An All Sky Search for Extended Gamma-Ray Sources

Introduction:

The goal of the analysis is the search for extended gamma-ray sources with Milagro. Air shower detectors are uniquely suited to search for localized gamma-ray sources that may be extended from a fraction of a degree to several degrees making their detection using atmospheric Cerenkov telescopes difficult. Furthermore, the likely candidates for extended gamma-ray sources include super-nova remnants which are likely to be located within or near the plane of the galaxy where ACTs encounter observation problems due to the large number and density of stars.

In this memo, I will search for extended sources by performing and allsky search, identical to the method recently published, while adding an additional parameter to the search: bin size. The bin size is expanded from 2.1 deg, found to be optimal for point sources, continuously up to 6.1 deg in steps of 0.2 deg.

The Data set:

The map making technique in this analysis employs the standard “direct integration” background subtraction method with an integration period of 2 hours. The implementation of the method uses the C++ direct integration class (MDIMap) for map creation. The analysis was done with the DC source analysis class (MDCAnalysis), derived from Gus's Milagro_Analysis class. Both are available in the current version of Milinda. The standard cuts were applied to the data: NFIT>=20 and X2>2.5. This analysis is bases on the online reconstructed data set including events collected between JD=5175 (The date X2 went online) to JD=53132 (May 6,2004).

Data Analysis:

The standard square bin analysis was employed for each candidate bin size. The smoothed map is then searched for candidate positions with significance greater than 5.0 sigma. The maximum significance point on the list is identified as a source candidate. All entries on the list located within a distance equal to 1 bin size, of the source candidate are removed. The next source candidate is then identified as the maximum significance point remaining on the list, with points in the vicinity subsequently removed. This process is repeated until no entries remain on the list. This method guarantees that source candidate positions are completely independent. There is no overlap in the smoothing bins. This algorithm has been implemented in the ScanMap() method of the MDCAnalysis class.

Results:
The list of source candidate positions are given in the tables below along with their significances. Note the following:

1) The Crab and Mrk 421 are observed at greater than 5 sigma for almost all bin sizes
2) 3 other source candidates are detected above the 5 sigma threshold. These sources are identified on the tables as “Source A”, “E0520”, and “Cygnus Region”.
3) “Source A” only appears at the smallest bin size and barely peeks above the threshold. It is a spot we will want to keep and eye on, but does not distinguish itself from a marginally unlikely fluctuation.
4) “E0520” is above threshold for bin sizes larger than 2.5 deg and stays on the list until the bin size is equal to its distance from the crab, and it and the crab combine to form a single source candidate. The label “E0520” is given here as this source is spatially coincident with egret source EG 0520+2556. For a 2.9 deg bin, this source candidate reaches a significance of 5.86 sigma!
5) The “Cygnus Region” is crosses the 5 sigma significance threshold when the bin sizes is greater than 3.5 deg, and appears in the list for all bin sizes up to the maximum and shows no sign of waning. It reaches a maximum significance for a bin size of 5.7 deg at 5.53 sigma.

2.1 deg bin

RA	Dec	Significance	Note
83.95	22.15	6.52	Crab
166.85	38.15	6.16	Mrk 421
0.25	34.35	5.09	Source A

2.3 deg bin

RA	Dec	Significance	Note
83.85	21.85	6.45	Crab
166.65	38.25	5.76	Mrk 421

2.5 deg bin

RA	Dec	Significance	Note
84.45	21.95	6.76	Crab
166.65	38.35	6.08	Mrk421

2.7 deg bin

RA	Dec	Significance	Note
83.95	22.85	6.59	Crab
167.35	37.75	6.20	Mrk421
79.95	26.35	5.41	E0520

2.9 deg bin

RA	Dec	Significance	Note
84.15	22.55	6.96	Crab
166.95	37.75	6.16	Mrk 421
80.05	26.25	5.86	E0520

3.1 deg bin

RA	Dec	Significance	Note
84.05	22.55	7.18	Crab
167.15	37.65	6.00	Mrk 421
80.15	26.35	5.73	E0520

3.3 deg bin

RA	Dec	Significance	Note
84.15	22.45	6.95	Crab
167.15	38.05	6.15	Mrk 421
80.15	26.55	5.7	E0520

3.5 deg bin

RA	Dec	Significance	Note
84.15	22.45	6.82	Crab
166.65	37.85	6.00	Mrk 421
80.05	26.55	5.55	E0520

3.7 deg bin

RA	Dec	Significance	Note
84.05	22.35	6.57	Crab
166.55	38.95	5.70	Mrk 421
79.95	26.35	5.49	E0520
304.45	38.95	5.06	Cygnus Region

3.9 deg bin

RA	Dec	Significance	Note
84.25	22.45	6.05	Crab
166.55	38.85	5.64	Mrk 421
79.85	26.25	5.28	E0520
304.65	39.05	5.13	Cygnus Region

4.1 deg bin

RA	Dec	Significance	Note
84.25	22.45	5.77	Crab
166.35	39.35	5.53	Mrk 421
79.45	26.15	5.14	E0520

4.3 deg bin

RA	Dec	Significance	Note
166.35	39.25	5.66	Mrk 421
83.55	21.95	5.58	Crab
304.85	38.95	5.03	Cygnus Region
79.55	26.05	5.03	E0520

4.5 deg bin

RA	Dec	Significance	Note
83.35	21.85	5.60	Crab/E0520
166.15	38.35	5.53	Mrk 421
304.95	38.85	5.01	Cygnus Region

4.7 deg bin

RA	Dec	Significance	Note
83.45	21.85	5.71	Crab/E0520
166.05	38.45	5.37	Mrk 421

4.9 deg bin

RA	Dec	Significance	Note
81.65	23.75	5.55	Crab/E0520
166.35	38.85	5.12	Mrk421
307.95	41.35	5.05	Cygnus Region

5.1 deg bin

RA	Dec	Significance	Note
81.65	23.85	5.53	Crab/E0520
166.25	38.85	5.18	Mrk 421
308.05	41.35	5.13	Cygnus Region

5.3 deg bin

RA	Dec	Significance	Note
81.95	23.85	5.53	Crab/E0520

RA	Dec	Significance	Note
308.35	44.15	5.30	Cygnus Region
166.75	38.85	5.05	Mrk 421

5.5 deg bin

RA	Dec	Significance	Note
81.05	23.85	5.81	Crab/E0520
308.15	41.65	5.35	Cygnus Region

5.7 deg bin

RA	Dec	Significance	Note
81.15	24.15	6.15	Crab/E0520
308.65	43.65	5.53	Cygnus Region

5.9 deg bin

RA	Dec	Significance	Note
81.15	24.05	6.04	Crab/E0520
308.55	43.25	5.43	Cygnus Region
167.75	36.65	5.14	Mrk 421

6.1 deg bin

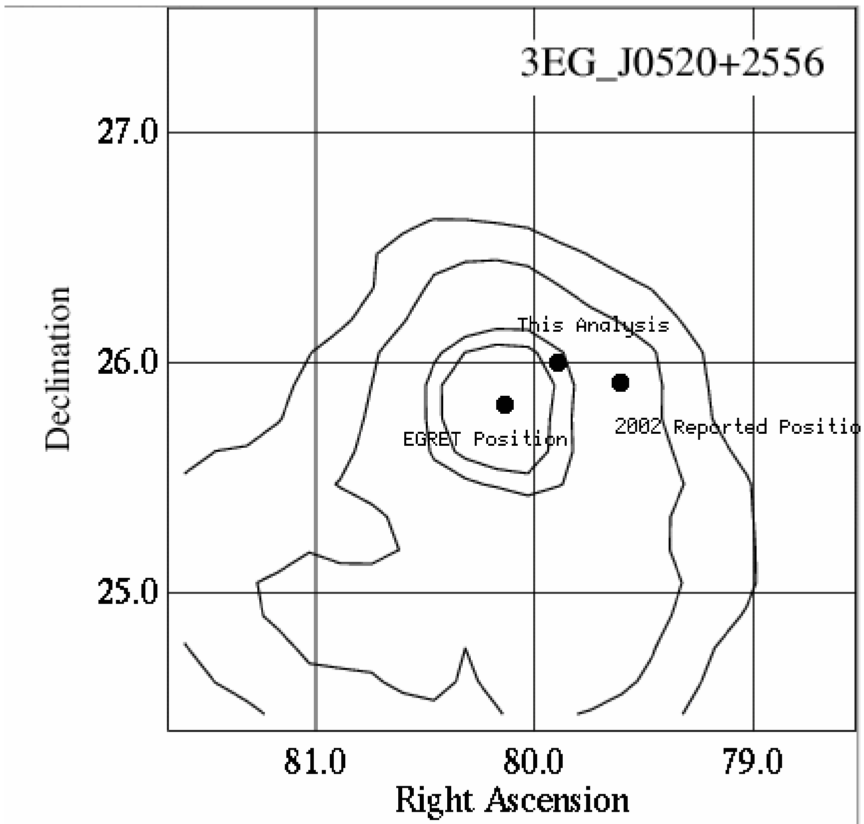
RA	Dec	Significance	Note
82.35	24.25	6.14	Crab/E0520
308.45	43.35	5.49	Cygnus Region
167.85	36.65	5.17	Mrk 421

EGRET Source 0520+2556:

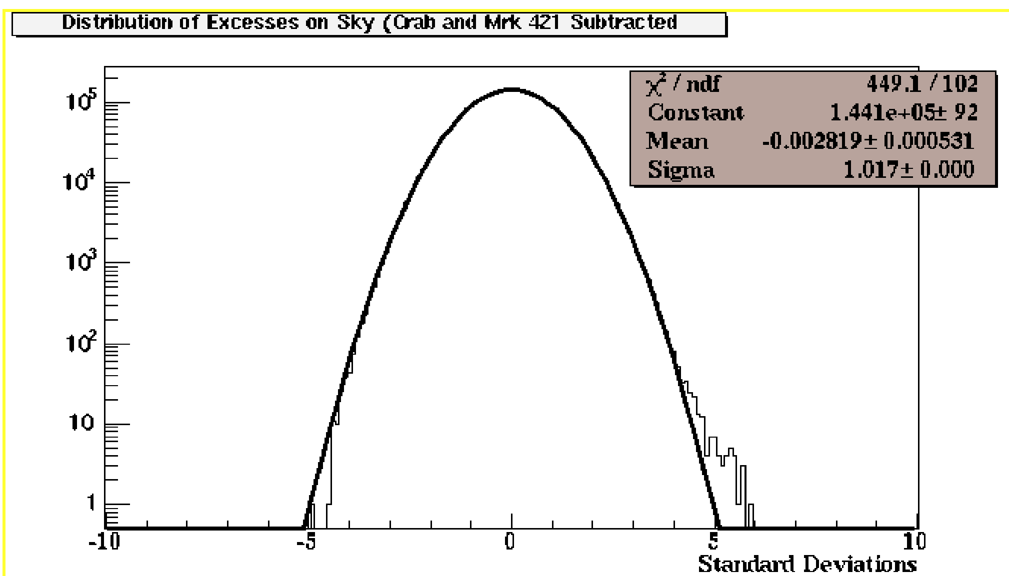
This source candidate is roughly at the position of a source identified by Gus 2 years ago. The source does not appear as a candidate in the standard 2.1 deg bin analysis, however, the source shines brightly when the bin size is increased. It is also spatially coincident with unidentified EGRET source 3EG_0520+2556 located at RA=80.14 deg and Dec=25.75. This source is ~6 deg off the galactic plane and nearly exactly opposite of the galactic center. Included below is an EGRET significance contour for the source. Estimation of the post-trials significance of this observed excess will be computed by simulating this analysis, and by computing the significance of the excess since we originally claimed this point as a source candidate.

Following our initial report of this object as a source candidate, Whipple followed up with observation of the region (Falcone et al, astro-ph 0305575). They ruled out the presence of a point source at our position and at the EGRET position. The limit for point sources in the neighborhood is not as good and they do not report an upper limit on diffuse emission. However, considering how much time they spent on this source, their diffuse emission limit would probably be consistent with our observation.

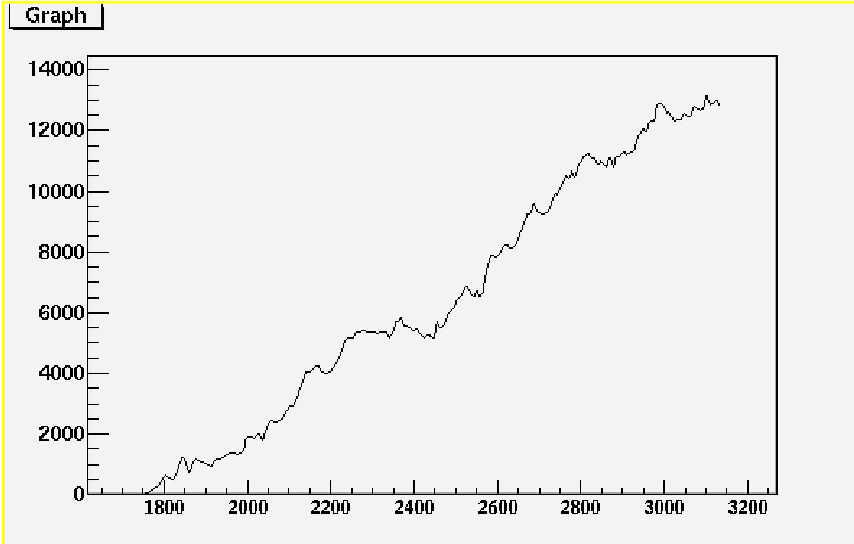
As mentioned above, one reason that Whipple did not observe this source is that it may not be a point source. The source may be extended. This conclusion is also consistent the source not appearing as a candidate with bin sizes smaller than 2.7 deg. To estimate the extension of the source, I first fit the radial event density of the Crab and Mrk 421 to a Gaussian to estimate the PSF of the detector. The fits yield a PSF with widths 0.95+/-0.15 deg and 1.05+/-0.24 deg for the Crab and Mrk421 respectively. The 2 measurement average to 1.00 deg. The radial distribution for the candidate source is then fit to the function F = A+exp(r*r/(2*(1.0*1.0+B*B))). In this parameterization, B is combined in quadrature with the PSF. Fits to point sources should produce a B consistent with 0. The fit to the candidate source region yields B=0.84+/-0.37, more than 2 sigma inconsistent with 0. A plot showing this fit is included below.



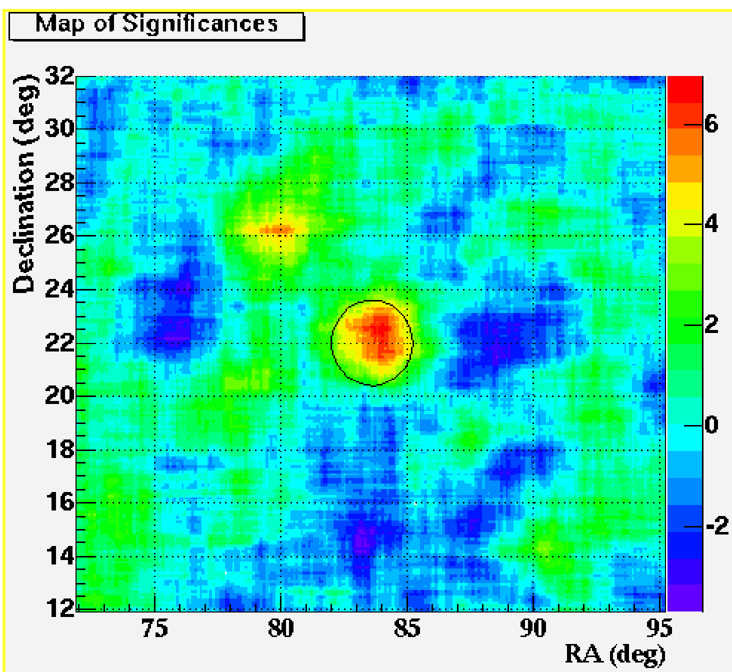
Egret significance contours for unidentified source 3EG J0520+2556.



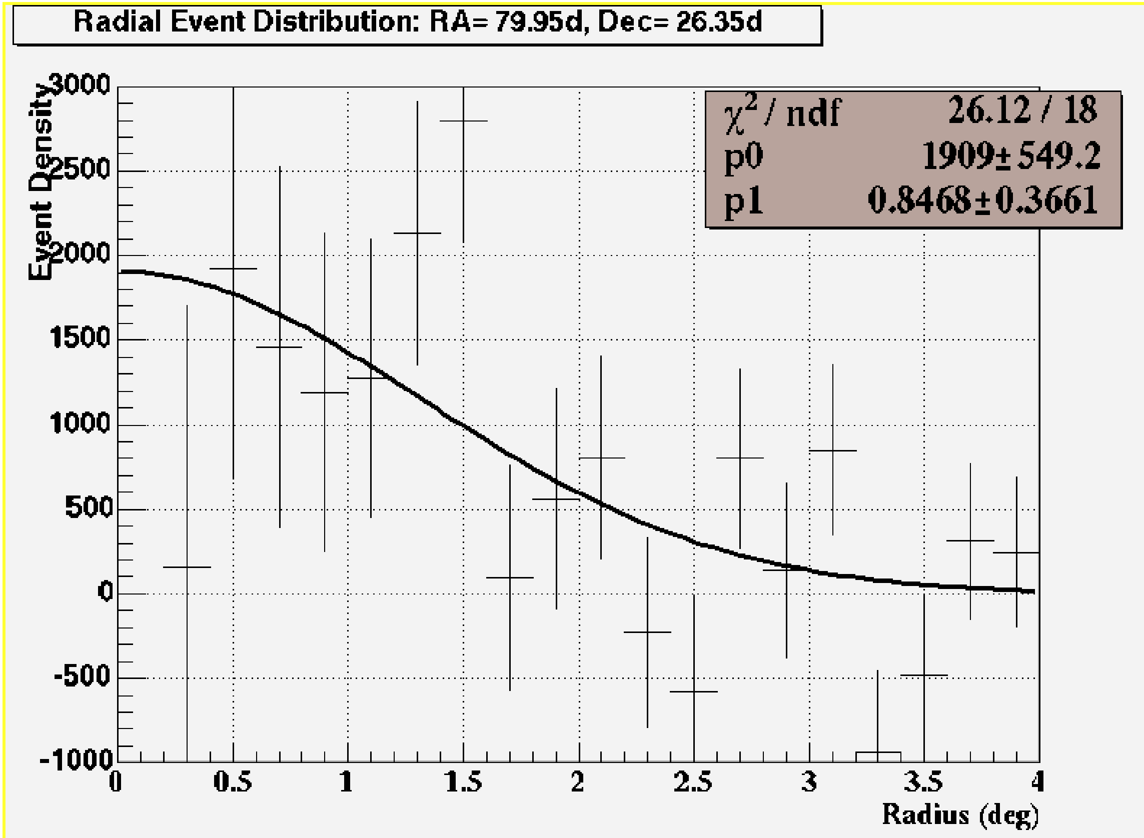
Distribution of sigmas with Crab and Mrk 421 regsions removed. The E0520 excess contributes the tail to the Gaussian distribution.



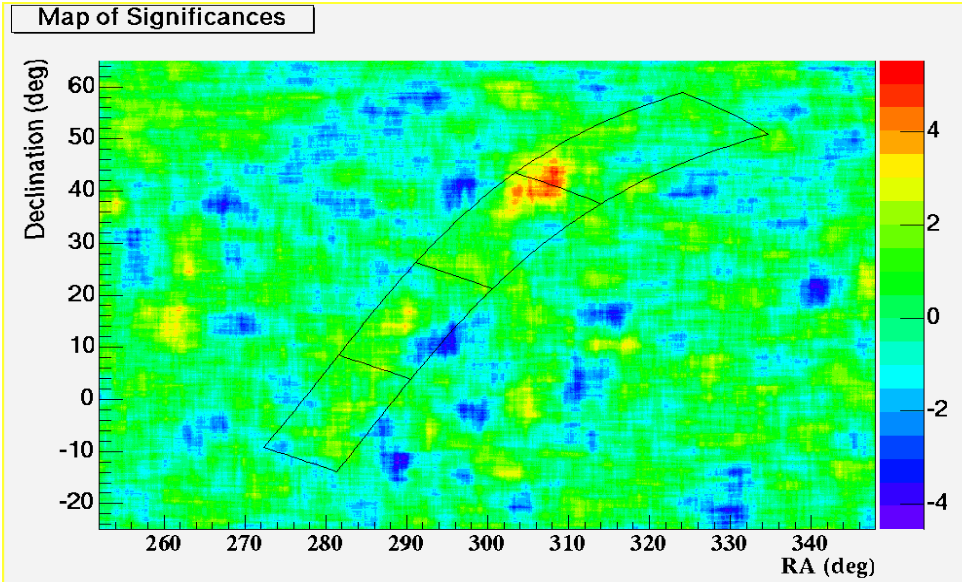
Accumulated excess plotted vs julian date for E0520 location.



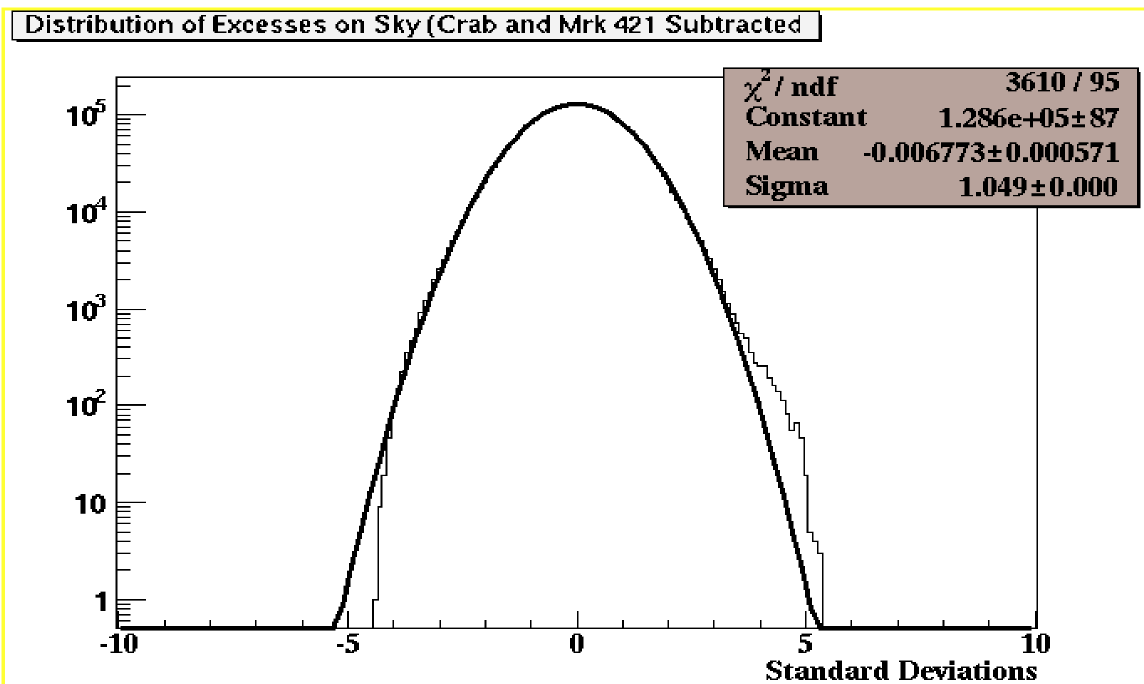
Significance Map of the vicinity of the crab (centered). E0520 excess can be seen up and to the left of the crab.



Cygnus Region:
The Cygnus region is another gamma-ray source already know to Milagro. This broad region, located at galactic longitude of ~80deg and galactic latitude ~+1 deg, is observed by EGRET to have a large gamma-ray excess. The direction of the Cygnus Region is down the spiral arm in which our sun resides. The Cygnus region provides much (most?) of the excess from the observed gamma-ray signal from the inner galaxy. It is probably not possible with this signal strength to distinguish gamma-rays from diffuse cosmic ray induced pi0 production from a collection of point/extended sources such as pulsars and super nova remnants with the Milagro data, however the examination of the morphology of the excess may be interesting and is shown later.



Significance map of the "Inner Galaxy". The smoothing was done with 5.7 deg square bins. The Cygnus region is clearly visible as a broad excess.



Distribution of sigmas with Mrk421 and crab regions removed. The shoulder on the right side of the plot is contributed by the excess in the Cygnus region.

Source Localization:

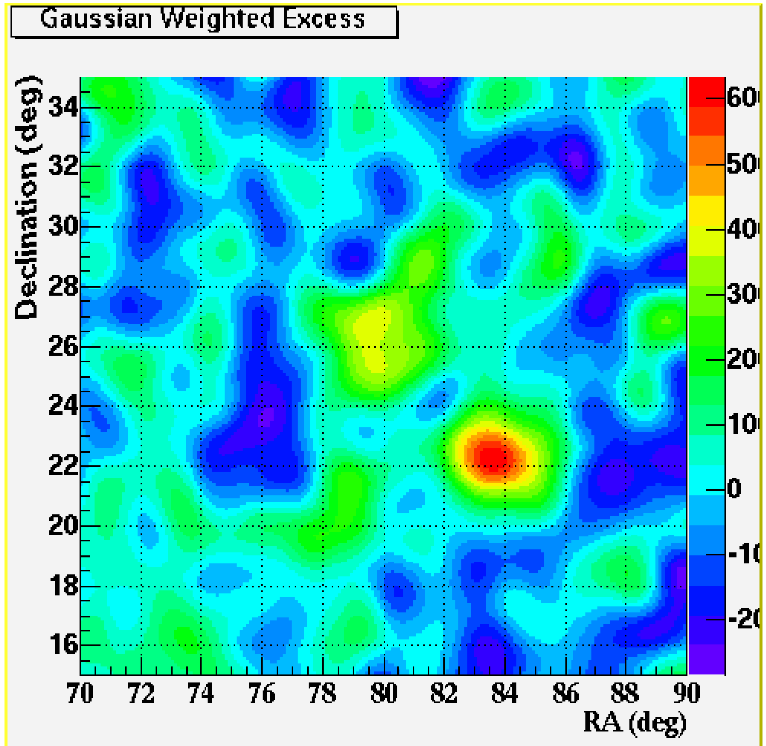
Locating the position of a candidate source by identifying them with the point of highest significance for as square bin analysis such as this is far from optimal. With square bins, no care is taken to treat events differently depending on where the events fall within the bin. An example of the poor source localization can be seen in this analysis. For the 2.5 deg and 2.7 deg bin candidate lists, the maximum significance bin in the Crab vicinity is different by 0.5 deg in RA and 0.9 deg in Dec. Certainly an instrument with a 0.75 deg angular resolution should be able to localize sources better than that.

To better localize the candidate source positions, the excess map is constructed by smoothing the region with a 2D Gaussian instead of a square bin. This Gaussian weighting method is not used to compute the significance of the excess, only to locate the point of maximum excess. The peak bin for the crab and Mrk 421 for Gaussian widths of 0.75 deg and 1.00 deg are shown below. The maximum position of these 2 known sources and indicates a consistent offset of a few tenths of a degree in declination and a one to two tenths of a degree in RA. The observed offset is consistent with the offset of the moon reported by Xu in the last collaboration meeting. This pointing pointing correction should be followed up and combined with the moon data to produce an overall pointing correction for Milagro.

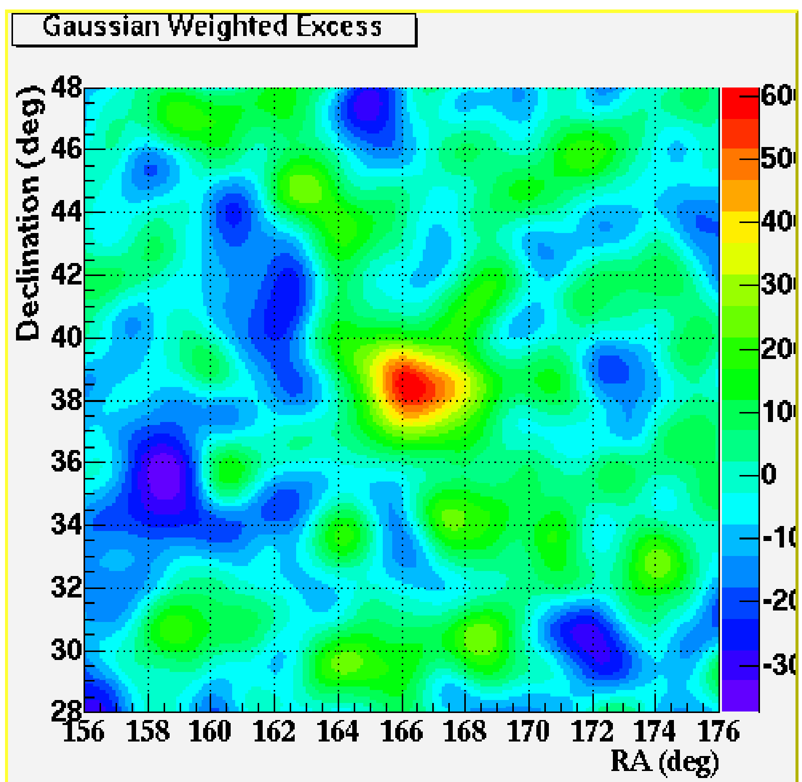
Source	**Gaussian width**	**Peak RA**	**Offset from true**	**Peak Dec**	**Offset from true**
Crab	0.75 deg	83.75	+0.15 deg	22.35	+0.35 deg
Crab	1.00 deg	83.75	+0.15 deg	22.35	+0.35 deg
Mrk421	0.75 deg	166.35	+0.15 deg	38.55	+0.35 deg
Mrk421	1.00 deg	166.45	+0.25 deg	38.45	+0.25 deg

The observed maximum position of the Milagro excess near EGRET source EG 0520+2556 is RA=79.95, Dec=26.35. Assuming a pointing offset as indicated by the measured offsets in the crab and Mrk421, the true maximum source position is RA=79.80, Dec=26.00.

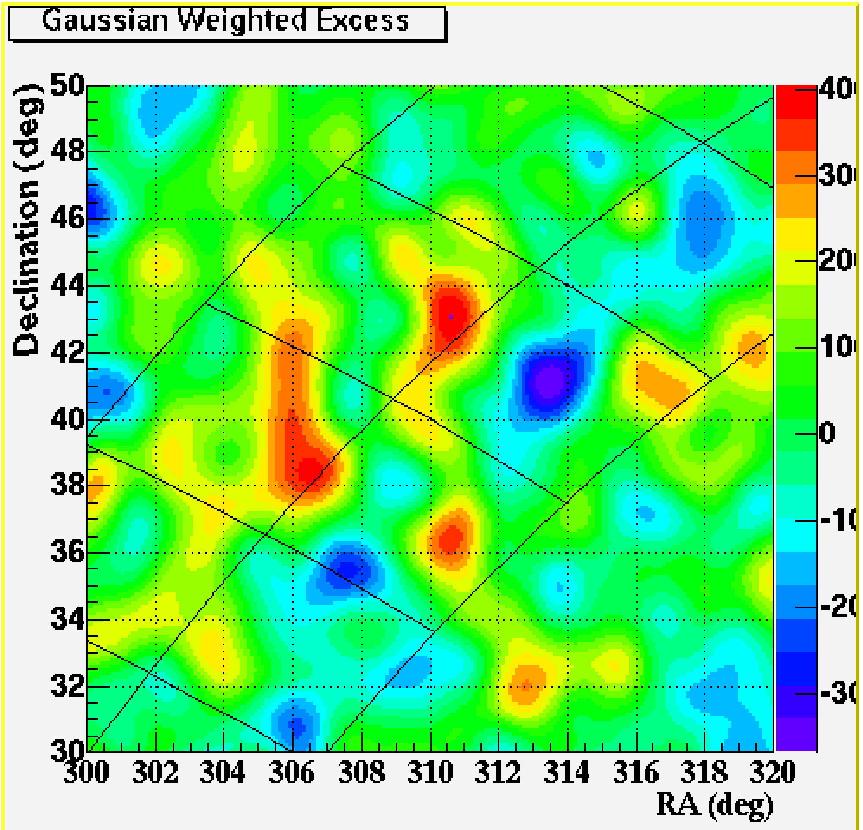
Shown below are Gaussian weighted maps of the Crab region, Mrk 421 and the Cygnus Region. These maps are useful to demonstrate the morphology of the region of excess. In these plots, source candidate E0520 is elongated north south. It is not clear whether the source shape is consistent with a point source. The Cygnus region excess shape is not consistent with a point source.



Gaussian weighted excess map of the crab region.



Gaussian weighted excess map of Mrk 421.



Gaussian Weighted map of the Cygnus Region. Galactic latitude and longitude lines are superimposed on the plot.