Improving the H.E.S.S. angular resolution using the Disp method

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Abstract: The angular resolution of imaging atmospheric Čerenkov telescopes depends on the employed event reconstruction methods. By taking the weighted average of intersections of shower axes, the H.E.S.S. experiment achieves a 0.08 degree angular resolution at 20 degree zenith angle with an image size cut of 160 p.e. for sources with a spectral index of 2. However, the angular resolution degrades to 0.14 degree at 60 degree zenith angle, due to the larger fraction of nearly parallel images. The Disp method reduces the impact of parallel images by including an estimation of the image displacement (disp), inferred from the Hillas parameters, in the reconstruction procedure. By using this technique, the angular resolution at large zenith angles can be improved by 50%. An additional cut on the estimated direction uncertainty can further improve the angular resolution to around 0.05 degrees at the expense of a loss of 50% of effective area. The performance of this reconstruction method on simulated γ-ray events and real data is presented.

Keywords: direction reconstruction, gamma-ray astronomy

1 Introduction

The imaging atmospheric Čerenkov telescopes (IACT) technique has been developed for several decades. IACTs detect the Čerenkov light emitted by relativistic charged particles in atmospheric air showers induced by very-high-energy ($\sim$ TeV) γ rays. The Čerenkov light distribution is imaged onto the cameras. Stereoscopic observation of air showers with IACT arrays has been proven successful in providing better direction reconstruction and background rejection. The quality of direction reconstruction can be quantified by the 68% containment radius, $R_{68}$, of the point-spread function which is also referred to as the angular resolution. For γ-ray sources with a given spectrum, the angular resolution depends on the design of the instruments, the analysis cuts, and the event reconstruction algorithm. As discussed in \cite{1}, the reconstruction algorithms mainly follow two approaches. The first kind is based on parameterizing the image as an ellipse, characterized by the first and second moments of image intensity distribution (the so-called Hillas parameters \cite{2}), and the second kind is based on a global fit to pixel amplitudes.

In the analysis, the raw data is first calibrated. In the Hillas-type approach, the pixel noise produced mainly by night sky background photon is reduced by image cleaning before image parameterization. The total image intensity is denoted as size and the center of gravity of pixel intensity distribution (the first moment) is c.o.g. (see Figure\textsuperscript{1}). The second moments of the Hillas ellipse are the length and width. The orientation of major axis with respect to the x-axis of the coordinate system is defined as φ. The event direction can be calculated by Algorithm 1 in \cite{1} using the pair-wise intersections of extended major axes averaged by weighting factors, composed of combinations of Hillas parameters.

The drawback of this method is that the angular resolution degrades rapidly at larger zenith angles where the impact parameters, defined as the perpendicular distance between the shower axis and the telescope, get on average larger. The images of showers at larger distances from the telescopes are more elongated. The axes of different images get more parallel than those of showers at smaller distances. This reflects the smaller difference in the viewing angles of different telescopes. The advantages of stereoscopic observation are thus reduced.

2 Method

Event reconstruction can be improved by introducing additional image parameters. The disp, defined as the angular distance between c.o.g. and event direction, the uncertainties of disp, c.o.g. and $\phi$: $\sigma_{\text{disp}}$, $\sigma_{\text{cog}}$, and $\sigma_{\phi}$. The prototype of this reconstruction method is referred to as Algorithm 3 in \cite{1}, also called the Disp method, and used in IACT experiments such as HEGRA \cite{1} and VERITAS \cite{3} for stereoscopic reconstruction. The image parameters can be calculated by experiential formulae or lookup tables. In this work, multi-dimensional lookup tables filled with Monte-Carlo simulated γ-ray events are used. The lookup

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig_1.png}
\caption{Schematic diagram representing the Hillas parameters and image parameters. The working principle of the Disp method (Algorithm 3) is illustrated. The definition of $\sigma_{\text{disp}}$, $\sigma_{\text{cog}}$, and $\sigma_{\phi}$ are displayed in the gray box.}
\end{figure}
tables are two-dimensional histograms stored as a function of azimuth angle, zenith angle, impact parameter, and optical collection efficiency. The layouts of the lookup tables are presented in Table 1. All parameters except the optical efficiency are pre-determined by using Algorithm 1 before used in Algorithm 3 to look up the values of image parameters. The disp lookup tables have one extra parameter, imp, which is the impact parameter reconstructed by Algorithm 1. Imp is used to reconstruct the new impact position. \( \hat{H}_{\text{max}} \) is the ratio of impact parameter over disp reconstructed by Algorithm 1.

TABLE 1: The layout of the image parameter (output) lookup tables used in the Disp method. Here opt, azm, and zen are the abbreviation of telescope optical efficiency, azimuth and zenith angle of the event. The disp and \( \sigma_{\text{disp}} \) lookup tables have one extra parameter, imp, which is the impact parameter reconstructed by Algorithm 1. Imp is used to reconstruct the new impact position. \( \hat{H}_{\text{max}} \) is the ratio of impact parameter over disp reconstructed by Algorithm 1.

| Output Parameters | X-axis | Y-axis |
|-------------------|--------|--------|
| disp              | opt, azm, zen, imp ln(size/p.e.) length | |
| \( \sigma_{\text{disp}} \) | opt, azm, zen, imp ln(size/p.e.) length | |
| \( \sigma_{\text{cog}} \) | opt, azm, zen ln(size/p.e.) width | |
| \( \sigma_{\varphi} \) | opt, azm, zen ln(size/p.e.) width/length | |
| imp'              | opt, azm, zen disp_{\text{true}} \( \hat{H}_{\text{max}} \) | |
Algorithm 3

The ring background is presented and compared with that of Algorithm 1 and Algorithm 3. In this work, the performance of the direction reconstruction technique, parameters derived from image shapes and reconstructed physical quantities of the shower such as the depth of shower maximum and the sample standard deviation of the energies reconstructed by participating telescopes are used to reject the background-like events.

The statistics of γ-like events are summarized in Table 2. The ring background method is used to derive these quantities following the procedure described in [3]. Due to the stricter γ-hadron separation cut, the significance of Crab nebula is not changed much although the $R_{68}$ is improved by using Algorithm 3. The significance of Mkn 421 is significantly increased due to larger excess of γ-like events from the direction of the target. The squared angular distributions of γ-like excess events are presented in Figures 7 and 8. The distribution of Mkn 421 using Algorithm 3 has a more pronounced peak around the target position and a shorter tail compared with that by Algorithm 1. The distribution of the Crab nebula by the hires cut has a ~17% smaller $R_{68}$ and also a shorter tail compared with that by Algorithm 3 with the 160-p.e size cut. The cut on the direction uncertainty reduces the number of γ-like events by ~50% but rejects even more hadronic events so the detection significance of point-like sources is kept ~80% as good as the configuration without this cut.

4 Conclusions

In this work, the performance of the direction reconstruction technique using the Disp method (Algorithm 3) is presented and compared with that of Algorithm 1. The angular resolution by Algorithm 1 degrades rapidly with the zenith angle and is significantly improved by the Disp method at zenith angles larger than 45°. For events from large zenith angles of between 45° and 60° at 0.5° to 1.5° offsets, the improvement is 20% – 40%. For offsets larger than 2.0°, there is an additional improvement of 5% – 10%. The hires configuration with an extra cut on the direction uncertainty achieves an angular resolution of ~0.05° at the expense of a loss of 50% of effective area.

This reconstruction technique can be applied widely to various kinds of sources taking the advantages of better angular resolution. The hires configuration with a significantly improved angular resolution is especially suitable for studies of sources with complicated morphology but high event statistics.

Acknowledgment: Please see standard acknowledgement in H.E.S.S. papers, not reproduced here due to lack of space.

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1. The analysis cuts presented here are optimized for sources with a spectral index of 2 and 1% Crab flux.
Table 2: Statistics of γ-ray-like events from Mkn 421 and the Crab nebula. The image size cut is 160 p.e.. $N_{\text{On}}$ is the event count within a circular integration region of the radius optimized for point-like source extraction which is $0.07^{\circ}$ for the hires configuration and $0.1^{\circ}$ for other configurations. $N_{\text{Off}}$ $\cdot \alpha$ is the normalized background count. The excess is given as $N_{\text{On}} - \alpha N_{\text{Off}}$ and the significance (Sig.) is calculated following the formula 17 in [7].

| Target     | Config. | $N_{\text{On}}$ | $N_{\text{Off}}$ $\cdot \alpha$ | Excess | Sig.$[\sigma]$ | $R_{68}[\text{deg}]$ |
|------------|---------|-----------------|-------------------------------|--------|----------------|---------------------|
| Mkn 421    | Alg. 1  | 884             | 50                            | 834    | 54             | 0.151               |
| Mkn 421    | Alg. 3  | 914             | 23                            | 891    | 63             | 0.092               |
| Mkn 421    | hires   | 506             | 4                             | 502    | 57             | 0.085               |
| Crab       | Alg. 1  | 1175            | 32                            | 1143   | 70             | 0.094               |
| Crab       | Alg. 3  | 1056            | 21                            | 1035   | 69             | 0.080               |
| Crab       | hires   | 548             | 4                             | 544    | 58             | 0.070               |

Fig. 5: Relative difference in effective area as a function of energy at 20° and 45° zenith angles. $A'_{\text{eff}}$: Effective area obtained by using Algorithm 3. $A_{\text{eff}}$: By using Algorithm 1. Dashed lines denote the safe energy threshold above which the energy bias is smaller than 10%.

Fig. 6: Relative difference in effective area as a function of energy at 50° and 60° zenith angles.

Fig. 7: Squared angular ($\theta^2$) distribution of the excess events for Mkn 421. $R_{68}$ is denoted by the dashed line. The angular distance is calculated with respect to the position of Mkn 421.

Fig. 8: Squared angular ($\theta^2$) distribution of the excess events for the Crab nebula. $R_{68}$ is denoted by the dashed line. The angular distance is calculated with respect to the position of the Crab pulsar.