Source Extent and Location of the Cygnus Hot Spot

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July 24, 2006

1 Introduction

The Cygnus Region currently appears to be a mixture of diffuse emission and point-like sources. The brightest point-like source (the 'hotspot'), located at $\sim (304.5, 37.0)$, has a flux around half that of the Crab. The location of the hotspot was previously observed by the Whipple telescope, but nothing was found [1]. The Whipple non-detection suggests that the source may be extended or multiple, have a hard spectrum, or some combination thereof. This memo outlines the estimation of the source extent and location using Milagro data.

2 Method

The best estimate of the source size and position will be obtained using events with large nFit values, since these have the best angular resolution. This analysis uses events with $nFit > 150$ and $A4 > 3.0$ for data with the outriggers included in the angle fit, running from Oct. 2004 to June 2006. According to the simulations, such events have an angular resolution of $\sim 0.35°$, as seen in Figure 1. Pre-outrigger data were not used because the angular resolution is significantly worse.

2.1 A4 Weighting

To accurately determine the extent and location of the Cygnus hotspot, it is helpful to have a high signal to noise ratio to minimize the effects of background fluctuations. Andy has shown that the gamma/hadron weighting improves the significance for both the Crab and the hotspot. Based on this, A4 weighting was used and was found to improve the signal to noise. The weighting scheme divided the data into 8 bins for $3 <= A4 < 4, 4 <= A4 <$

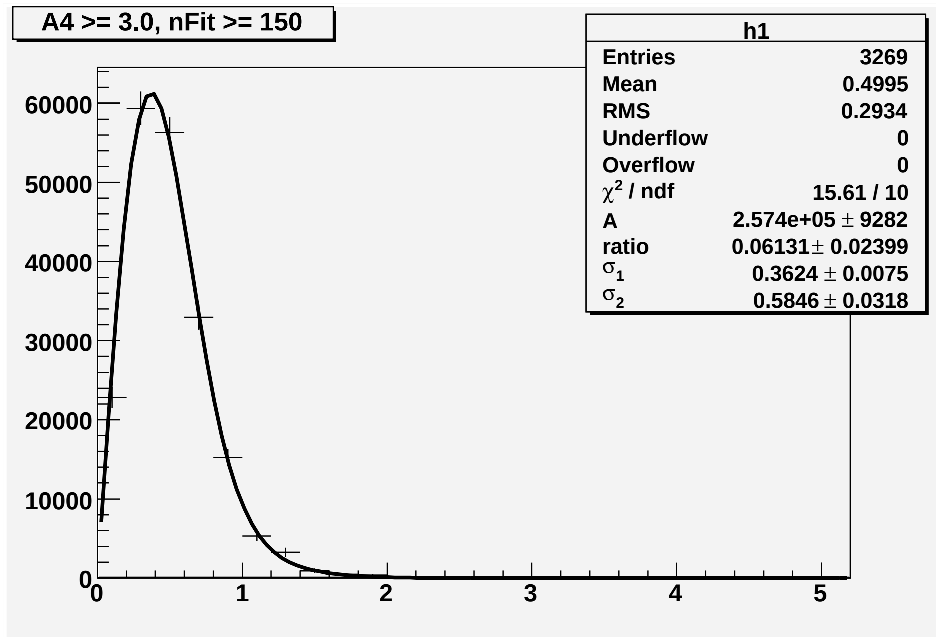

Figure 1: dAngle distribution for simulated gammas using the 2-layer fitter with $A4 >= 3.0$ and $nFit >= 150$. The fitting function is of the form $Ar(e^{-r^2/2\sigma_1^2} + (ratio)e^{-r^2/2\sigma_2^2})$.

5, . . . , 10 <= $A4$. The weights for each bin were determined using the simulations and will be discussed at greater length later.

There is a question as to whether the weighting is appropriate for estimating the source extent. To address this, a simulation was run to compare weighting vs no weighting. A background was thrown uniformly across a grid, and a signal of Gaussian width 0.5° was thrown on top of it. To accomodate weighting, the events were thrown with a simulated gamma/hadron parameter that followed an exponential distribution ($e^{-\alpha x}$, where x is the parameter, and α is larger for background than it is for signal). Once the events were thrown, root was used to fit the width of the source either by fitting a 2-D Gaussian to the unsmoothed excess map, or by binning the excess radially and then fitting. Figure 2 compares the unweighted and weighted fit width distributions for many throws, and the vertical line marks the true width of 0.5°. According to the simulation, the weighting analyses give more accurate fits, although the distribution for the radial fit is slightly shifted for reasons that are not understood.

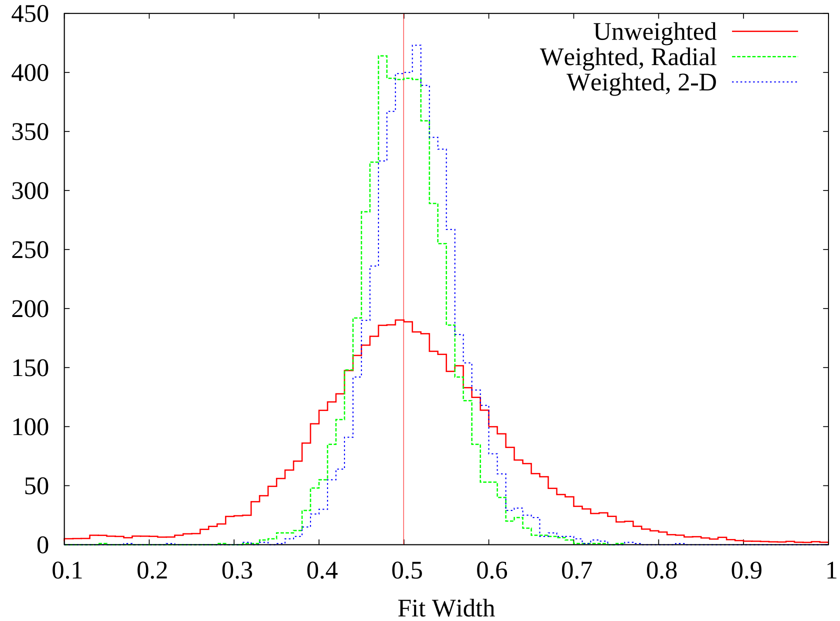

Figure 2: Fitted width distributions from the simulation. The radial and 2-D methods produced very similar results, but the distribution for the radial is shifted to slightly higher fit values.

The simulation also shows that the errors produced by the root fit are believable. Figure 3 compares the distribution of the error from the fit with the distribution of the absolute value of the true error, defined as $True = |FitWidth - 0.5|$. Both distributions have a mean of 0.056, while the standard deviation of the true error distribution is 0.077.

3 Analysis and Results

The analysis was applied to REC data taken with outriggers used in the angle fit, running from Oct. 2004 to Jun. 2006. There were a number of changes during this period, and consequently the data were broken into four sets: 3-layer (Andy's nFit_2LayerEquiv was used), 2-layer before the repair, 2-layer after the repair, and 2-layer with the 603 calibration. Weights were derived by comparing gammas that were simulated for each period to REC data from the same period. Also, since the A4 distribution varies greatly

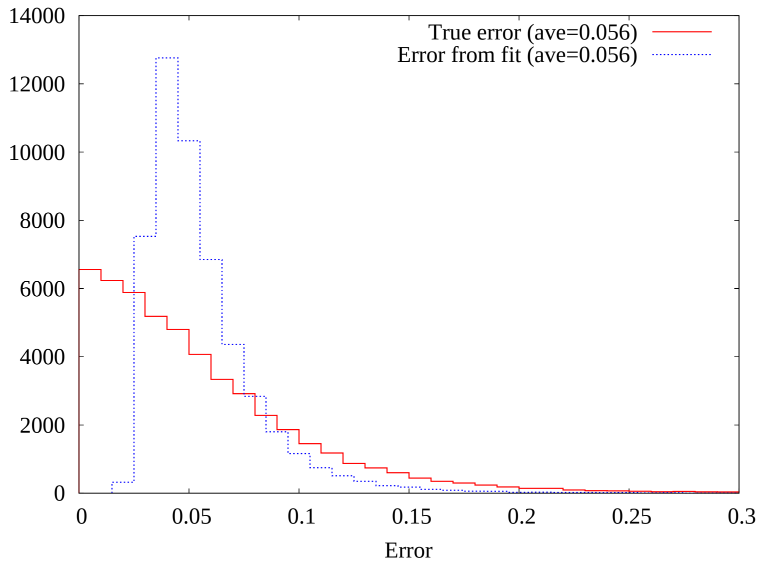

Figure 3: Distributions of the statistical error from the root fit vs. the absolute value of the true error, defined as $True = |FitWidth - 0.5|$.

across the four data sets, the weights for each period were scaled relative to the other periods. A summary of the datasets and weights is given in Table 1. After applying the A4 weighting and the Gaussian smoothing to these data, the Crab significance is $\sim 9.5\sigma$, while the peak significance for the hotspot is just over 8σ, as seen in Figure 4.

Root was used to fit a 2-D Gaussian to the unsmoothed, A4-weighted map for both the Crab and the Cygnus hotspot. The Crab fit was centered at RA=$83.60° \pm 0.06°$, Dec=$22.10° \pm 0.05°$, with Gaussian width $\sigma = 0.38° \pm 0.04°$. (The true location of the Crab is RA=83.63°, Dec=22.01°.) For the Cygnus fit, a constant offset was included as one of the parameters to account for possible contribution from the diffuse background. The fitting function had the form $A + Be^{-((x-x0)^2+(y-y0)^2)/(2\sigma^2))}$, where A, B, $x0$, $y0$, and σ are the fitting parameters. The fit centered the hotspot at RA=$304.66° \pm 0.13°$, Dec=$36.96° \pm 0.08°$, with Gaussian width $\sigma = 0.50° \pm 0.07°$.

The excess can also be binned into radial bins, as shown in Figure 5, with the Crab in red and the hotspot in blue. A fit was performed on these points using a Gaussian fitting function (with an offset included for Cygnus). The fit width in this case was $0.40° \pm 0.04°$ for the Crab and $0.59° \pm 0.09°$ for

Table 1: Weights for each of the datasets used in the analysis.

A4 Slice	3Layer (Oct04-Apr05)	2LayerBefore (Apr05-Sep05)	2LayerAfter (Sep05-Mar06)	2Layer603 (Mar06-Jun06)
3-4	0.51	1.0	0.49	0.29
4-5	1.3	2.9	0.94	0.34
5-6	2.3	4.8	1.4	0.47
6-7	4.7	7.5	2.7	0.58
7-8	5.6	16	4.0	0.92
8-9	9.0	23	7.1	2.0
9-10	15	29	10	3.0
10-∞	41	50	30	12

the hotspot.

3.1 Width Calculation

Assuming a Gaussian source and a Gaussian point spread function (this is a good approximation for events with $nFit > 150$), the measured angular extent is given by $\sigma_m^2 = \sigma_s^2 + \sigma_r^2$, where σ_m is the measured extent, σ_s is the width of the source, and σ_r is the angular resolution. Therefore, the source width and the error in the estimate (from the error propagation formula) are given by

$$\sigma_s = \sqrt{\sigma_m^2 - \sigma_c^2}$$

$$\delta_s = \frac{\sqrt{\sigma_m^2 \delta_m^2 + \sigma_r^2 \delta_r^2}}{\sigma_s}$$

Assuming the measured width of the Crab, 0.38° from the 2-D fit, is the best estimate of our angular resolution (use in place of σ_r), the numbers from the 2-D fit for the Cygnus hotspot give a Gaussian source width of $0.32° \pm 0.12°$ for the hotspot. If the values from the radial fit are used instead, the calculated hotspot width is $0.43° \pm 0.13°$. Since the simulation showed that the radial fit systematically gives slightly higher values (see Figure 2), it is slightly preferential to use the result from the 2-D fit.

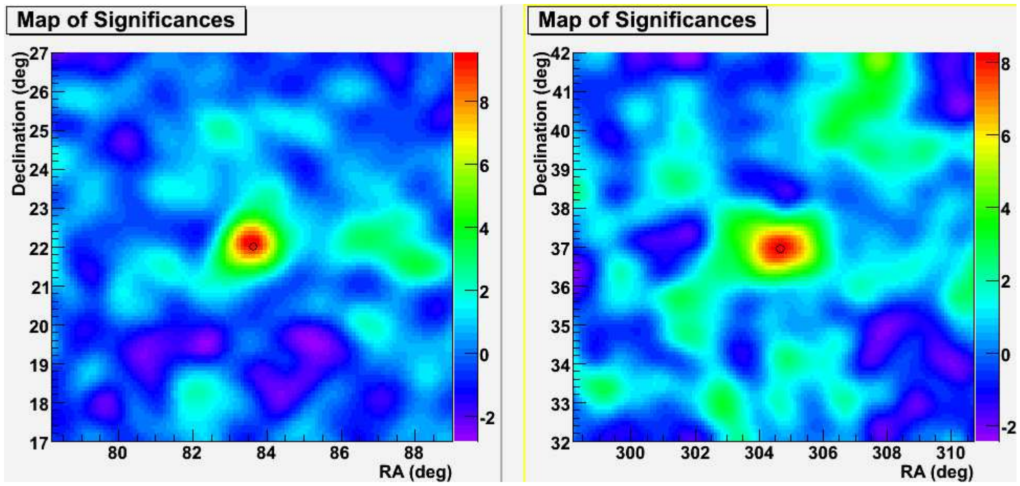

Figure 4: Significance maps for the Crab and the Cygnus hotspot. The circle in the Crab plot marks the true location of the Crab, while the circle in the Cygnus plot marks the location from the fit. Note that the yscale is 10° in both, but the xscale has been set to give an accurate aspect ratio at the center.

3.2 Hotspot Location

As noted above, the 2-D fit gives the location of the Cygnus hotspot as $RA = 304.66° \pm 0.13°$, $Dec = 36.96° \pm 0.08°$, where the included errors are statistical. To get a handle on possible systematic errors, it is useful to look at the location of the Crab and the hotspot across the epochs. Figures 6 through 12 show the weighted, Gaussian smoothed maps for data broken into epochs for OFF, ORCOM, 3Layer, 2LayerBefore, 2LayerAfter, and 2Layer603. (Data from the COM fitter were not included because neither source is visible.) The circle in each of the Crab maps shows the true position of the Crab, while the circle in the Cygnus maps marks the fit location quoted above. Three of the datasets that were used in the fit (3Layer, 2LayerBefore, 2LayerAfter) seem to have consistent pointing. The fourth map, for 2Layer603, is too short to determine whether the calibration change has affected the pointing. In the ORCOM data there may be pointing issues (maps with nFit>40 and nFit>125 are shown), but this is not clear and has not yet been fully investigated. In the OFF map (from data with the OFF core fitter), the significance is not high enough to draw conclusions about the pointing. The fit positions for the Crab and the hotspot

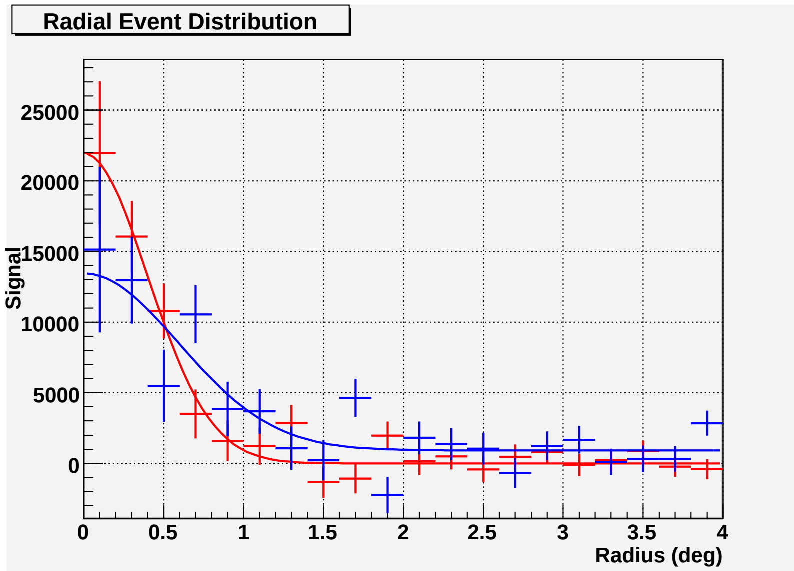

Figure 5: Radial distribution of excess for the Crab (from the fit position) and the Cygnus hotspot (again from the fit position). The Crab was fit using a Gaussian ($\chi^2 = 15.6$ for 18 degrees of freedom), while the hotspot used a Gaussian with an offset ($\chi^2 = 30.3$ for 17 degrees of freedom).

for each dataset are listed in Table 2.

To further investigate the systematic error, a variety of different weights were used, and the fitted locations were not found to be statistically different. Also, a fit was performed on the same data set but with nFit$>$ 40, and again there was no statistically compelling difference. One contribution to the systematic error comes from the fit position of the Crab, which is 0.1° (2σ) off in declination from the true location. Another potential contributor is the 0.3° global correction that was applied to these data to center the Crab – are we certain that the shift is uniform for the entire sky? According to Andy, such an effect would have to be simulated, and if there is such an error, it would be much smaller than the magnitude of the shift. In the end, the systematic pointing uncertainty is difficult to analyze, and so it may be best to quote a reasonable value like 0.2° or 0.3°.

Table 2: Fit positions for the datasets corresponding to Figures 6 through 12. Note that the COM dataset (Epoch 1) is not included because neither source was visible. The true Crab position is RA=83.63°, Dec=22.01°, while the best fit hotspot position is RA=304.66°, Dec=36.96°.

		Crab		Cyg Hotspot	
Dataset	Duration	RA	Dec	RA	Dec
OFF	896 Days	$83.42° \pm 0.18°$	$22.05° \pm 0.15°$	$305.09° \pm 0.43°$	$36.75° \pm 0.27°$
ORCOM	500 Days	$83.69° \pm 0.13°$	$22.19° \pm 0.09°$	$305.57° \pm 0.26°$	$36.90° \pm 0.16°$
3Layer	177 Days	$83.27° \pm 0.19°$	$22.15° \pm 0.26°$	$305.00° \pm 0.45°$	$36.80° \pm 0.30°$
2LayerBefore	163 Days	$83.43° \pm 0.16°$	$22.01° \pm 0.12°$	$304.47° \pm 0.36°$	$36.88° \pm 0.15°$
2LayerAfter	176 Days	$83.65° \pm 0.22°$	$22.13° \pm 0.25°$	$304.53° \pm 0.17°$	$36.91° \pm 0.22°$
2Layer603	98 Days	$83.52° \pm 0.17°$	$21.95° \pm 0.14°$	$305.67° \pm 0.20°$	$36.75° \pm 0.16°$

References

[1] Fegan, S.J. et al. 2005, ApJ, 624, 638..

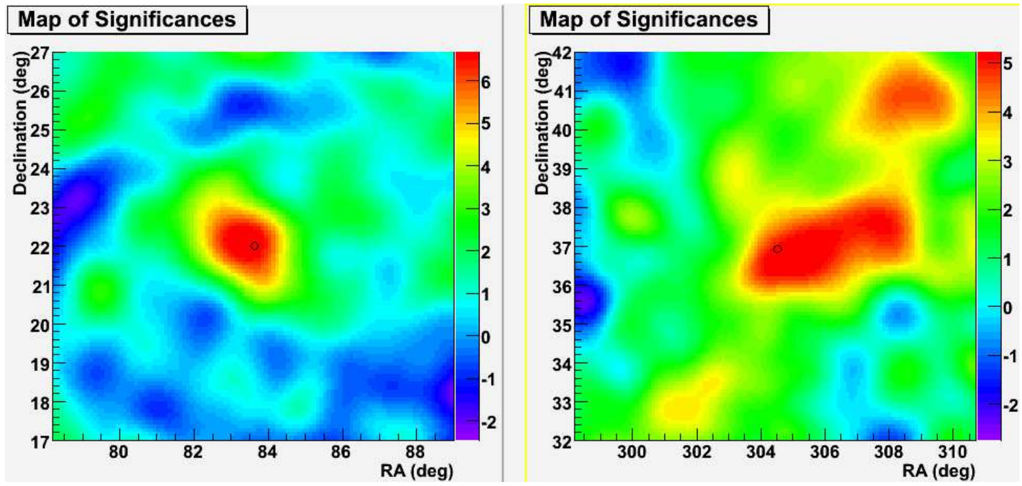

Figure 6: Gamma/hadron weighted, Gaussian smoothed map for the Crab and the Cygnus hotspot, made using data from the 1-layer fit with the OFF core fitter, spanning 896 days. An nFit cut of 40 was used.

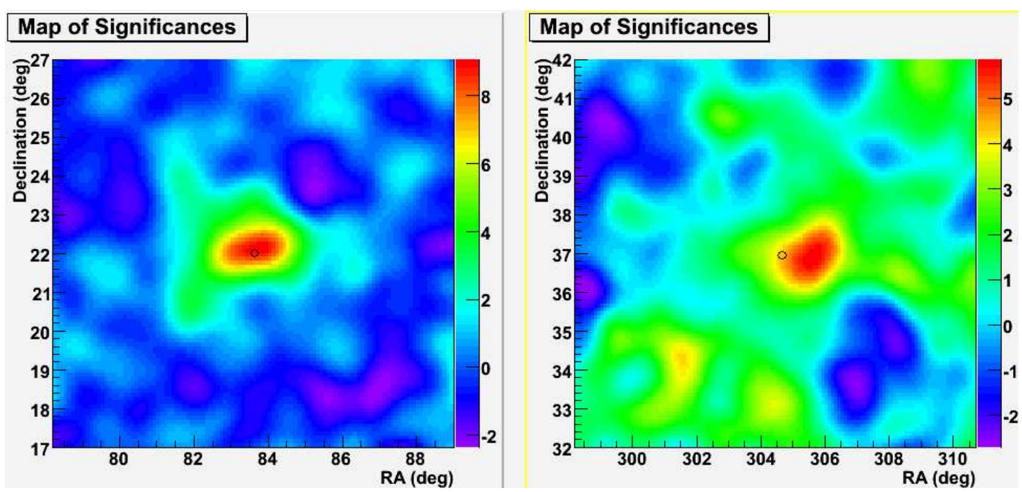

Figure 7: Gamma/hadron weighted, Gaussian smoothed map for the Crab and the Cygnus hotspot, made using data from the 1-layer fit with the ORCOM core fitter, spanning 500 days. An nFit cut of 40 was used.

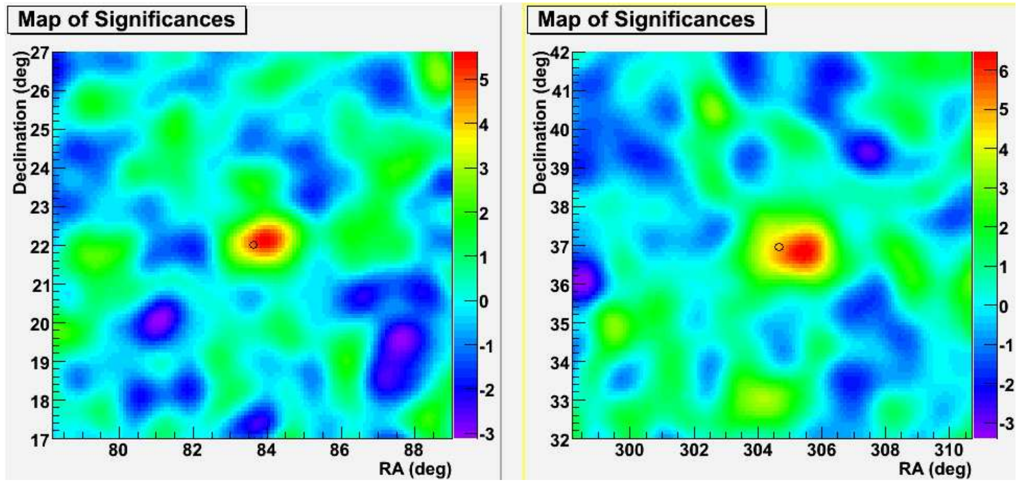

Figure 8: Gamma/hadron weighted, Gaussian smoothed map for the Crab and the Cygnus hotspot, made using data from the 1-layer fit with the ORCOM core fitter, spanning 500 days. An nFit cut of 125 was used for improved angular resolution.

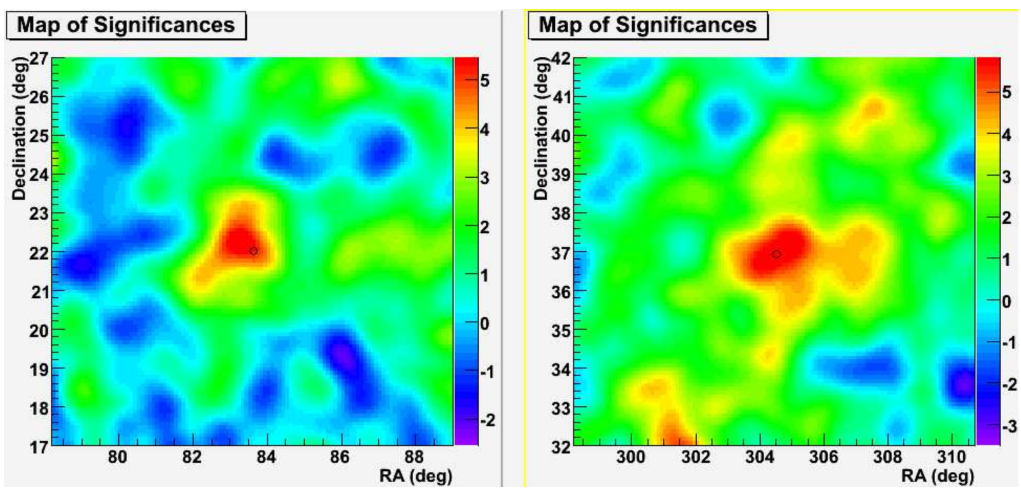

Figure 9: Gamma/hadron weighted, Gaussian smoothed map for the Crab and the Cygnus hotspot, made using data from the 3-layer fit with the Gaussian core fitter, spanning 177 days. An nFit cut of 40 was used.

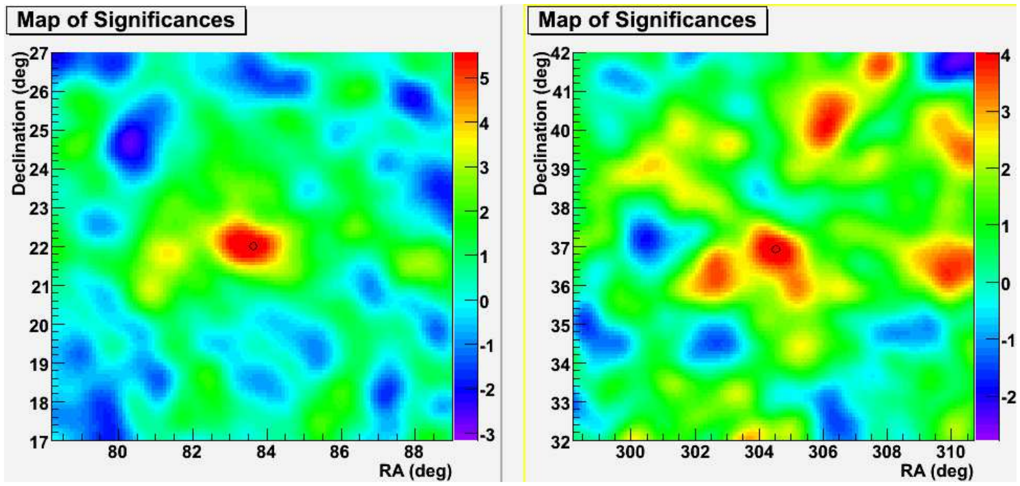

Figure 10: Gamma/hadron weighted, Gaussian smoothed map for the Crab and the Cygnus hotspot, made using data from the 2-layer fit with the Gaussian core fitter, before the 2005 repair, spanning 163 days. An nFit cut of 40 was used.

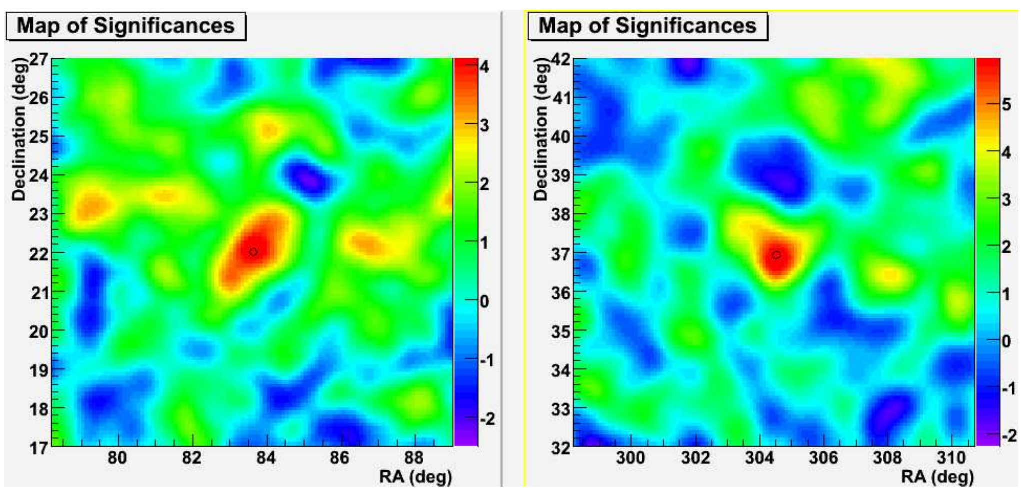

Figure 11: Gamma/hadron weighted, Gaussian smoothed map for the Crab and the Cygnus hotspot, made using data from the 2-layer fit with the Gaussian core fitter, after the 2005 repair, spanning 176 days. An nFit cut of 40 was used.

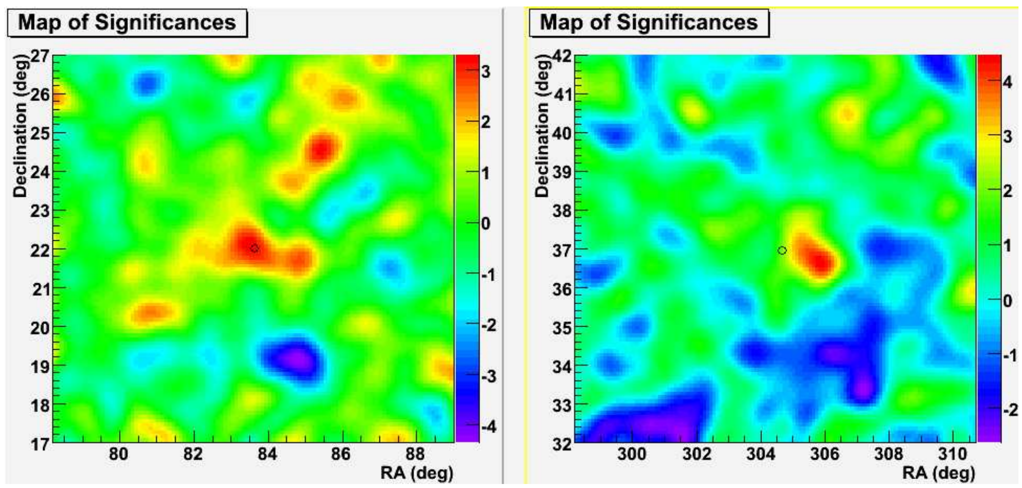

Figure 12: Gamma/hadron weighted, Gaussian smoothed map for the Crab and the Cygnus hotspot, made using data from the 2-layer fit with the Gaussian core fitter with the 603 calibration, spanning 98 days. An nFit cut of 40 was used.