A Novel Maximum Likelihood Method For VERITAS Analysis

Tom Brantseg
for the VERITAS collaboration

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Outline

1. Motivation
2. 3D MLM overview
3. Preliminary Results
4. Current and Future Work
Extended gamma-ray sources

- Recent developments (T. Linden talk Tuesday, D. Hooper talk Wednesday, J. Hewitt talk Monday):
  - HAWC: Extended TeV emission from Geminga/Monogem
    - Also seen by Milagro, PAMELA, AMS02
  - Important physics! (Positron excess)
  - IACTs could fill in a nice part of the physical picture...
    - Good energy/spatial resolution, wide energy range
    - ... but it’s a little tricky

- 499 pixels/camera
- Energy range: 85 GeV to > 30 TeV
- Energy resolution: 20% @ 1 TeV
- Angular resolution (68% containment): 0.08° @ 1 TeV
- Point source sensitivity: 1% Crab in ~25h

G. Hughes
IACTs and extended sources

- Standard analysis methods have difficulty with extended sources
  - Large sources can "crowd out" background regions in field
  - Difficult to get enough background for statistically meaningful analysis of sources > about 0.3°
  - Hard to analyze sources like Geminga, Cygnus Cocoon, etc.

![Image showing ON and OFF regions for the ring background model (left) and reflected region model (right). Image from Berge et al. (2007).](image-url)
3D Maximum Likelihood

- Developed by ISU VERITAS group led by Amanda Weinstein
  - Most of the figures here are from Amanda’s (recently defended) student Josh Cardenzana
- 3DMLM adds a third dimension to standard spatial ML fitting for gamma-ray/background separation
  - Mean scaled width (MSW)
  - Average Hillas width parameter for all images contributing to an event

![Gamma-ray MSW distribution](image1)

![Background MSW distribution](image2)
Likelihood calculation

\[
\log \mathcal{L}(\vec{s}) = N_{\text{obs}} \log(N_{\text{exp}}) - N_{\text{exp}} \\
+ \sum_i [S_{\text{src}}(\vec{r}_i|\vec{s})W_{\text{src}}(w_i|\vec{s}) + S_{\text{bkg}}(\vec{r}_i)W_{\text{bkg}}(w_i)]
\]

- **Red**: likelihood term measuring observed (obs) vs. expected (exp) counts
- **Blue**: likelihood term measuring correlation of the source and background spatial (\(S\)) and MSW (\(W\)) models with the data
Data binning

- Collect observed data with similar spatial/MSW background distributions \((\text{field})\) to improve stats.

- Spatial and MSW background distributions depend on:
  - Detector configuration
  - Atmospheric conditions
  - Observational parameters
  - Telescope pointing
  - Energy

- Each field can be fit to its own set of spatial and MSW models.
Spatial Models

- Calculated from:
  - Effective area ($A$)
  - Energy dispersion ($R$)
  - PSF ($P$)
  - Source spatial morphology ($B$)
  - Spectral parameters ($S$)

- Spatial model $M$ calculated as:

$$M(\vec{r}_{i,j}|\vec{s}) = \sum_{k,m,n} B_{m,n} P_{m,n}(\vec{r}, E'_k) A_{m,n}(E'_k) \int_{E_{min}}^{E_{max}} R_{m,n}(E, E'_k) dE \times \int_{E_{klo}}^{E_{kup}} S(E'|\vec{s}) dE'$$

- Red term can be pre-computed based on simulations and templates for each field
- Blue term must be recalculated at each fit iteration
Spatial model morphology

- Source models generated from pre-existing templates
- Background models taken from data on weak sources and blank fields
- Bright stars and potential sources excluded
- Correction for zenith angle dependence of Cherenkov light
- Approximated by polynomial fit to generate spatially symmetric background model
MSW models

- Source models calculated from standard VERITAS simulations
- Background models calculated from observational blank field data

**Figure 6.7:** (a) MSW distribution for both the entire Crab nebula field of view and (b) only events within 0.1 of the source position. Plotted are the data (black points), background model (blue dashed), source (red dashed), and full models (purple solid).

- **Red:** source MSW model from simulations
- **Blue:** background MSW model
- **Purple:** total MSW model
MLM vs. RBM check (Crab)

- Want to check quality of both spectral and spatial fits
- Spectral fit:
  - Log parabola model
    \[
    \frac{dN}{dE} = A \left( \frac{E}{E_0} \right)^{\alpha + \beta \log(E/E_0)}
    \]
- Spatial fit:
  - Measure quality of spatial models with residual map
  - Sky map - (source spatial model + background spatial model)
  - Should be basically blank if we’ve gotten it right
MLM vs. RBM check (Crab)

Figure 6.5: (a) Spatial significance map of the Crab nebula computed without the Source model and (b) with the source model.

<table>
<thead>
<tr>
<th></th>
<th>MLM</th>
<th>Standard</th>
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<tbody>
<tr>
<td>Norm at 1 TeV</td>
<td>$3.49 \pm 0.09$</td>
<td>$4.05 \pm 0.07$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$-2.49 \pm 0.02$</td>
<td>$-2.44 \pm 0.02$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$-0.12 \pm 0.03$</td>
<td>$-0.15 \pm 0.03$</td>
</tr>
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Known (small) extended source: IC443

- Field for this is larger than for the Crab case
- **NOTE** Not a realistic analysis, more of a software check
  - Only uses a portion of the IC443 data set
  - Higher than normal lower energy threshold (modeling issues at low energy)
- Spatial fit and spectral fit checks as before
  - Power law spectral model
  - Models computed using disk templates
  - 0.15° - brightest part of the emission
  - 0.35° - entire shell
IC443 sky maps

(a) Significance Map

(b) Zoomed Significance Map

(c) 0.15 Disk Subtracted Significance Map

(d) 0.35 Disk Subtracted Significance Map

Figure 6.18: (a) Spatial significance map of IC443 computed without the Source model. (b) Significance map showing 1°×1° around IC443. The second row shows the spatial significance map including (c) the 0.15° disk model and (d) 0.15° disk model.

Overall skymap

Source detail

Spatial residuals (0.15°)

Spatial residuals (0.35°)
IC443 spectral fits

- **Blue** line: standard VERITAS analysis fit
- **Red**: 3D MLM spectral fit
Overall

- General agreement with standard analysis results on point sources (Crab, sample of blazars)
- Fitting extended source (IC443) with extended templates gives promising results!
- Background statistics in low-count areas subject of ongoing work
Blank-Field Issue

- "Phantom sources" detected fitting blank fields to extended source templates
- Issue partially tracked to low-count bins in MSW distributions
- Clear that a significant portion of the problem is due to handling background statistics
- Examining ways to modify the likelihood statistic (Barlow & Beeston 1993) to resolve the issue
Future course of work

- Resolve statistical and implementation issues with Barlow-Beeston test statistic to resolve blank field issue
- Re-check previous validation studies
- Further studies on other extended sources/3ML plugin
Possible fix

- Treat MSW distribution with modified likelihood stat from Barlow & Beeston (1993)

\[ \log \mathcal{L} = \sum_i d_i \log f_i - f_i - \sum_{i,j} a_{ji} \log A_{ji} - A_{ji} \]

- Term in red is a 'penalty' term that measures contribution of individual model components
- Each component in each bin varies independently if that improves overall \( \mathcal{L} \)
- Currently resolving with statistical/implementational issues for this method
  - Toy MC studies of MSW distributions + blank field samples
How well can you do?

- Flux UL for a sample of 50 runs

![Graph showing differential flux versus energy for different angular sizes and Crab nebula strengths. The graph displays the upper limits on the differential flux for extended sources based on the results from the blank field extended source cross checks on Ursa Minor. Also plotted are the spectral curves for a 100%, 10%, and 1% Crab nebula strength source.](image-url)