Alternative Methods to Finding Patterns in HiRes Stereo Data.

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Abstract

We applied a Hough Transform to look for arcs of events in the sky. Such an arc structure is expected when the charged cosmic rays pass through the galactic magnetic field. The arcs searched for could represent a broad or a small scale anisotropy depending on the proposed source model for the ultra-high energy cosmic rays. No statistically significant arcs were found in this study.

Key words:
Anisotropy, Hough Transform, Ultra high-energy cosmic rays.

1 Introduction

The Hough transform is a class of duality transformations commonly used to identify structures in graphical images [1]. The goal of this study is to use a Hough transform to look for arc structures in the HiRes stereo data set. Here we use the term "arc" to describe segments of great circles across the dome of the sky.

When cosmic rays pass through the galactic magnetic field they are deflected. The amount of deflection depends upon their energy. This deflection can produce either large scale or small scale anisotropy in the cosmic ray arrival direction. Such scale would depend on the source model producing the ultra-high energy cosmic ray. The pointing directions of the deflected cosmic rays may form an arc in the sky as illustrated in Figure 1 [2]. These are the structures we would like to identify.

The Hough Transform is a duality transformation. In our case, it is applied on a sphere, where the pointing direction of each event is mapped to a great circle that is perpendicular to it. For events that lie on an arc, their associated great circles would intersect at two points, as illustrated in Figure 2. We then divide the sky into equal sized and shaped bins. A coarsely binned example (for illustration purposes) is shown in Figure 3. The data analysis consists of looping over all events. For each event, we increment those bins through which the corresponding great circles passes. The bin values therefore represent the total number of great circles that lie within its boundaries. The arcs are then identified by significant excess in a particular bin.

Consider, for example, an arc containing five points. Each point is transformed

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into its perpendicular great circle as shown in Figure 2. The sky is then binned into 6°, equal area bins (a total of 4584 bins). This bin size was not optimized. It was arbitrarily chosen. The main idea is that the bin size is not so small that we would loose signal or so big that we would over estimate one. Each bin is then arbitrarily numbered in latitude from north pole to south and around the axis. Finally, the bins values are plotted and an excess is found in the two bins were the great circles meet.

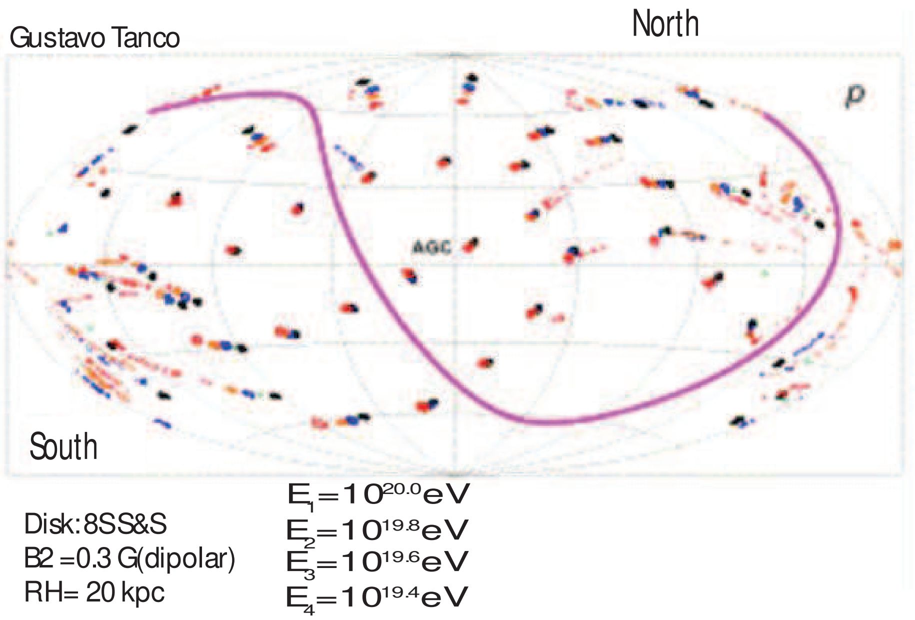

Fig. 1. Simulated polarization plot by Gustavo Medina-Tanco [2]. It shows cosmic rays with energies between $10^{19.4}$ and 10^{20} eV. The events are deflected while passing through the galactic magnetic field forming arcs shapes. While the events originate at point sources, the magnetic field deflects the events to form the arc shapes which one sees in the plot.

2 Applying The Hough Transform.

We apply the Hough transform method to the stereo HiRes data to search for arcs of events in the data. The HiRes stereo data has excellent angular resolution of $\sim 6°$. The data selected are those events with energies $> 10^{19}$eV (particles with energies $< 10^{19}$ eV are deflected by larger angles). This data set

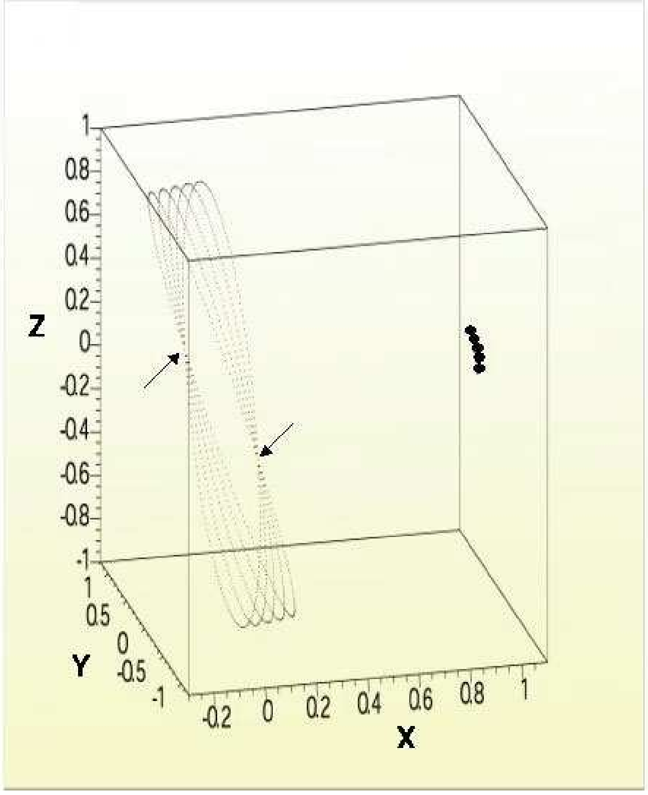

Fig. 2. When there are points in an arc, the great circles perpendicular to them will all meet in the same place. The positions at where they meet is pointed indicated by the arrows in this example.

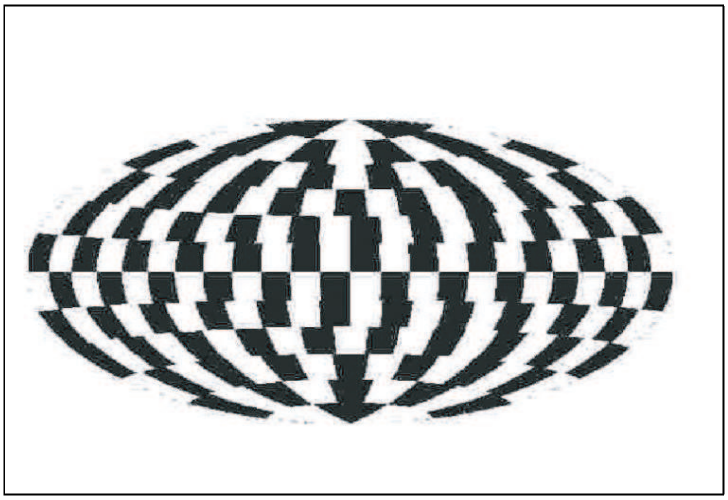

Fig. 3. An illustration of the sky divided into equal-sized and equal-shaped bins. This illustration is coarsely binned to demonstrate the technique. In practice, during this analysis, the sky gets binned much more finely.

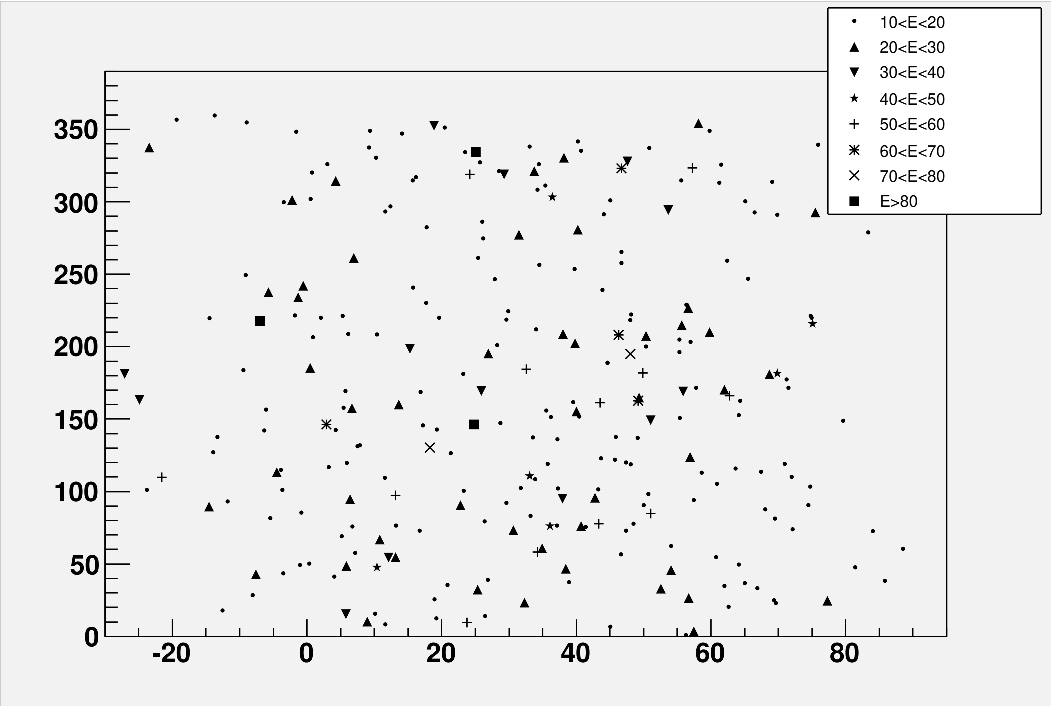

Fig. 4. The pointing direction, right ascension vs. declination in degrees, of the 271 events used in this analysis. The box on the top right of the figure shows the color key for the energies (in EeV) of the events.

contains 271 events collected between December 1999 and 31 January 2004. More details about this data set are given in [3].

Figure 4 shows the particle's arrival direction (in equatorial coordinates) for the 271 events used in this analysis. The same data is also shown in Hammer-Aitoff projection in Figure 5. After applying the Hough Transform to the data set, the bin occupancy for the great circles is calculated. The resulting histogram is shown in Figure 6.

3 Search for significant excess.

In order to identify arcs, we look for apparent excess over what is expected from an isotropic background. To estimate the significance of such excess in each bin, we compared the data distribution to that of 2×10^4 isotropic simulated data sets. Each simulated data set contained 271 events distributed according to the actual HiRes stereo exposure (taking into account missing mirrors, etc) and assuming an isotropic initial distribution.

From the Monte Carlo data sets, we calculate the probability for each bin to have a simulated occupancy greater than or equal to that found in the data.

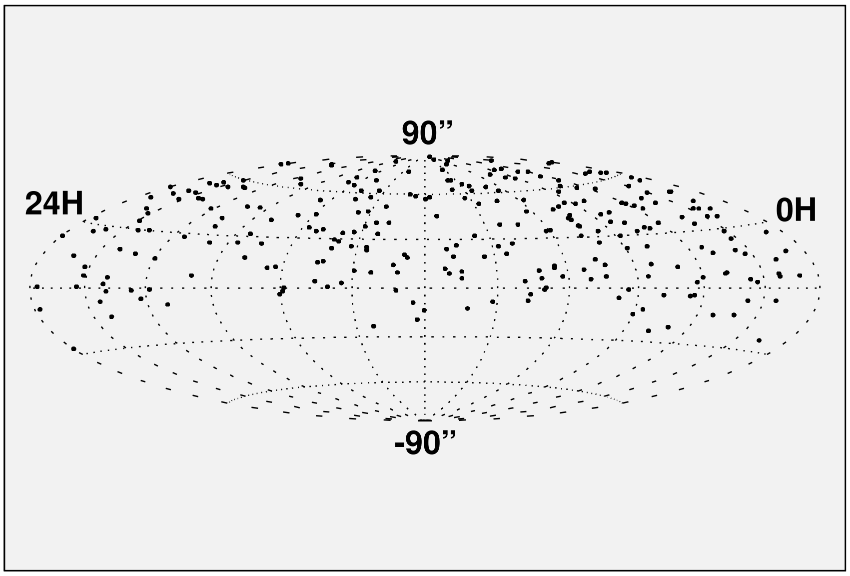

Fig. 5. The 271 event stereo data set in Hammer-Aitoff projection.

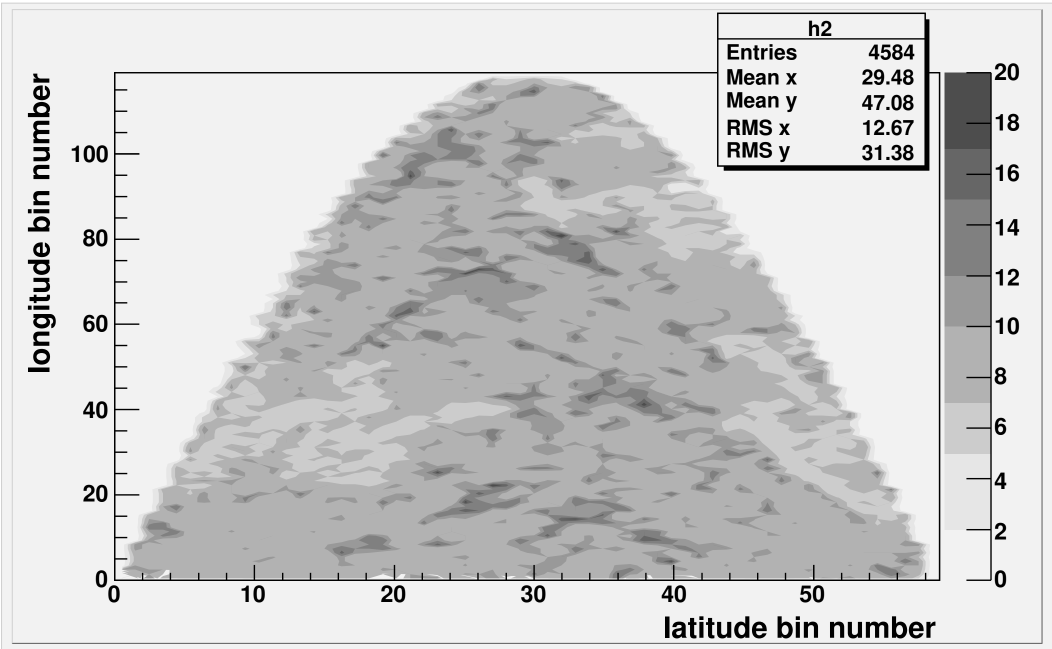

Fig. 6. The bin occupancy values of normal great circles to the stereo data set . The sky was divided into 4584 number of bins of equal size (6°) with the north pole at the zenith. The bins are arbitrarily numbered in latitude from north pole to south and around the axis.

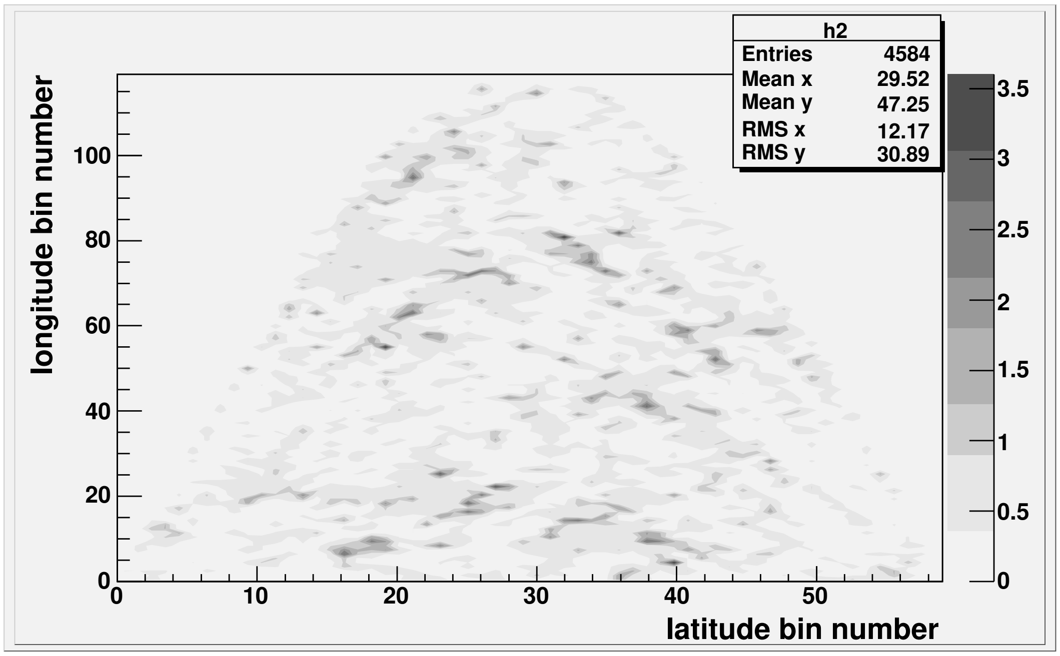

Fig. 7. Significance values for each bin

We define the significance, S, for a bin to be given by $S = log(\frac{1}{P})$ and $P = \frac{M}{N}$, where N is the total number of simulated data sets, and M is the number of MC sets which recorded an occupancy greater or equal to that seen in the data bin.

The resulting significance values are shown in Figure 7, where each bin is indexed by both a longitudinal (RA) and a latitudinal (DEC) bin number. Bins with S > 2.5 designated as "high significance". This cut was chosen *a priori*.

For the seven high-significance bins we show the occupancy histogram for the 2×10^4 isotropic MC set, Figure 8 shows the histograms of the logarithm of the occupancy level vs. the number of events in the arc. A vertical line is drawn on each plot at the bin occupancy level found in the data. The probability of randomly finding at least this occupancy level in an isotropic data set is then the ratio of the area under curve to the right of the line to the whole area (2×10^4). The significance value is than calculated and recorded in the boxed number for each bin.

4 Global Significance of data excess

The next study we made was to determine whether the arcs found in the data in consistent with random fluctuations over the full sky, not just in the location in which they occurred. To do this, we compare our 2×10^4 isotropic

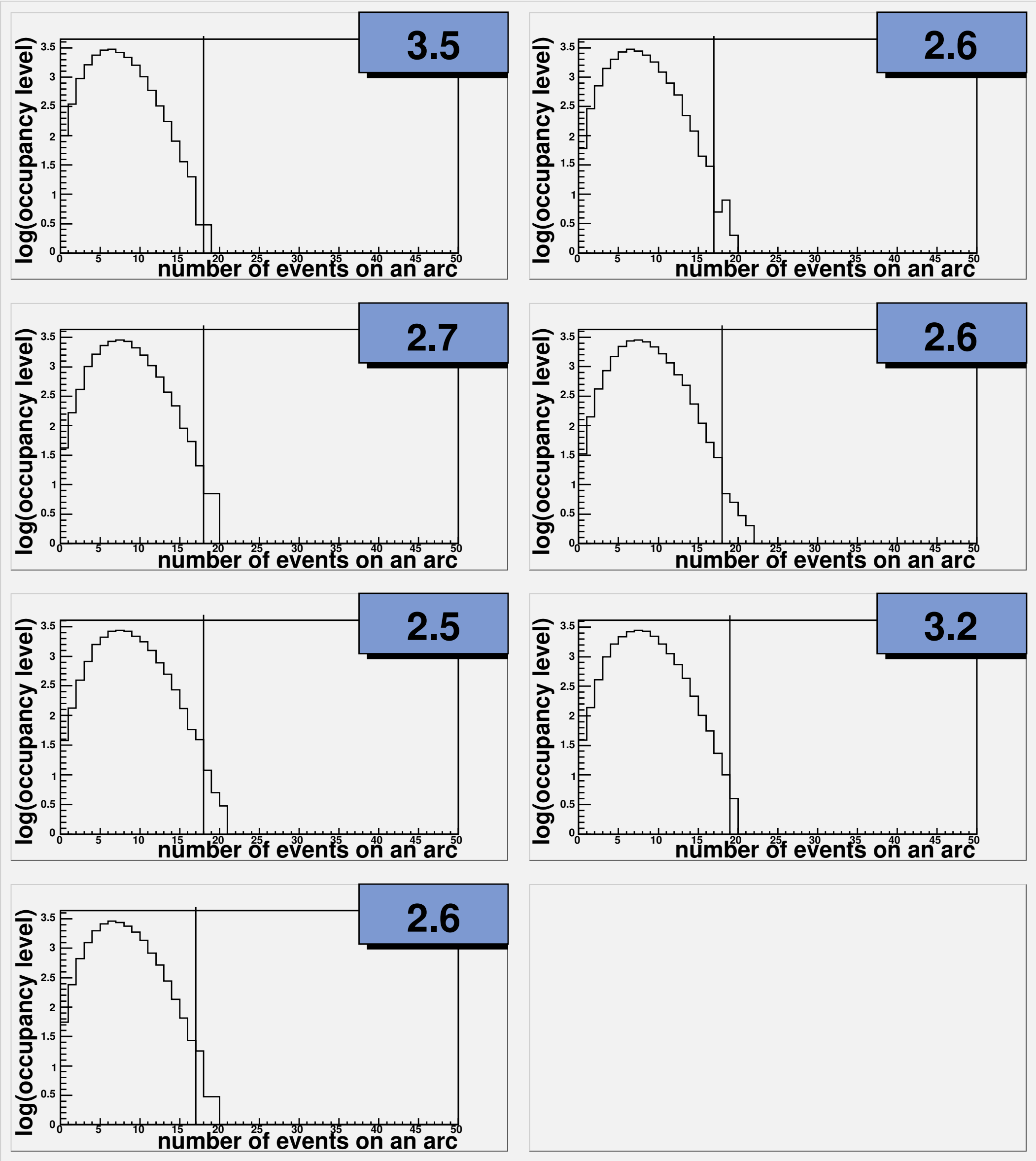

Fig. 8. For the 2×10^4 isotropic MC sets, we histogramed the occupancy level for the bins which showed "high significance" in the data. The histograms above show the logarithm of the occupancy level vs. the number of events in the arc. A vertical line is drawn on each plot at the number of events in the arcs found in the data. The probability of randomly finding at least this many events in an isotropic data set is then the ratio of the area of the curve to the right of the line to the whole area (2×10^4). The significance value is than calculated and recorded in the boxed number for each bin.

simulated sets to a new set of 1000 isotropically simulated data sets, each with 271 events. We applied the same analysis and cuts as we did to the real stereo data set. Including the "significance cut" of S> 2.5. We found that 99.6% of the time, the maximum significance of the isotropically generated data sets is greater than 2.5. Also, in 41.2% of the samples, the simulated data sets recorded a significance ≥ 3.5, which is the highest significance found in the real data set.

Finally, the greatest number of events found on an arc in the real data is 19, as shown in Figure 8. This was also found to be quite common in the simulation, since arcs with S> 2.5 and at least 19 events were found in 90.4% of the simulated isotropic sets.

5 Conclusion

The Hough transform has been applied to the HiRes stereo data and seven arcs were found. However, when a global significance analysis was performed, similar results were commonly reproduced within isotropic data sets of equivalent size. Hence, the observation of seven arcs in the data is not significant.

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References

[1] V.F.Leavers, Shape Detection in Computer Vision Using the Hough Transform, London, New York:Springer-Verlag, 1992.

[2] G.M. Tanco, M. Teshima & M.Takeda, Constrains on the Galactic magnetic field from the two dimensional correlation function of AGASA events, 28th International Cosmic Ray Conference, Tsukuva, pp. 747-750, Universal Academy Press, Inc. 2003.

[3] R.U. Abbasi *et. al.*, Astrophys. J.610, L**73**, 2004.