

The Shadow of the Moon in IceCube

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IceCube is the world’s largest neutrino telescope, recently completed at the South Pole. As a proof of pointing accuracy, we look for the image of the Moon as a deficit in down-going cosmic ray muons, using techniques similar to those used in IceCube’s astronomical point-source searches.

1 Introduction

One of the main goals of the the IceCube detector at the South Pole is to look for astrophysical point sources of neutrinos: essentially, to use IceCube as a telescope using neutrinos instead of light. Other telescopes can calibrate their signals with known standard candles (the Crab nebula is a traditional standard candle in gamma ray astronomy, for example). In the absence of known neutrino source, IceCube can use the deficit of cosmic ray muons from the direction of the Moon for calibration. This “Moon Shadow” is valuable because of its well-known position. While a muon calibration is not as directly applicable to neutrino astronomy as a Crab gamma calibration would be to gamma astronomy, it does provide valuable information about the pointing accuracy and resolution of the detector.

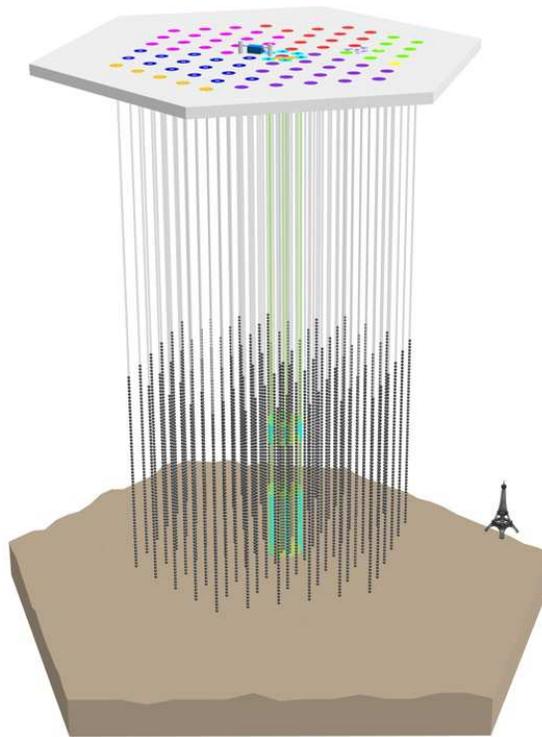


Figure 1: A schematic view of the IceCube detector, with the Eiffel Tower also shown for scale. The colors of the dots where each string connects to the surface of the glacier represent the year in which that string was deployed.

The IceCube detector was built modularly, with strings deployed during each austral summer. This creates an annual discreteness in the data based on the size of the detector. A Moon shadow analysis was developed for several of the detector setups; this work focuses on a 40-string setup analysis¹ from when the detector was about half complete,

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1 and the 59-string setup analysis^{2,3}, from when
 2 it was about three-quarters complete.

3 **2 Data Sample**

4 Because of bandwidth restrictions on the satellite transporting data from the South Pole to the
 5 North for analysis, a subset of available IceCube data is used. For these analyses, the data were
 6 collected in the following way: tracks were reconstructed quickly, and their direction of origin
 7 was compared to the current position of the Moon. If an event came from a position within 40°
 8 in azimuth or 10° in zenith, it was sent north. These data were collected only when the Moon
 9 was 15° or more above the horizon at the South Pole, which neatly splits the data into lunar
 10 months. This sample was used for both a Moon measurement and an off-source background
 11 estimate.

12 The estimated angular resolution of the reconstructions used here is of order 1°, similar to
 13 the 0.5°-diameter Moon, so for this analysis the Moon was considered point-like.

14 **3 Binned 40-string analysis**

15 One analysis of the Moon Shadow was performed on the data set from the 40-string detector
 16 setup, out of 86 strings total. This dataset contained 13 lunar months. The data sample was
 17 cut to optimize the expected signal (balancing passing rate with the expected improvement to
 18 the point spread function). Using simulation, the search bin size was optimized, and a band 1.2°
 19 tall at constant zenith with respect to the Moon was used. Figure 2 shows the number of events
 20 in this zenith band, using the same optimized bin size of 1.2° in azimuth as in zenith. Taking
 21 the mean of all the bins excluding the central 4 as a comparison, and using simple statistical
 22 \sqrt{N} errors, we see a deficit of 7.58 σ in the central bin at the position of the Moon.

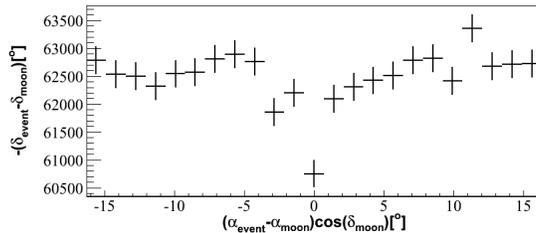


Figure 2: Events in a 1.25° zenith band around the Moon, using the 40-string detector setup. A deficit from the direction of the Moon can be clearly seen at 0.

23 **4 Likelihood 59-string analysis**

24 A subsequent analysis² used data from the 59-string setup of the detector. The approach
 25 for this analysis was similar to the likelihood approach taken for the IceCube point source
 26 searches: an expected signal shape and background shape were developed, and then a likelihood
 27 was maximized at every point in the sky, allowing the number of signal events to vary. The
 28 likelihood formula used is:

$$L(\vec{x}_s, n_s) = \sum_i^N \log \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

29 where \vec{x}_s is the position being considered, n_s is the number of signal events, N is the total
 30 number of events, S_i is the expected signal shape, and B_i is the expected background shape.

Note that this has no explicit energy term; this a major difference between the IceCube Moon analysis and the IceCube point source searches. For the Moon shadow, we expect the number of signal events to be negative, as the Moon produces a deficit.

Each event’s contribution to the signal shape was assumed to be gaussian, with a width given by the estimated error on the reconstructed position.

The background shape was estimated using two off-source regions: to the right and left of the moon in azimuth, at the same zenith. For each region, the event rate was assumed constant in azimuth, and an 80 bin histogram (with interpolation between bins) was used to describe the zenith distribution. One can test the quality of this fit by assuming it as the background truth, and examining the size of fluctuations in the background region (calling the background region data “signal” for the purposes of this test). For a perfect fit, this should result in only random fluctuations around zero. The result is shown in Figure 3 on the left. There are still fluctuations of the background around this fit (which show up in the figure as the color axis). To test that these fluctuations are random, the value of each bin from the left plot is plotted in a histogram in the right plot of Figure 3. The distribution of these values is consistent with a gaussian fit centered at 0. The rms width of this distribution is about 680 signal events, which we take as the definition of 1σ . A similar analysis was performed on the other background sample, and as the two rms values were slightly different, the significance reported here should be taken only approximately.

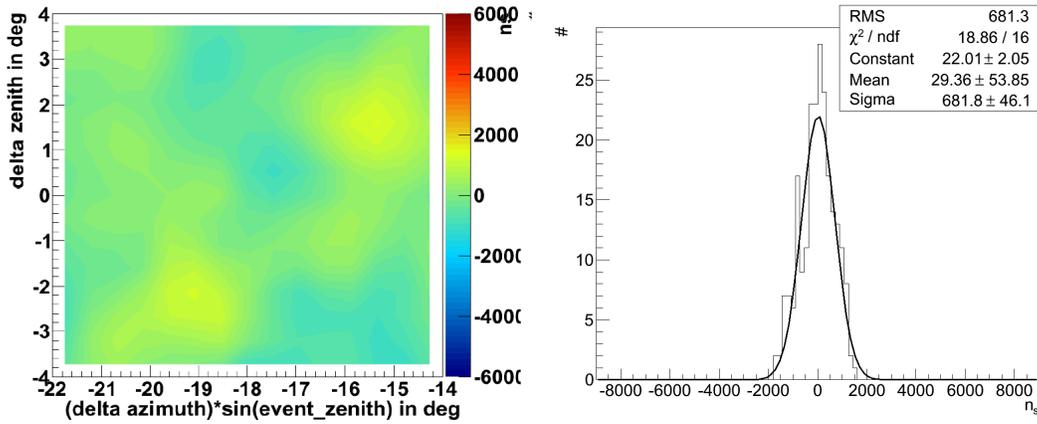


Figure 3: Left: fluctuations around the background model of an off-source region, defined in relation to the position of the Moon. The color axis is the best-fit number of total signal events given the response at that point. Right: the distribution of bins from the left plot, which can be fit to a gaussian curve, confirming that the background is fluctuating randomly around 0. From [2].

This procedure is then applied to the signal region around the known Moon position: the polynomial model in zenith and azimuth as a background description, and the sum of the observed data as the signal. The resulting plot is shown as Figure 4. Each point represents the number of events shadowed if the Moon were at that point; the maximum of these is at the expected position of the Moon, with 8200 events shadowed.

The expected number of shadowed events, based on the background rate and the size of the Moon, was 8192 ± 91 . The observation of a 8660 event deficit at the central grid position is within one “RMS value of the two background distributions. The observed deficit is an 13 σ underfluctuation compared to the off source regions.

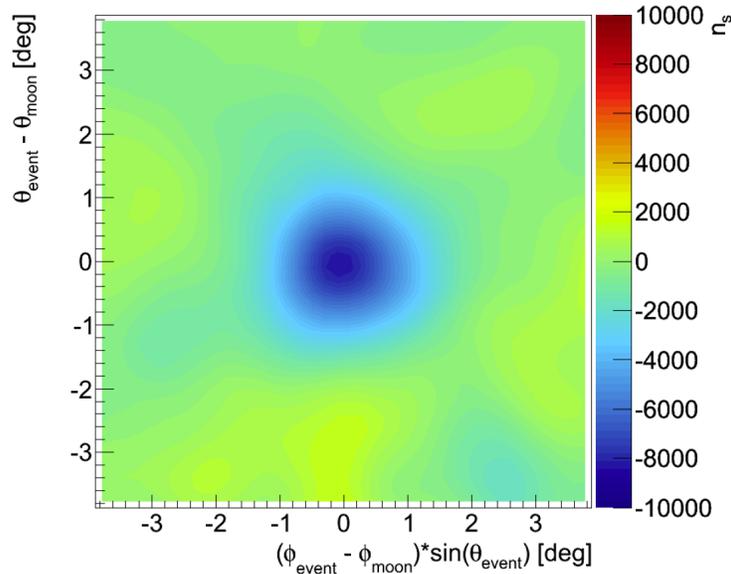


Figure 4: The Moon Shadow from the 59-string detector setup, using a likelihood analysis approach. The position is given relative to the Moon position, and the color represents the number of total shadowed events for each point, assuming the Moon is at that point. From [2].

1 5 Conclusions

2 In each of two years of data during the construction of the IceCube detector, a shadowing effect
 3 was observed in cosmic rays from the direction of the Moon. In the 40-string setup, this deficit
 4 was observed with 7.6σ using a binned analysis. In the 59-string setup, this deficit was observed
 5 with 12σ using a likelihood analysis. This confirms the pointing resolution of IceCube to within
 6 order 1° . Further studies of this shadowing effect are forthcoming.

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 10 Office of Scientific Research, National Defense Science and Engineering Graduate (NDSEG)
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