# Large-scale anisotropies of the All Triggers Dataset

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**Abstract**

We analyse the large angular scale distribution of the All Triggers dataset, including ToTd and MoPS triggers. We study the first harmonic in right ascension of events with energy between 0.25 EeV and 2 EeV, separated in three energy bins.

There are mainly two techniques that are used to study the large-scale anisotropies in right ascension of the distribution of the arrival directions of cosmic rays (CR) measured by the Pierre Auger Observatory: the Rayleigh and the East-West methods. These methods are based on studying modulations of the cosmic rays flux $I(\alpha)$ using harmonic functions, where $\alpha$ stands for the right ascension.

For a given energy range, the Rayleigh method consists in performing a Fourier analysis of the distribution in right ascension of the events to estimate the amplitude and phase of an anisotropy, as well as the probability of measuring a larger or equal amplitude as a fluctuation from an isotropic distribution of cosmic rays. The analysis can be performed at different frequencies, like sidereal, solar and anti-sidereal. Possible systematic effects, like a dependence of the energy reconstruction on atmospheric variations associated to the weather condition and changes in the number of active detectors cells are expected to have mainly daily and yearly modulations. The spurious effects are then expected to appear mostly in the solar frequency and in the sidereal and anti-sidereal ones through the combination of daily and yearly effects. The resolution in frequency of this analysis is of $1/n$ cycles per year where $n$ is the period of the time in years to be analyzed [1]. To use the Rayleigh method instrumental effects must be kept well under control because these effects induce spurious amplitudes in the analysis.

On the other hand, the East-West method consists in the harmonic analysis of the difference of the rates of events measured by the Observatory arriving from the East and West directions recorded as a function of the sidereal time angle $\alpha^0$, i.e. the zenith's right ascension at the time when the event is recorded. The instrumental effects are removed from the analysis without any further corrections because they are similar for events arriving from East and the West. But a downside of this method is that it has a lower sensitivity than the Rayleigh analysis [2].

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# 1 Rayleigh method

The Rayleigh method estimates the first harmonic of the modulation of the CR flux $I(\alpha)$ in the following way:

1. Given $N$ events to study, first we obtain the parameters $a$ and $b$:

$$a = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos\alpha_i \qquad b = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin\alpha_i \tag{1}$$

   where $\alpha_i$ is the right ascension of the $i$-th event and $w_i$ is the weight, that is equal to the inverse of the total relative exposure towards the direction of the zenith of the Observatory at the arrival time of the event. The sum of all these weights is $\mathcal{N} = \sum_i^N w_i$.

2. Then we compute the amplitude, uncertainty and phase of the first harmonic $r$, $\sigma$ and $\phi$,

$$r = \sqrt{a^2 + b^2}, \qquad \sigma = \sqrt{\frac{2}{\mathcal{N}}}, \qquad \phi = \arctan\frac{b}{a}. \tag{2}$$

   The probability of obtaining an amplitude equal or larger than $r$ from an isotropic distribution is given by:

$$P(r) = \exp\left(-\mathcal{N}\frac{r^2}{4}\right) \tag{3}$$

   At the 99 % confidence level, amplitudes are smaller than

$$r_{99} = \sqrt{-\log(0.01)\frac{4}{\mathcal{N}}} \tag{4}$$

   for an isotropic distribution.

3. To generalize this analysis to any frequency, instead of using the right ascension $\alpha$, we use the variable: $\tilde{\alpha} = 2\pi f_x t_i + \alpha_i - \alpha_i^0(t_i)$, where $f_x$ stands for the frequency of interest, $t_i$ is the time in which the event was measured, $\alpha_i$ is the right ascension of the event, and $\alpha_i^0(t_i)$ is the right ascension of the Observatory's zenith at time $t_i$.

# 2 East - West method

The East-West method estimates a derivative of the modulation of the CR flux $I(\alpha^0)$ through the difference $I_E^{obs} - I_O^{obs}$ in the following way:

1. Given $N$ events to study, first we obtain the parameters $a_{EW}$ and $b_{EW}$:

$$a_{EW} = \frac{2}{N} \sum_{i=1}^{N} \cos(\alpha_i^0 - \beta_i) \qquad b_{EW} = \frac{2}{N} \sum_{i=1}^{N} \sin(\alpha_i^0 - \beta_i) \tag{5}$$

   where $\alpha_i^0$ is the Observatory's zenith right ascension at the moment of measurement of the $i$-th event and $\beta_i = \pi$ if the event came from the East, $\beta = 0$ otherwise.

2. Then we compute the amplitude and phase of the first EW harmonic $r_{EW}$ and $\phi_{EW}$:

$$r_{EW} = \sqrt{a_{EW}^2 + b_{EW}^2} \qquad \phi_{EW} = \arctan \frac{b_{EW}}{a_{EW}} \tag{6}$$

where the amplitude $r_{EW}$ and phase $\phi_{EW}$ are related to $r$, $\sigma$ and $\phi$ as follows:

$$r = \frac{\pi}{2}\frac{\langle\cos\delta\rangle}{\langle\sin\theta\rangle} r_{EW}, \qquad \sigma = \frac{\pi\langle\cos\delta\rangle}{2\langle\sin\theta\rangle}\sqrt{\frac{2}{N}}, \qquad \phi = \phi_{EW} + \frac{\pi}{2}. \tag{7}$$

The values $\langle\cos\delta\rangle$ and $\langle\sin\theta\rangle$ are the mean values over all the events $i$, with $\delta$ being the declination and $\theta$ the zenith angle. We can calculate $P(r)$ and $r_{99}$ as

$$P(r_{EW}) = \exp\left(-\frac{N}{4} r_{EW}^2\right), \qquad r_{99} = \frac{\pi}{2}\frac{\langle\cos\delta\rangle}{\langle\sin\theta\rangle}\sqrt{-\log(0.01)\frac{4}{N}}. \tag{8}$$

3. To generalize this analysis to any frequency, instead of using the variable $\alpha^0$ we use the variable: $\tilde{\alpha} = 2\pi f_x t_i$, where $f_x$ stands for the frequency of interest, and $t_i$ is the time in which the event was measured. This allows us to study the amplitude of the modulation at any other frequency.

The first harmonic modulation in right ascension $r$ is related to the equatorial component of the dipole $d_\perp$ through:

$$d_\perp \simeq \frac{r}{\langle\cos\delta\rangle} \tag{9}$$

where $\langle\cos\delta\rangle$ is the mean value of all studied events in an energy bin. The uncertainty associated to its components, $\sigma_{x,y}$, are

$$\sigma_{x,y} = \frac{\pi}{2\langle\sin\theta\rangle}\sqrt{\frac{2}{N}} \tag{10}$$

In this note, we present the novel results of the analysis applied to the All Triggers dataset from Herald: these triggers include the standard ToT & TH and the newer ToTd & MoPS triggers. The results are obtained using the East-West method for three different energy ranges between 0.25 and 2 EeV and are compared with the last published results obtained with the ToT & TH Triggers dataset [3]. Using all triggers the detector has full efficiency for energies above ~1 EeV, thus we also applied the Rayleigh analysis in this energy range.

## 3 Datasets characteristics

We analyse 6T5 events detected with the ToT & TH triggers from 1/1/2004 to 1/8/2018 (the same dataset used in [3]) and with All Triggers from 1/1/2014 to 1/1/2020 reconstructed with Herald. The characteristics of both datasets are presented in Table 1.

| | | | |
|---|---|---|---|
| Time span | All Triggers 6 years | From | January $1^{st}$, 2014 |
| | | To | January $1^{st}$, 2020 |
| | ToT & TH 14.7 years | From | January $1^{st}$, 2004 |
| | | To | August $1^{st}$, 2018 |

| Energy range [EeV] | | 0.25 - 0.5 | 0.5 - 1 | 1 - 2 |
|---|---|---|---|---|
| Events | All Triggers | 3 967 368 | 3 638 226 | 1 081 846 |
| | ToT & TH | 770 316 | 2 388 467 | 1 243 103 |
| Mean Energy | All Triggers | 0.38 | 0.69 | 1.32 |
| | ToT & TH | 0.43 | 0.70 | 1.28 |

Table 1: Datasets characteristics for several energy ranges.

# 4 Results

## 4.1 Results for the 0.25 EeV - 0.5 EeV energy range

We report in Table 2 the results obtained using the East - West method for the solar and sidereal frequency for the All Triggers dataset. The results for the ToT & TH triggers reported in [3] are also shown. They are compatible within systematic uncertainties The uncertainty $\sigma_{x,y}$ for the All Triggers dataset is smaller than that in [3] since this dataset is $\sim 5$ times larger than the ToT & TH triggers dataset. Both results are also compatible with isotropy. The upper limit at 99 % CL of the equatorial dipole component for the All Triggers dataset, $d_{\perp}^{UL} = 0.008$, is a factor of two smaller than the published one in [3], $d_{\perp}^{UL} = 0.018$.

| | All Triggers | | ToT & TH Triggers |
|---|---|---|---|
| Frequency: | Solar | Sidereal | Sidereal [3] |
| Amplitude $r$ [%]: | $0.17^{+0.22}_{-0.07}$ | $0.12^{+0.24}_{-0.03}$ | $0.5^{+0.4}_{-0.2}$ [5] |
| $r_{99}$ [%]: | 0.58 | | 1.1[5] |
| $r^{UL}$ [%]: | 0.67 | 0.64 | 1.4[5] |
| $\sigma$[%]: | 0.19 | | 0.38[5] |
| Amplitude $d_{\perp}$[%]: | - | $0.16^{+0.31}_{-0.04}$ | $0.6^{+0.5}_{-0.3}$ |
| $d_{99}$ [%]: | - | 0.73 | 1.5 [5] |
| $d_{\perp}^{UL}$[%] | - | 0.80 | 1.8 |
| $\sigma_{x,y}$[%]: | - | 0.24 | 0.48 |
| Probability : | 0.66 | 0.81 | 0.45 |
| Phase [$^o$]: | 221±77 | 280±90 | 225±64 |
| $\langle\cos\delta\rangle$ | 0.79 | | 0.79 [5] |
| $\langle\sin\theta\rangle$ | 0.46 | | 0.52 [5] |

Table 2: Results for the All Triggers and ToT & TH Triggers datasets using the East-West method for the first harmonic in the 0.25 EeV - 0.5 EeV energy bin. The ToT & TH Triggers results were obtained using the code written for the paper Aab et al. 2020 [3].

Figure 1 shows the phase for the All Triggers dataset and that reported in [3] for the ToT & TH Triggers dataset. The dashed line indicates the direction of the galactic center, and the solid areas indicate the 68 % CL uncertainties of the phase using its probability density function [4]. The previous table and this figure indicate that the uncertainty for the All Triggers dataset is wide in this energy bin, due to the small $r$ amplitude compared to $\sigma$.

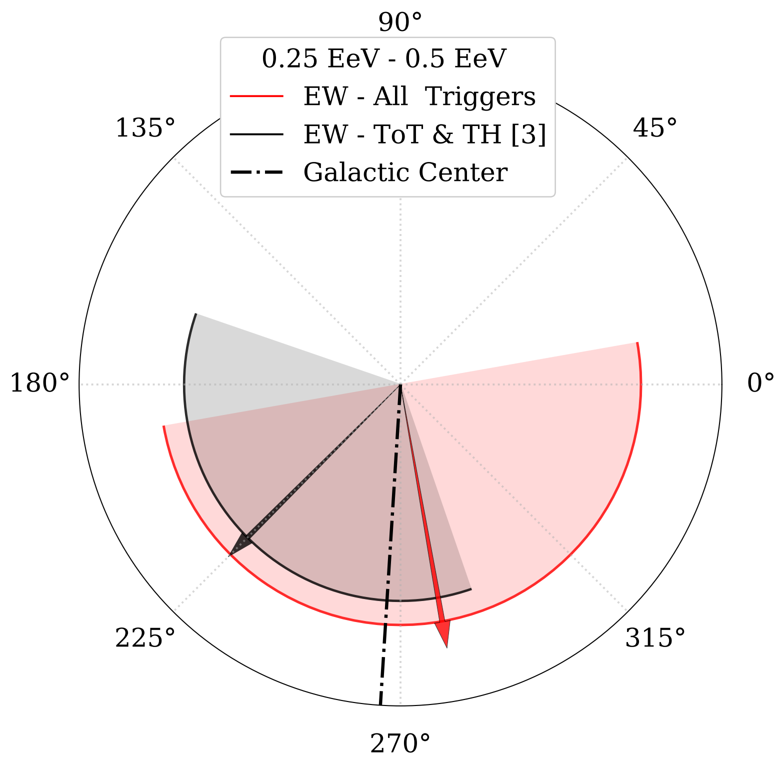


Figure 1: Phases of the first harmonic for the sidereal frequency in the 0.25 EeV - 0.5 EeV bin, as they were obtained here for the All Triggers dataset, and reported by Aab A. et al. (2020) [3] for the ToT & TH Triggers, with their respective uncertainties.

Using the generalized variable $\tilde{\alpha}$, we extended the analysis to an arbitrary frequency. Figure 2 shows the resulting amplitude $r$ as a function of the frequency. The dotted vertical lines represent, from left to right, the anti-sidereal (364.25 cycles/year), solar (365.25 cycles/year), and sidereal (366.25 cycles/year) frequencies. It is common to use these as references for this kind of analysis: instrumental and weather spurious effects are present mainly at the solar frequency and at the anti-sidereal and sidereal frequencies through the combination of daily and yearly effects. Both the solar and anti-sidereal amplitudes are below the horizontal line, corresponding to the 99 % CL for isotropy, as it is expected since spurious effects are cancelled in the East - West method. Meanwhile, the amplitude calculated in the sidereal frequency corresponds to the first harmonic in right ascension.

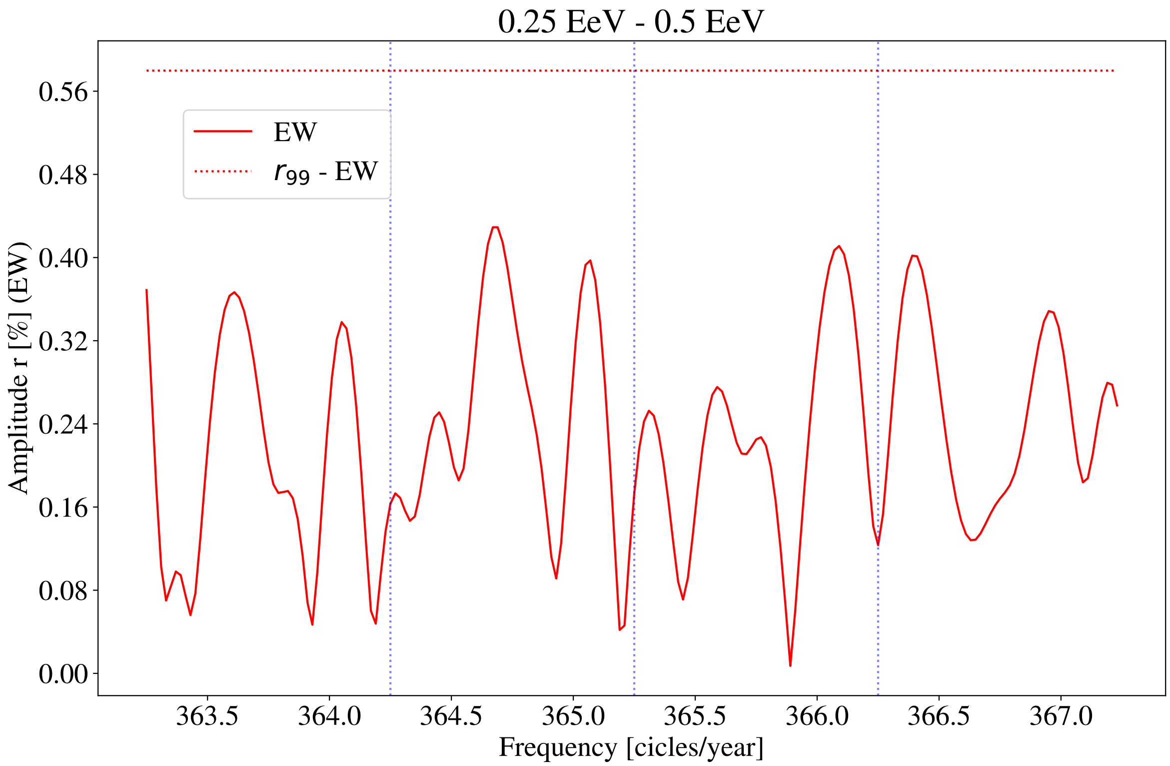


Figure 2: Fourier analysis of the modified variable $\tilde{\alpha}$ for events in the 0.25 EeV - 0.5 EeV bin from 2014 to 2020, using the East-West method for the All Triggers dataset. The dotted vertical lines represent, from left to right, the anti-sidereal, solar, and sidereal frequencies, whereas the horizontal line represents the limit of the 99% chance probability for an amplitude produced by an isotropic flux of cosmic rays.

### 4.2 Results in the 0.5 EeV - 1 EeV energy range

We report in Table 3 the results for the All Triggers dataset for the solar and sidereal frequencies. The results for the ToT & TH triggers reported in [3] are also shown. They are compatible within the systematic uncertainties.

In Figure 3, we compare the phases obtained in this note and in [3]. Their direction and uncertainty are similar. They are both close to the galactic center direction, indicated with a dashed line in the figure.

The Fourier analysis with the generalized variable $\tilde{\alpha}$ for this energy range is shown in Figure 4. The dotted horizontal line represents the $r_{99}$, none of the frequencies in the range showed in the figure exceeds the 99% CL for isotropy. Also, this indicates that there are no spurious amplitudes in the anti-sidereal and solar frequencies.

| | All Triggers | | ToT & TH Triggers |
|---|---|---|---|
| Frequency: | Solar | Sidereal | Sidereal [3] |
| Amplitude r [%]: | $0.43^{+0.21}_{-0.14}$ | $0.44^{+0.21}_{-0.14}$ | $0.38^{+0.20}_{-0.14}$ [5] |
| $r_{99}$ [%]: | 0.56 | | 0.64[5] |
| $r^{UL}$ [%]: | 0.89 | 0.90 | 0.90 [5] |
| $\sigma$[%]: | 0.18 | | 0.21 [5] |
| Amplitude $d_\perp$[%]: | - | $0.56^{+0.27}_{-0.18}$ | $0.5^{+0.3}_{-0.2}$ |
| $d_{99}$ [%]: | - | 0.71 | 0.8 [5] |
| $d_\perp^{UL}$[%] | - | 1.1 | 1.1 |
| $\sigma_{x,y}$[%]: | - | 0.23 | 0.27 |
| Probability : | 0.065 | 0.055 | 0.20 |
| Phase [$^o$]: | 205±34 | 258±34 | 261±43 |
| $\langle\cos\delta\rangle$ | 0.79 | | 0.79 [5] |
| $\langle\sin\theta\rangle$ | 0.50 | | 0.54[5] |

Table 3: Results for the All Triggers and ToT & TH Triggers datasets using the East-West method for the first harmonic in the 0.5 EeV - 1 EeV energy bin.

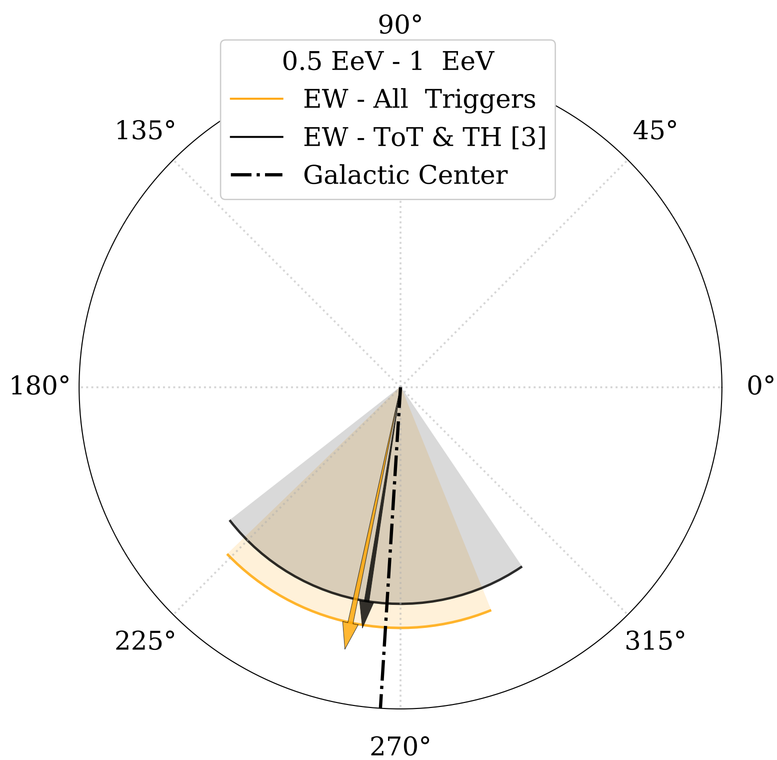


Figure 3: First harmonic phases for the sidereal frequency in the 0.5 EeV - 1 EeV energy bin, as they were obtained here for the All Triggers dataset, and reported by Aab A. et al. (2020) [3] for the ToT & TH Triggers, with their respective uncertainties.

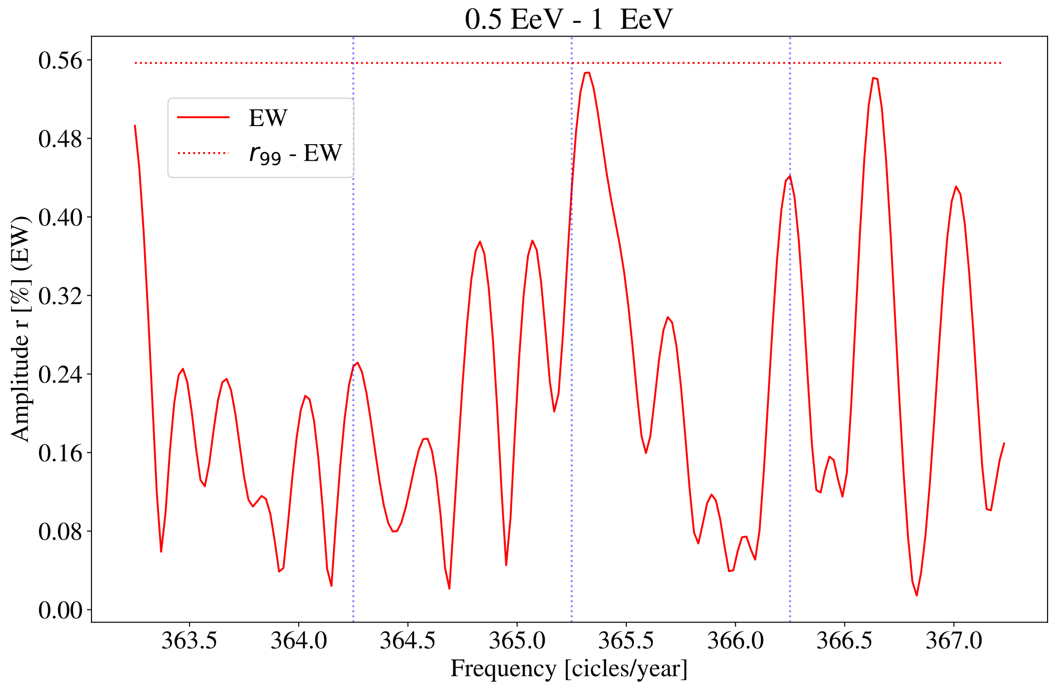


Figure 4: Fourier analysis of the modified variable $\tilde{\alpha}$ for events in the 0.5 EeV - 1 EeV bin from 2014 to 2020, using the East-West method for the All Triggers dataset. The dotted vertical lines represent, from left to right, the anti-sidereal, solar, and sidereal frequencies.

### 4.3 Results in the 1 EeV - 2 EeV energy range

In the previous energy ranges we focused in the East-West method because the effects of the weather conditions on the trigger efficiency are difficult to account for. For this energy range, it is possible to use both Rayleigh and East-West analyses, since the All Triggers selection has full efficiency for events with energy above $\sim$ 1 EeV. Therefore, we compare also the results of both methods in this section.

In Table 4, we compare the results of East-West and Rayleigh analyses for the solar frequency. The amplitudes are below the $r_{99}$ and are compatible between them. The results of both methods indicate that weather modulation amplitudes in the solar frequency are low for the All Triggers dataset.

| All Triggers | Rayleigh | | East - West |
|---|---|---|---|
| Frequency: | Solar | | |
| Amplitude $r$[%]: | $0.24^{+0.16}_{-0.09}$ | | $0.28^{+0.35}_{-0.11}$ |
| $r_{99}$ [%]: | 0.41 | | 0.91 |
| $r_{UL}$ [%]: | 0.58 | | 1.1 |
| $\sigma$: | 0.14 | | 0.30 |
| Probability: | 0.22 | | 0.65 |
| Phase [$^o$] : | 260±48 | | 279±76 |

Table 4: Comparing results of the All Triggers dataset for the solar frequency using the Rayleigh and East-West methods for the first harmonic in the [1- 2] EeV energy bin.

Figure 5 shows the first harmonic amplitude of the Fourier analysis with the weighted Rayleigh method for the All Triggers dataset. The dotted vertical lines indicate the reference frequencies mentioned above, and the horizontal line is $r_{99}$. In this case, there are several amplitudes over the 1% chance probability for isotropy: one close to the sidereal frequency, another one near the anti-sidereal frequency and another at a smaller frequency. These peaks are a signal of the possible presence of an unaccounted systematic error in the dataset.

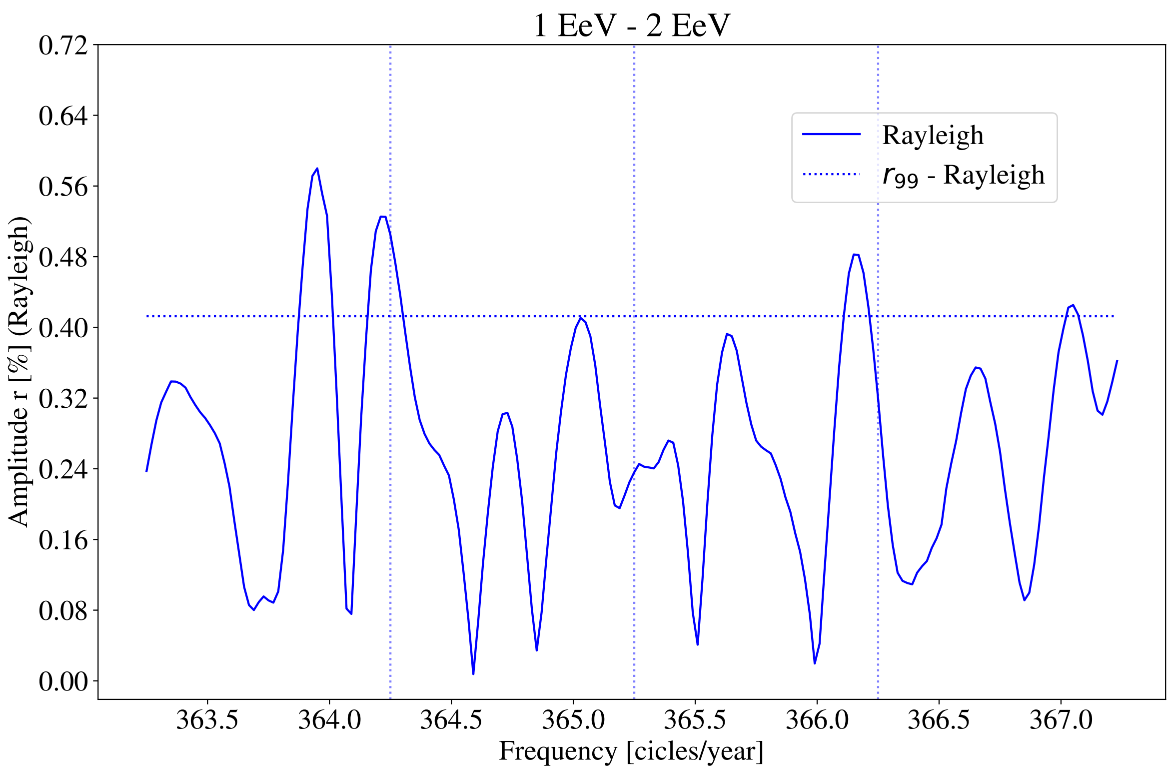


Figure 5: Fourier analysis using the modified variable $\tilde{\alpha}$ for events in the [1 - 2] EeV bin from 2014 to 2020, using the East-West method on the All Triggers dataset. The dotted vertical lines represent, from left to right, the anti-sidereal, solar, and sidereal frequencies, whereas the horizontal line represents $r_{99}$.

Therefore, it is safer to use the East-West method that is not as sensitive as the Rayleigh one to systematic effects. The same Fourier analysis now using the East-West method is shown in Figure 6, now neither sidereal nor anti-sidereal frequencies show significant amplitudes.

The results for the sidereal frequency can be found in Table 5: Rayleigh and East-West results for the All Triggers dataset, and values reported in [3] for the ToT & TH Triggers dataset using the East - West analysis. The amplitudes and phases are all compatible within the statistical uncertainties. The phases obtained with the different methods and datasets are shown in Fig.7, all the results are compatible within $1\sigma$ uncertainty.

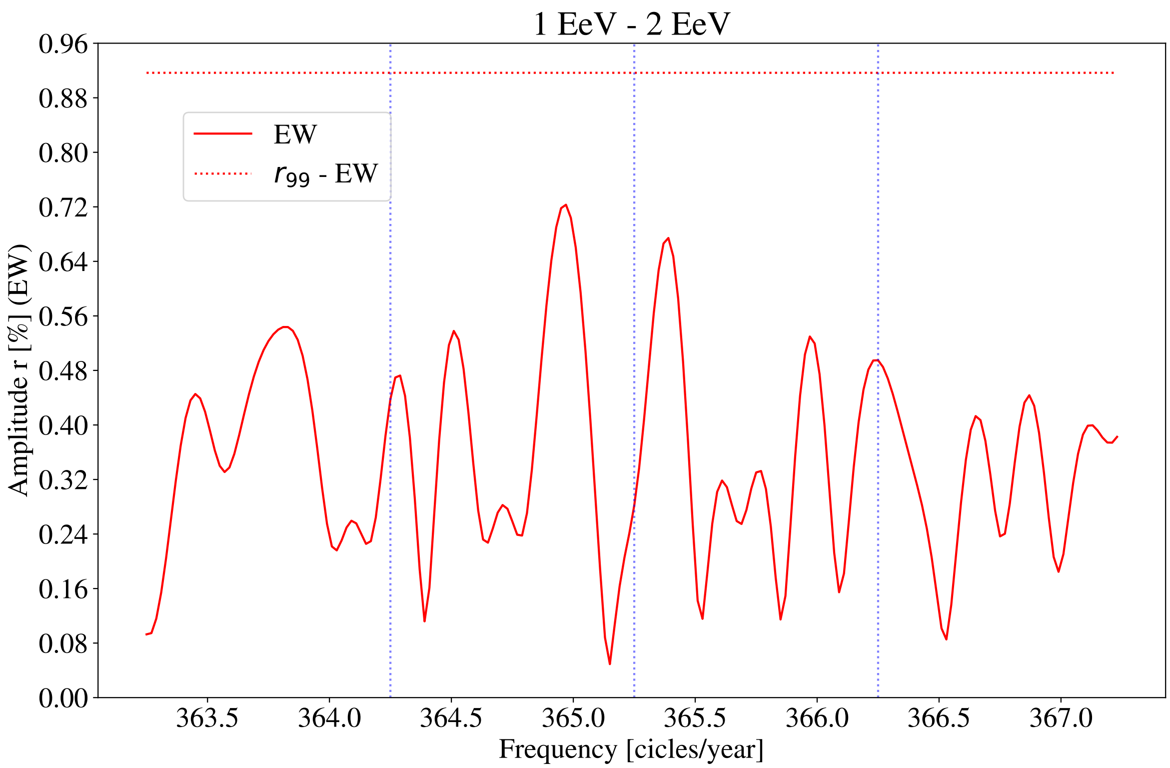


Figure 6: Fourier analysis of the modified variable $\tilde{\alpha}$ for events in the [1 - 2] EeV energy bin from 2014 to 2020, using the East - West method for the All Triggers dataset. The dotted vertical lines represent, from left to right, the anti-sidereal, solar, and sidereal frequencies.

Let us note that in this energy bin a determination of the equatorial dipole was also performed on a previous ToT & TH Herald dataset using the Rayleigh method and correcting for the weather effect on the trigger efficiency in GAP2017-059 [6]. The estimated value, $d_\perp = 0.008 \pm 0.002$, pointing to $\phi = 325° \pm 13°$, is also consistent with the values reported in this note.

## 5 Discussion

The new triggers ToTd and MoPS allow a substantial increment in the number of detected events in the range from 0.25 EeV to 2 EeV with the SD1500 array. We have explored here the All Tiggers dataset, including 6 years measurements from January 2014 to January 2020, to analyse the large scale distribution in right ascension. We analysed the data in three energy bins, [0.25 - 0.5] EeV, [0.5 - 1] EeV and [1 - 2] EeV as done in previous publications. We obtained the first harmonic amplitude and phase using the East-West method. In all the bins the results are compatible with the last published results using the ToT & TH triggers dataset up to August 2018 [3]. In the lowest energy bin, the increased statistics allows to put an upper bound to $d_\perp$ a factor of 2 lower than the last published one [3].

| | All Triggers | | | ToT & TH Triggers |
|---|---|---|---|---|
| | Rayleigh | | East - West | East - West[3] |
| Frequency: | Sidereal | | | Sidereal |
| Amplitude $r$ [%]: | $0.32^{+0.16}_{-0.10}$ | | $0.5^{+0.3}_{-0.2}$ | $0.14^{+0.37}_{-0.02}$[5] |
| $r_{99}$[%]: | 0.41 | | 0.91 | 0.84[5] |
| $r^{UL}$[%] | 0.66 | | 1.3 | 0.89 [5] |
| $\sigma$[%]: | 0.14 | | 0.30 | 0.28 [5] |
| Amplitude $d_\perp$ [%]: | $0.41^{+0.20}_{-0.13}$ | | $0.6^{+0.4}_{-0.3}$ | $0.18^{+0.47}_{-0.02}$ |
| $d_{99}$[%]: | 0.53 | | 1.1 | 1.1[5] |
| $d_\perp^{UL}$[%] | 0.84 | | 1.6 | 1.1 |
| $\sigma_{x,y}$[%]: | 0.17 | | 0.38 | 0.35 |
| Probability: | 0.063 | | 0.26 | 0.87 |
| Phase [$^o$]: | 357±35 | | 320±48 | 291±100 |
| $\langle\cos\delta\rangle$ | 0.78 | | 0.78 | 0.78 |
| $\langle\sin\theta\rangle$ | 0.55 | | 0.55 | 0.57 |

Table 5: Results for the All Triggers and ToT & TH Triggers datasets for the sidereal frequency using the East-West and Rayleigh methods for the first harmonic in the [1 - 2] EeV energy bin.

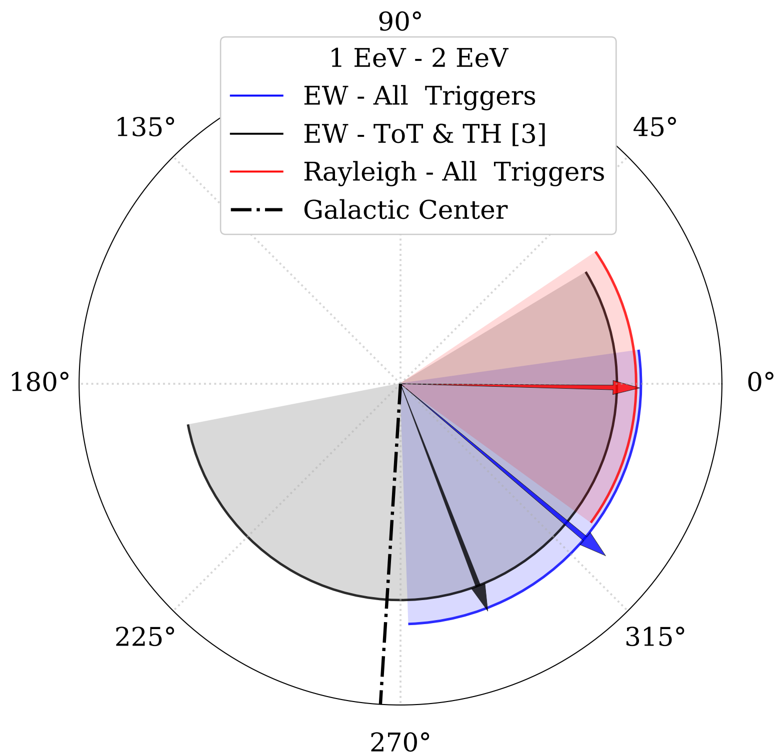


Figure 7: Phases values for the solar and sidereal frequencies in the [1 - 2] EeV bin, as they were obtained in this note and as reported in Aab A. et al. (2020) [3], with their respective uncertainties.

Since including ToTd and MoPS triggers the SD1500 is fully efficient for energies above $\sim 1$ EeV, in the energy bin from 1 EeV to 2 EeV we have used both the weighted Rayleigh and the East West methods. The results are compatible in both analyses at the sidereal frequency, with a better sensitivity in the Rayleigh analysis. However, to check for possible remaining spurious effects, we applied the method performing a scan in frequency, and we found significant amplitudes at frequencies close to the antisidereal one. Thus, further checks in the dataset need to be performed before the weighted Rayleigh analysis results can be adopted.

As a summary, we can see the results obtained for the two datasets (with both methods for the [1 - 2] EeV energy bin) for the equatorial dipole in Figure 8. The empty circles are centered on the values reported in [3] using the ToT & TH Triggers dataset, and their radius are given by $\sigma_{x,y}$. The solid circles correspond to the All Triggers dataset reported in this note. The arrow length is proportional to $d_\perp$ and its direction indicates the phase for the Rayleigh (Ray) and East-West (EW) results of the All Triggers dataset.

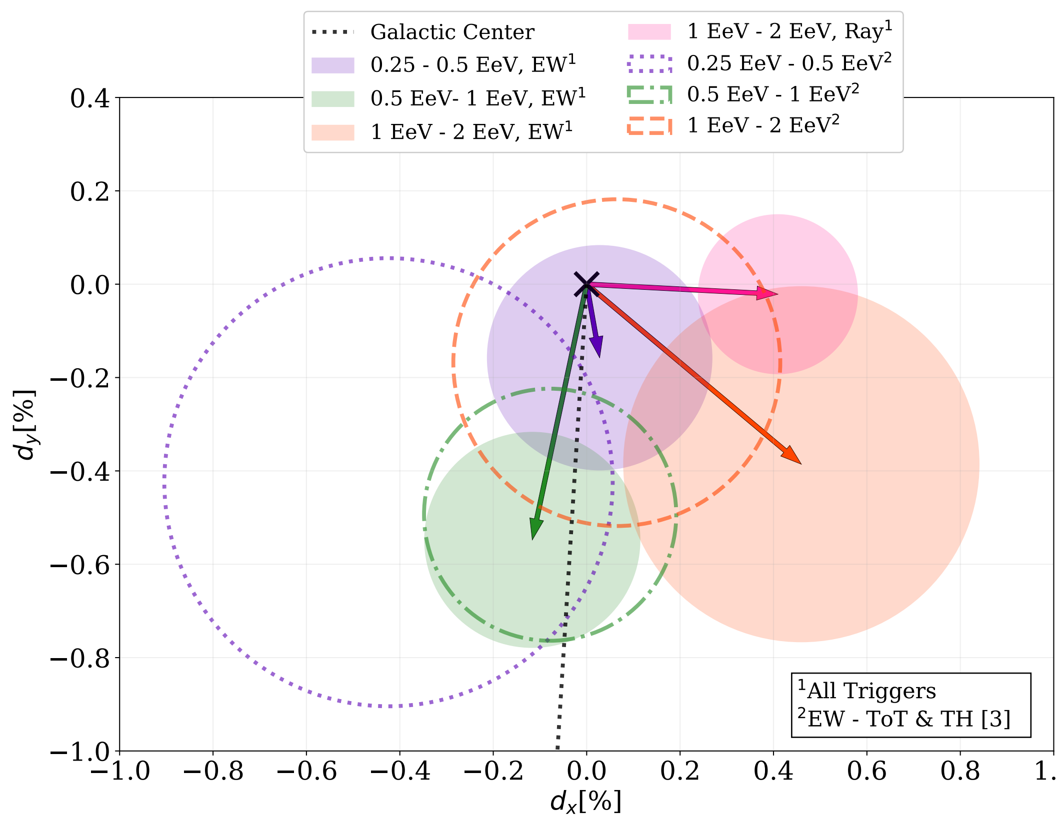


Figure 8: Components of the dipole amplitude $d_\perp$ in the equatorial plane for several energy bins. The circles are centered on the measured values and the radius is taken as $\sigma_{x,y}$. Empty circles represent the values reported in [3] for the ToT & TH Triggers dataset, whereas solid circles correspond to the results obtained here for the All Triggers dataset. The dotted line indicates the direction of the galactic center.

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