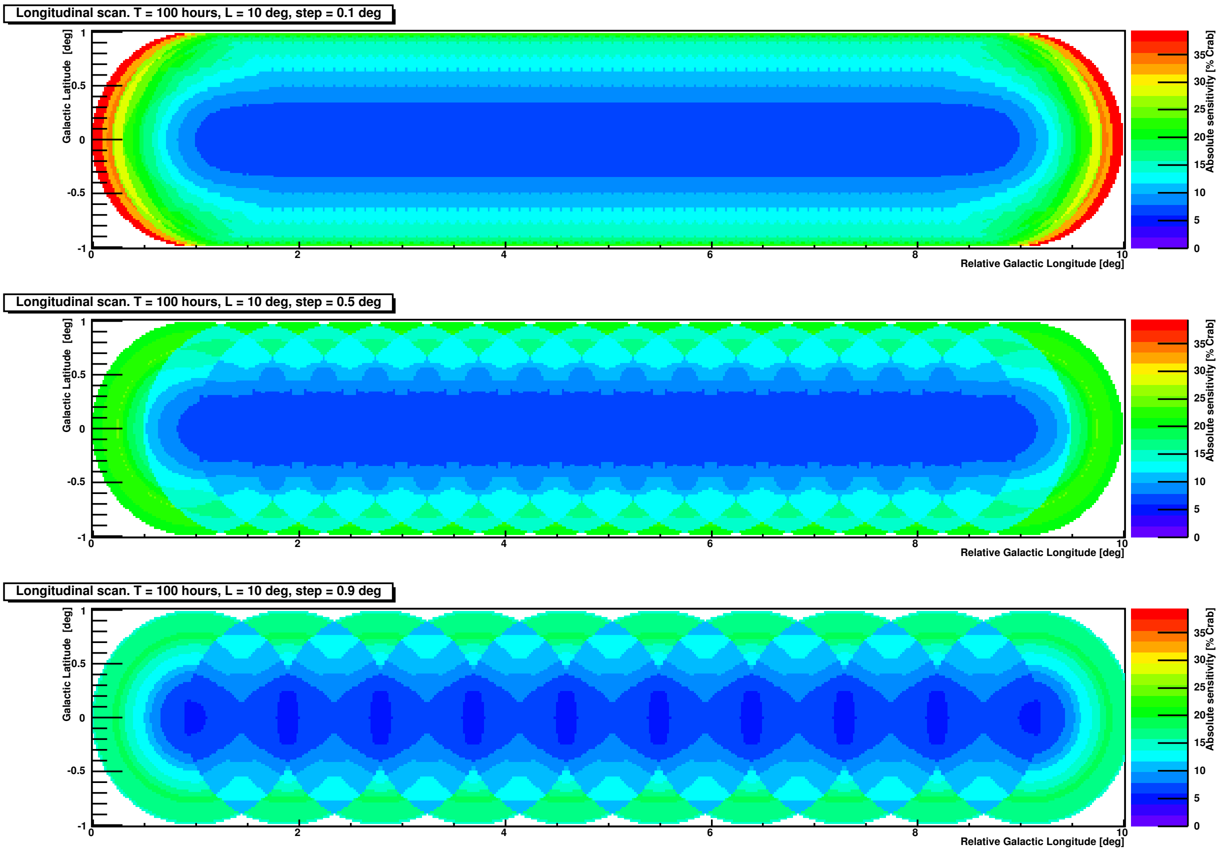

Figure 2: Absolute flux sensitivity of a sky-scan with $L = 10°$ and T=100 hours and three different values of the pointing step, d = 0.1, 0.5 and 0.9 degrees.

- Time spent at each step: $t = Td/(L - 2R + d)$
- Number of times a given point within the interval $[2R, L - 2R]$ is observed: $m = 2R/d$
- Average sensitivity in the interval [2R,L-2R]: $s \simeq \sqrt{\frac{t_{50}(L-2R+d)}{2RT}}\frac{\sqrt{\bar{\epsilon}_h}}{\bar{\epsilon}_\gamma}s_0$, where t_{50} is 50 h, and $\bar{\epsilon}_h$ and $\bar{\epsilon}_\gamma$ are the relative hadron and gamma detection efficiency averaged between off-axis distances 0 and R.

Previous expression already shows that the lower the value of d, the better the absolute sensitivity. This is further illustrated in the following plots.

Figure 2 shows the absolute flux sensitivity in Crab units for the study-case scan (10 degrees in Galactic Longitude and 100 hours of observations). We get more homogeneus coverage of the scanned region for smaller step size. In order to investigate the average absolute sensitivity we produce the Galactic Latitude and Longitude profiles.

Figure 3 shows the Galactic Latitude integrated profile of the average flux sensitivity in the region $2° < l < 8°$ for the study-case and three different steps. Both the mean and RMS of the sensitivity distribution are shown. The smaller step achieves the better sensitivity (peaking at 6% Crab for the central part of the scanned region). The average absolute sensitivity between -0.5 and 0.5 degrees in Galactic Latitude is 10% Crab flux.

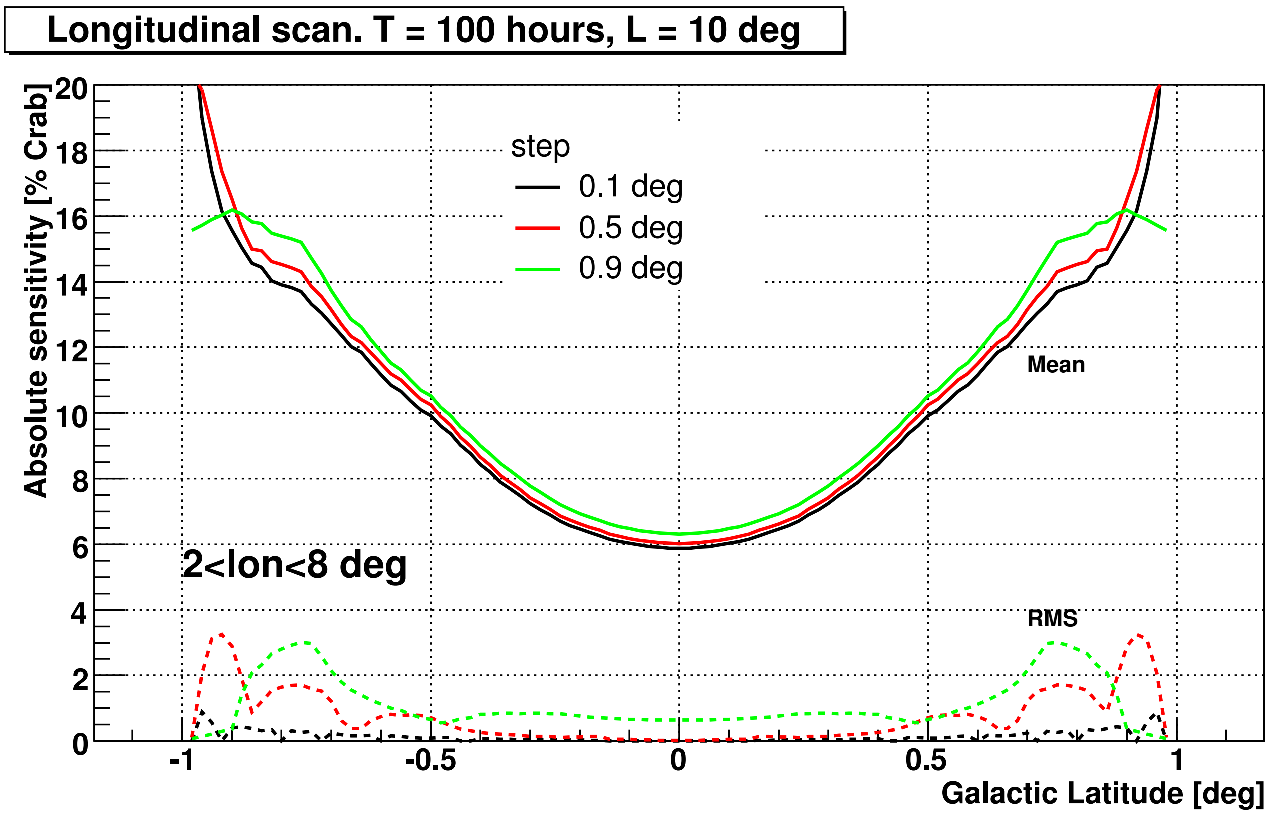

Figure 3: Galactic Latitude integrated profile of the mean and RMS flux sensitivity in the region $2^\circ < l < 8^\circ$ for a sky-scan with $L = 10^\circ$ and T=100 hours and three different values of the pointing step, $d = 0.1$, 0.5 and 0.9 degrees.

Figure 4 shows the Galactic Longitude profile of the flux sensitivity for three Galactic Latitude values (namely 0, 0.5 and 0.9 degrees) the study-case and three different steps. The smaller step achieves the better sensitivity. The sensitivity is degraded by a factor 2 at ~ 1 degree from the border of the scanned region, and it is smaller for larger steps betwen observation positions.

Given that the scanned area is not homogeneously covered, the probability of a detection depends on the exact poisition of the source along the scanned area. In Figure 5 we show the probability for a source detection (assuming a uniform distribution probability for the source position) as a function of the intensity, for the three considered scan steps. The results are shown considering the inner scanned area only ($2^\circ < l < 8^\circ$, $-0.5^\circ < b < 0.5^\circ$) at the left, and for the wholed scanned region at the right. Again, for the inner part of the scan we get a better performance for smaller steps whereas considering the whole scanned area there is no significant difference.

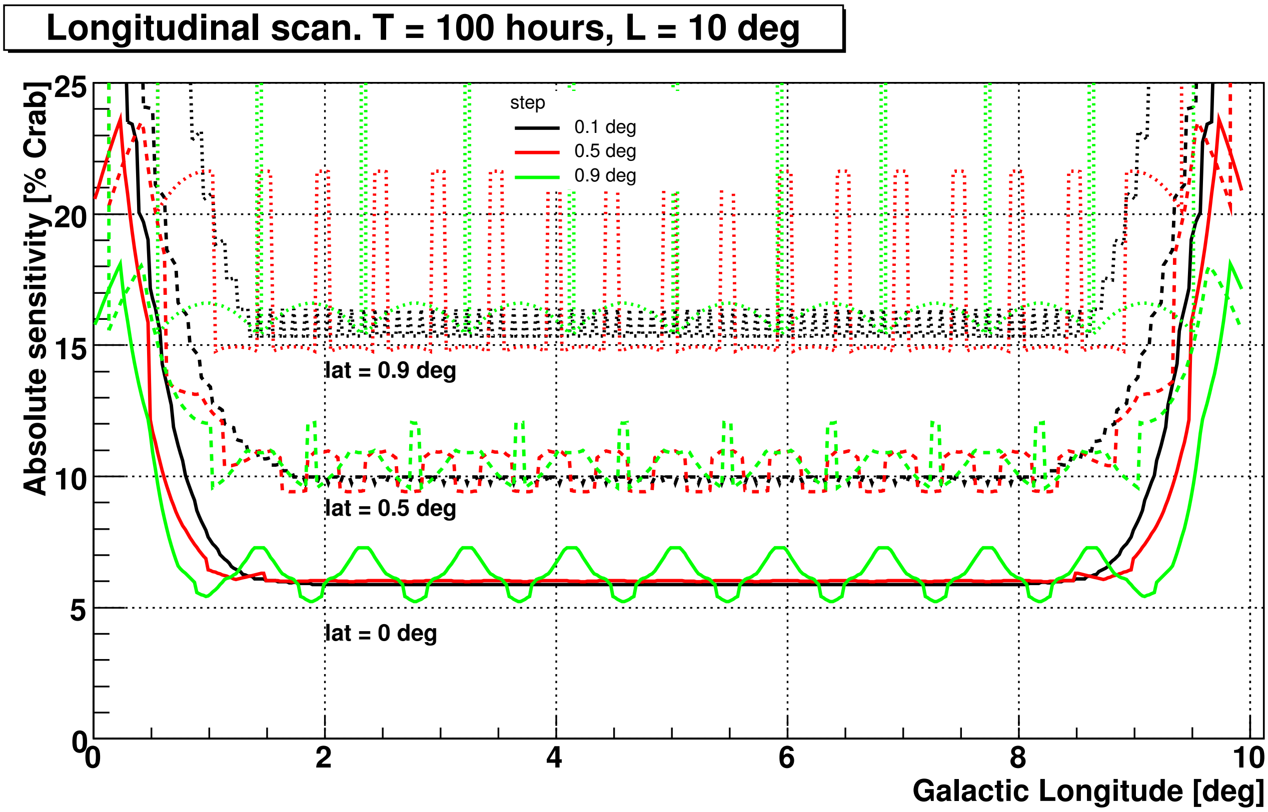

Figure 4: Galactic Longitude profile of the flux sensitivity for three Galactic Latitude values (namely 0, 0.5 and 0.9 degrees) for a sky-scan with $L = 10°$ and T=100 hours and three different values of the pointing step, d = 0.1, 0.5 and 0.9 degrees.

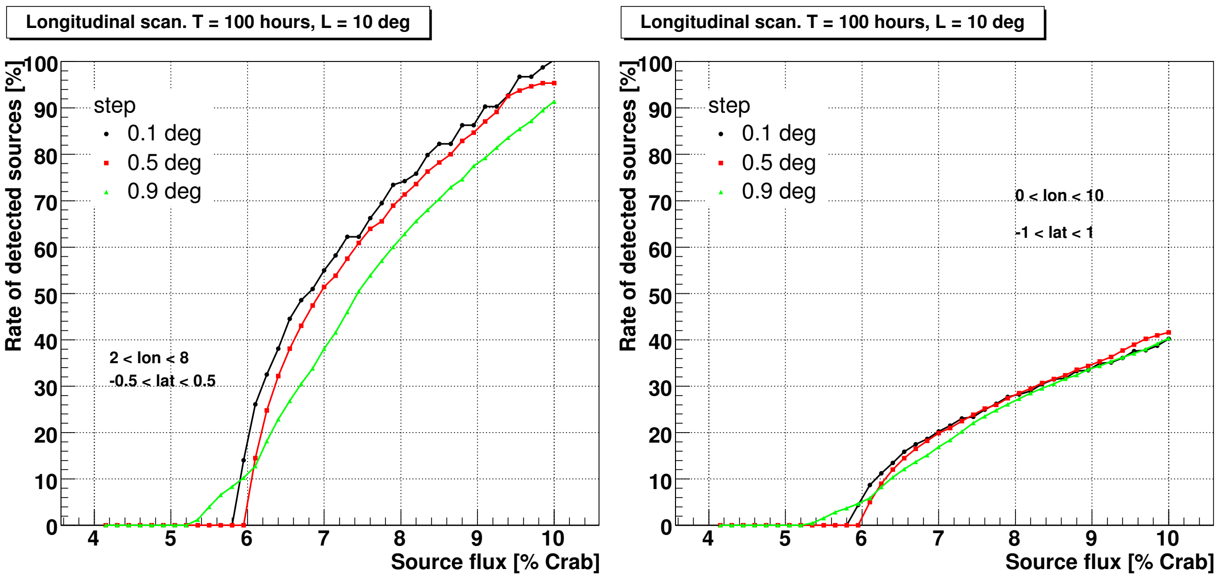

Figure 5: Probability of source detection (assuming a uniform distribution probability for the source position) as a function of the intensity for a sky-scan with $L = 10°$ and T=100 hours and three different values of the pointing step, d = 0.1, 0.5 and 0.9. Left plot considers only the inner part of the scanned region. Right plot considers the whole scanned region.

2 HOW DOES IT COMPARE WITH HESS AND VERITAS?

Let us compare the sensivity of the three instruments:

- We have seen that our sensitivity drops to 50% for sources 0.5° away from the camera center (see figure 1). Our sensitivity is 3% of a crab for point-like sources in the camera center.
- The HESS cameras have 5° diameter and the whole field of view is in the trigger. Their sensitivity drops to 50% at 1.5° (ApJ 636 (2006) 777). The sensitivity of HESS for point sources in the camera center is a factor 2 better than ours.
- The VERITAS cameras have 3.5° diameter and the whole field of view is in the trigger too. No dependence of the sensitivity on the off-axis angle are public yet, but by comparison with HESS their sensitivity probably drops to 50% at 1.0°. For all we know the sensitivity of VERITAS for point sources in the camera center is a factor 1.5 better than ours with three telescopes and a relatively preliminary analysis. Given that the mirror diameter and pixel size of VERITAS and HESS are roughly equal, there is no reason to expect their sensitivities to differ, so VERITAS is only worse in terms of field of view.

By combining the sensitivity at the camera center and the effective field of view (defined as the area for which the sensitivity is more than 50% of the sensitivity in the camera center), we can approximately compare the capability of the three experiments to perform scans. The sensitivity and effective FOV of all telescopes are tabulated in table 1, along with the time it would take to make the HESS scan of the central galaxy with the same sensitivity of this telescope.

Telescope	Sensitivity (50 hrs, C.U.)	Effective FOV (deg^2)	Time
MAGIC	3	0.25	8280 h
HESS	1.5	2.25	230 h
VERITAS	1.5	1	517 h

Table 1: *Sensitivity in crab units, effective area out to the radius where the γ-ray detection efficiency drops to 50% and time to perform the HESS scan of the central galaxy.*

In summary it takes us roughly 36 times longer than HESS and 16 times longer than VERITAS to make the same scan with the same sensitivity.

3 HOW MANY SOURCES DO WE EXPECT TO DETECT?

We can try to estimate the TeV source density in the Cygnus region out of the density of source which HESS has measured in the central galaxy. HESS has discovered 14 new sources at flux levels between 5 and 15% of a crab in a scan from -30° to +30° galactic longitude and -2° and +2° in galactic latitude. All sources were aligned in the strip between -1° and +1° galactic latitude, so in the following we will refer to a source density per linear degree in longitude. This density is about 0.23 sources/deg longitude, i.e., one source for every 4.3° in longitude. Figure 6 shows the time that is required to discover a given number of sources with the TeV source density in the central galaxy, for 5σ and 4σ detections and the different considered steps.

There are good reasons to believe that the source density in the Cygnus arm is lower than the density in the central galaxy. The HESS sources cluster at very small galactic latitude and that matches well

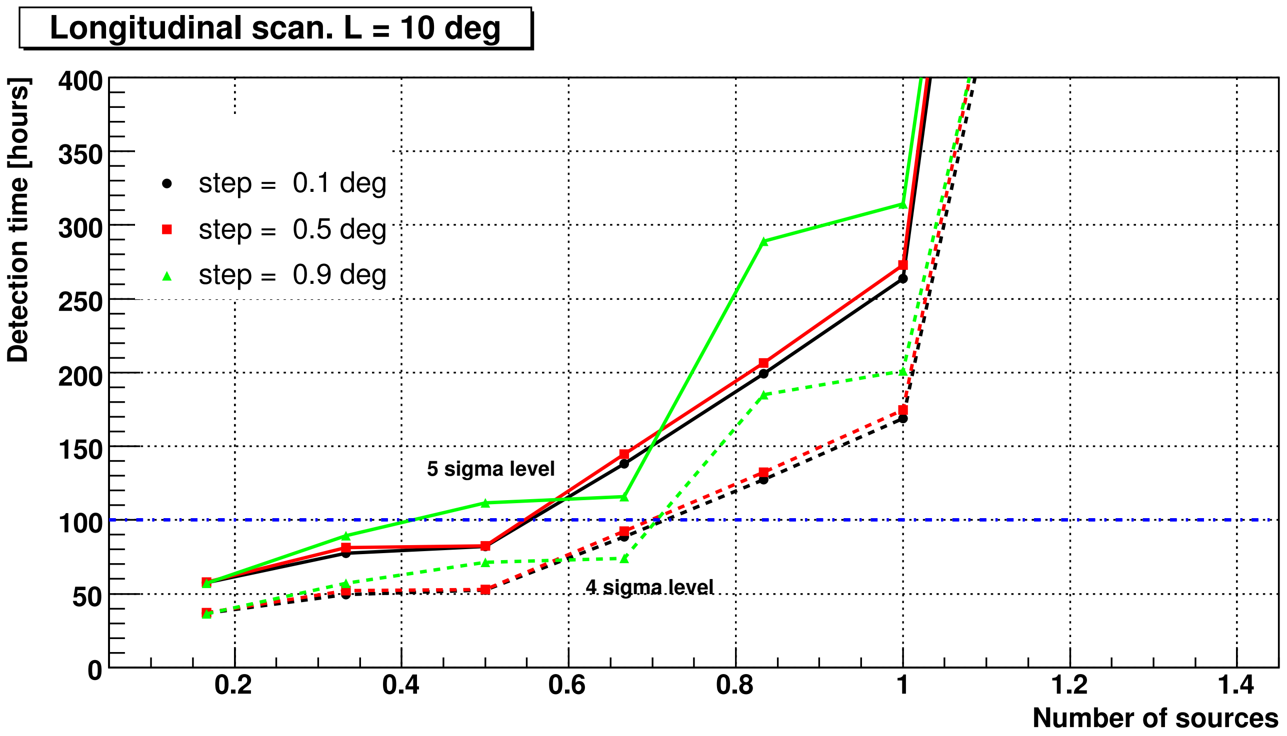

Figure 6: Time needed for new source discovery assuming that the source density is similar to that in the HESS scan.

the distribution of molecular material in the galaxy which in turn traces regions of star formation, SNR, pulsars etc which are counterparts for most of the HESS sources (see Dame, ApJ 547 (2001) 792). The molecular density in the Cygnus region (in particular in the longitude range 70-80°) is lower than the density in the central ±30° of the galaxy by a factor of 3 (see figure 2 of Dame, ApJ 547 (2001) 792). If we assume that the TeV source density is proportional to the molecular density, we can estimate a TeV density of 0.077 sources/deg or one source per every 13° in longitude, always for a flux level above 5% crab. For >10% crab fluxes, the source density would drop to one source every 26° in longitude in the Cygnus arm region.

It must be stressed that 12 out of the 14 sources detected by HESS were extended, a fact that makes them harder to detected by MAGIC. In fact two out of them have an extension σ_{src} larger than 0.2°.

Source name	Dist. to gal. plane	Obs. Time	Sensitivity 1deg^2
PSR B1951	2.75°	33 h	6%
Cyg X-1	3°	48 h	5%
γ Cyg	1.75°	57 h	5%
Cyg X-3	0.5°	29 h	6%
TeV2032	1°	91 h	4%
3EGJ2021+37	0.29°	16 h	9%
OffSadr-1	2°	9 h	12%
OffTeV2032-1	1.27°	7 h	14%

Table 2: *The source name, the distance to the galactic plane, the total observation time and the average sensitivity in the central 1 deg^2 for all sources which have been observed with MAGIC in the Cygnus region.*

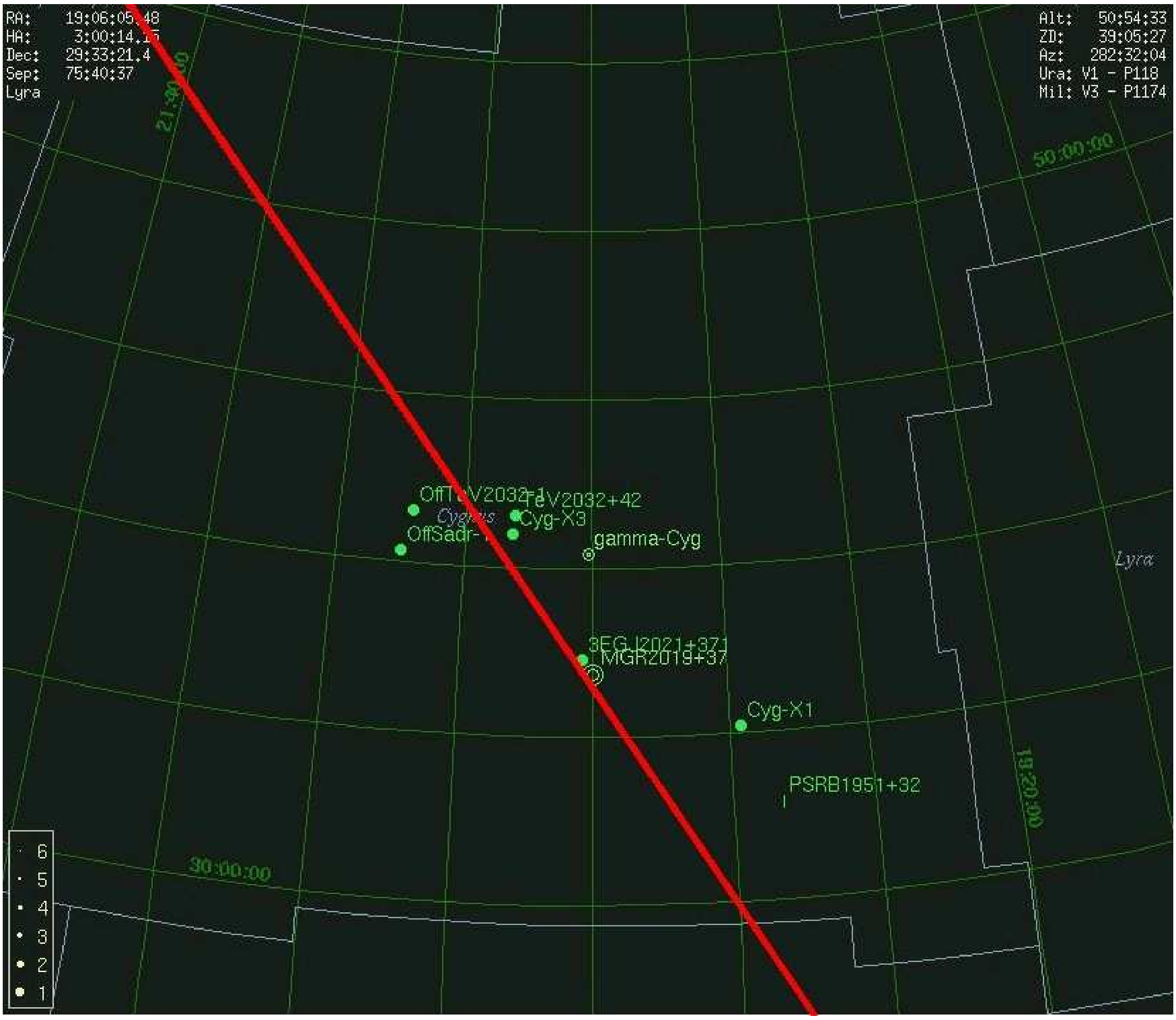

Figure 7: Sources which have been observed by MAGIC in the Cygnus region. The red line corresponds to the galactic plane.

Indeed MAGIC has already observed several sources in the Cygnus region for a substantial amount of observation time. Table 2 shows the number of observation hours which have been recorded for each of these sources and the average sensitivity that one expects in the 1 deg^2 centered on the source. Figure 7 a sky map of these sources. The sensitivity in the FOV of the 6 sources is around 5%. For the OFF sources it is worse, although still comparable to the sensitivity which we will obtain for each pointing of the proposed scan. The total observed time in the Cygnus region is already 290 hours.

We are not aware of any sky map of the OFF sources (although any bright source would appear as a "defect" in a sky map that makes use of these data), so let us restrict the discussion to the 6 sources. The sensitivity is similar to that of the HESS scan. Assuming the HESS source density for >5% crab sources, one expects 0.5 sources. We have not detected anything in these fields, so the source density in the Cygnus region cannot be much higher than that measured by HESS.

It is also worth mentioning that HESS has extended its scan to $\pm 60^\circ$ in longitude. Even if the results of the scan are not known yet, members of the collaboration have said publicly that the TeV source density is lower in the extended scan.

4 T. SAITO'S PROPOSAL FOR A REDUCED SCAN OF CYGNUS

4.1 Expected number of detections

Takayuki Saito et al propose to scan a reduced section of the Cygnus arm, namely the region between 73 and 78° galactic longitude and 0 and 2° galactic latitude. The total proposed observation time is 100 hours. The estimated sensitivity that can be achieved in this region is about 10% crab. This estimate is in good agreement with the calculations of the first section.

As we have made clear in the first section, the scanning mode using only 10 pointings is not optimal: more pointings should be used in order to achieved a flatter coverage in sensitivity of the scan region. In any case the average sensitivity stays at 10% crab.

Assuming the TeV source density which HESS has measured in the central galaxy for >10% crab fluxes, we estimate that such a scan would detect 0.6 sources, i.e., we would need to scan the region for 170 hours to detect one source in average. With the much more probable density which we have estimated for the Cygnus arm, the expectation is 0.2 sources, what is to say, that we need to increase the scanning time to 500 hours to reach the one source level. In the event that the sources were extended, the expectation would be even lower and the required observation time even longer than 500 hours.

4.2 SNR and other sources in the scan region

The proposers list four SNRs, three OB associations and nine Wolf Rayet stars in the scan region. Such a density of possible coounterparts for TeV sources is even larger for the central galaxy, so there is no reason to believe that the scan region is particularly rich in TeV candidates.

The Wolf-Rayet stars have been studied systematically (see e.g. Reimer et al. 2006, or the talk by D. Torres at the galactic cycle 3 proposal meeting) and those in the scan region are not good candidates for detection with MAGIC.

D. Torres has also evaluated the observability of OB association and star clusters and again none of those mentioned in T. Saito's proposal are good candidates for detection. In turn the proposers fail to mention that there is a very good candidate in the vicinity of 3EG2021+37, namely the open cluster Berkeley 87 (see D. Torres's talk at the galactic meeting and below).

4.3 G78.2+2.1, a.k.a γ-Cygni

The SNR G78.2+2.1, compatible with the error box of the EGRET source 3EGJ2020+40, is also known as γ-Cygni, W66 (or Sadr and SadrHHS in our catalogues). It has been already observed by MAGIC during cycle 1 and cycle 2 for 56 hours. It was analyzed by H. Bartko and C. Delgado. There is no significant emission in its field of view (see report of galactic PWG conveners in the general meeting in Madrid).

4.4 3EGJ2021+37 and the MILAGRO source MGR2019+37

3EGJ2021+37 was accepted for observation in cycle 2 and allocated 25 hours. Unfortunately it has been observed for only 15 hours.

3EGJ2021+37 and MGR2019+37 are about one degree away, so the idea came soon after starting the cycle 2 observations to choose the wobble positions of 3EGJ2021+37 so that part of the data could be used to search for emission of the MILAGRO source. Currently about 7 hours can be used for this purpose.

It is worth to mention that a good candidate for MAGIC detection, the open cluster Berkeley 87, is 9 arcminutes away from 3EG2021+37 (see D. Torres's talk at the galactic meeting). This is probably mildly extended (few arcminutes width).

Two independent analyses of these data were presented during the cycle 3 proposal meeting at IFAE (see presentation of conveners on the corresponding web page). One of the analyses (A. Robert) shows a not very significant hot spot close to MGR2019+37. The other analysis (H. Bartko) shows no excess. None of the analyses shows any excess at the position of 3EGJ2021+37 or Berkeley 87.

During the above mentioned meeting, the decision was taken to allocate even more time during cycle 2 to this observation. After discussions with the scheduler, the total time that will still be taken during cycle 2 (period 54) is 30hours. These 30 hours will be taken during period 54 (may 2007). They are distributed so that they cover both 3EGJ2021+37 and MGR2019+37.

4.5 The MILAGRO source MGRJ2033+42

The MILAGRO source MGRJ2033+42 is compatible with the HEGRA source TeV2032+41. This source has been observed with MAGIC in cycles 1 and 2 for a total of 80 hours. E. de Oña and A. Robert have detected a γ-ray source at a position and flux which are compatible with those measured by HEGRA ($\sim$5% crab). There is no evidence for other emission in the same field of view. Upper limits for point-like emission can be set at the level of $\sim$3% crab. Either the emission is very extended, or the source is point-like but its spectrum is very hard, or the whole analysis of MILAGRO is wrong. If MGR2019+37 is similar to MGRJ2033+42, a detection will be hard to achieve.

5 FINAL CONCLUSIONS

We have evaluated the capability of our telescope to make scans. The off-axis sensitivity drops to 50% of the sensitivity at the camera center at an angular distance of 0.5°. We can achieve a sensitivity of 10% of a crab in a strip of 10° length in galactic longitude and 1° width in galactic latitude, and 100 hours observation time. This result depends weakly on the scan step but smaller steps feature a more uniform coverage of the scanned region.

However VERITAS or HESS have scan capabilities far superior than ours. It is not worthwhile to dedicate a substantial amount of time to scans. In fact the northern regions of the galactic plane are probably less abundant in TeV sources than the inner galaxy and any scan would prove less rewarding than the HESS ±30° latitude scan.

Considering the sensitivity of our telescope, the TeV source density which has been measured by HESS and the fact that the Cygnus region has a lower molecular density, we believe that there is a low probability (around 20%) to detect a TeV source in the scan proposed by T. Saito.

There is no strong argument in favor of the detection of any of the SNR, OB associations and Wolf-Rayet stars in the proposed scan region. Similar objects were scanned by HESS and showed no TeV emission.

We are in the process of completing an observation of 30 hours of MGR2019+37 during cycle 2. We suggest to wait until the completion of this observation to make any further measurement in this area.