The *East-West method*: an exposure-independent method to search for large scale anisotropies of cosmic rays

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Abstract: The measurement of large scale anisotropies in cosmic ray arrival directions at energies above 10^{13} eV is performed through the detection of Extensive Air Showers produced by cosmic ray interactions in the atmosphere. The observed anisotropies are small, so accurate measurements require small statistical uncertainties, *i.e.* large datasets. These can be obtained by employing ground detector arrays with large extensions (from 10^5 to 10^9 m^2) and long operation time (up to 20 years). The control of such arrays is challenging and spurious variations in the counting rate due to instrumental effects and atmospheric effects are usually present. These modulations must be corrected very precisely before performing standard anisotropy analyses, *i.e.* harmonic analysis of the counting rate versus local sidereal time. In this paper we discuss an alternative method to measure large scale anisotropies, the "East-West method", originally proposed by Nagashima in 1989. It is a differential method, as it is based on the analysis of the difference of the counting rates in the East and West directions.

Keywords: Cosmic rays, large scale anisotropies.

1 Introduction

The measurement of the anisotropy in the arrival directions of cosmic rays (CRs) is a complementary tool, with respect to the energy spectrum and mass composition, to investigate the origins of these particles. From the observational point of view indeed, the study of the CR anisotropy, and especially its evolution over the energy spectrum, is closely connected to the problem of CR propagation and sources.

The most commonly used technique, originally proposed in [1], is the analysis in right ascension only, through harmonic analysis (Rayleigh formalism) of the counting rate within the declination band defined by the detector field of view. The greatest difficulties of this technique are in the treatment of the data, *i.e.* of the counting rates themselves. Both for large scale anisotropies linked to diffusive motions or for the ones due to the Compton-Getting effect (*i.e.* due to the observer's motion with respect to a locally isotropic population of cosmic rays), the expected amplitudes are very small ($10^{-6} - 10^{-2}$), with related statistical problems: long term observations and large collecting areas are needed. Instrumental effects must be kept as small as possible, requiring detectors to operate uniformly (both in size and over time), and being as stable as possible. Moreover, extended air shower (EAS) arrays are mostly located in remote sites (generally at mountain altitude), being thus subject to large atmospheric variations, both in temperature and in pressure. Meteorological induced modulations can affect the CR rate: indeed the EAS properties themselves depend on air density (through variations of the Molière radius) and on pressure (due to the absorption of the electromagnetic component in the air) [2].

The *East-West method*, being based on a differential technique, was designed to avoid introducing such corrections, preventing the possible associated systematics to affect the results. Originaly proposed in [3], it was applied to the data of the Mt. Norikura array. It was later applied by other

EAS arrays such as the Tibet experiment [4], EAS-TOP [5] and the Pierre Auger Observatory [6, 7].

In section 2, we explain the principle and give the mathematical basis of the method, demonstrating that the East-West technique is largely independent of any instrumental/atmospheric effect. The derivation of the amplitude and phase of the anisotropy from the harmonic analysis of the differences in East and West directions is illustrated in section 3. Here we show also how to extract from the derived amplitude and phase those corresponding to the equatorial component of the dipole. In section 4, we apply the East-West method to different mock EAS data sets, characterized by different spurious effects.

2 The principle of the East-West method

The total counting rate of events observed in either the Eastern or the Western half of the field of view of an EAS array experiences different kind of variations during a sidereal day. Those may be caused either by experimental effects and/or by real variations in the primary CR fluxes from different parts of the sky. The East-West method is aimed at reconstructing the equatorial component of a genuine large scale pattern by using only the difference of the counting rates of the Eastern and Western hemispheres. The effects of experimental origin, being independent of the incoming direction, are expected to be removed through the subtraction. In the presence of a genuine dipolar distribution of CRs, as the Earth rotates Eastwards, the Eastern sky is closer to the dipole excess region for half a day each day; then, after the field of view has traversed the excess region, the Western sky becomes closer to the excess region and thus bears higher counting rates than the Eastern sky. The East-West differential counting rate is thus subject to oscillations whose amplitude and phase are expected to be related to those of the genuine large scale anisotropy.

The counting rates $I_E^{obs}(t)$ and $I_W^{obs}(t)$ at local sidereal time t for the two halves of the sky can be computed from the CR flux Φ in local coordinates (θ, ϕ) as :

$$I^{obs}(t) = A \int \mathrm{d}\phi \int_0^{\theta_{\max}} \mathrm{d}\theta \sin\theta\cos\theta\epsilon(\theta,t)\Phi(\theta,\phi,t), \quad (1)$$

where ϕ has to be integrated from $-\pi/2$ to $\pi/2$ and from $\pi/2$ to $3\pi/2$ for the Eastern and the Western sectors respectively. $A\cos\theta$ denotes the effective area of the experiment at an angle of incidence θ and $\epsilon(\theta, t)$ is the detection efficiency function which includes the time-dependent spurious effects. To guarantee that the Eastern and Western sectors are equivalent in terms of counting rates, any dependence of ϵ in azimuth ϕ needs to be symmetrical. For simplicity, we assume hereafter a uniform detection efficiency in azimuth; but similar conclusions still hold as long as the symmetry between the sectors is respected, which is a reasonable assumption in practice. It is also reasonable to assume that the relative amplitude η of the temporal variations of the exposure is small, and that those variations decouple from the zenith angle dependent ones. The most basic approach to probe a large scale variation is to describe the flux by a combination of an isotropic component and a dipolar component:

$$\Phi(\alpha,\delta) = \Phi_0\left(1+\hat{u}(\alpha,\delta)\cdot\vec{D}\right), \quad \vec{D} = D\hat{u}(\alpha_d,\delta_d), \quad (2)$$

with $\vec{D}$ being the dipole vector defined by its magnitude D and its orientation (α_d, δ_d). As it is explained in details in [9], after developing Eqn 1 and neglecting second order terms, the East-West counting rate and the differential total counting rate are proportional at first order :

$$I_E^{obs}(t) - I_W^{obs}(t) \simeq \frac{2}{\pi\cos\ell}\frac{\langle\sin\theta\rangle}{\langle\cos\theta\rangle}\frac{dI_{tot}^{true}(t)}{dt}. \quad (3)$$

where $I_{tot}^{true}(t)$ is the true total counting rate and ℓ the Earth latitude of the experiment location.

3 First harmonic analysis

3.1 First harmonic analysis of $I_E - I_W$

To probe a dipolar structure of the CR arrival direction distribution, Eqn. 3 is an ideal starting point to estimate the dipolar modulation of dI_{tot}^{true}/dt parameterised through the amplitude r and the phase φ:

$$\frac{dI_{tot}^{true}(t)}{dt} = r\cos(t-\varphi). \quad (4)$$

From a set of N arrival times from events coming from either the Eastern or the Western directions, r and φ can be estimated by applying to the arrival times of the events the standard first harmonic analysis [1] slightly modified to account for the subtraction of the Western sector to the Eastern one. The Fourier coefficients a and b are thus defined by:

$$a = \frac{2}{N}\sum_{i=1}^{N}\cos(t_i+\zeta_i), b = \frac{2}{N}\sum_{i=1}^{N}\sin(t_i+\zeta_i), \quad (5)$$

where ζ_i equals 0 if the event is coming from the East or π if coming from the West[1]. The amplitude and phase estimates $(\hat{r}, \hat{\varphi})$ of dI_{tot}^{true}/dt are then obtained through:

$$\hat{r} = \frac{\pi\cos\ell}{2}\frac{\langle\cos\theta\rangle}{\langle\sin\theta\rangle}\sqrt{a^2+b^2}, \ \hat{\varphi} = \arctan\left(\frac{b}{a}\right). \quad (6)$$

By integrating dI/dt, the amplitude and phase estimates $(\hat{r}_I, \hat{\varphi}_I)$ of the intensity $I(t)_{tot}^{true}$ itself are obtained:

$$\hat{r}_I = \frac{N}{2\pi}\hat{r}, \ \hat{\varphi}_I = \hat{\varphi} + \frac{\pi}{2}. \quad (7)$$

1. We are grateful to Paul Sommers for suggesting this simple way of accounting for the difference between the contributions from the East and West sectors.

3.2 Estimation of the dipole equatorial component

The power of the standard Rayleigh analysis in right-ascension (RA) is the largest when the dipole is oriented in the equatorial plane. Under such an assumption, the first harmonic amplitude r_{RA} is related to the dipole amplitude D through [8]:

$$r_{RA} = D_{\perp} \langle cos\delta \rangle \tag{8}$$

where $D_{\perp}$ denotes the component in the equatorial plane and δ the declination of the detected events. Similarly, the first harmonic amplitude and phase reconstructed by the East-West method, namely $(\hat{D}_{\perp}, \hat{\alpha}_d)$, are not directly the dipole amplitude and phase. Neglecting second order terms, $(\hat{D}_{\perp}, \hat{\alpha}_d)$ are given by the following formulas [9] :

$$\hat{D}_{\perp} = \frac{\pi}{2\langle \sin\theta \rangle}\sqrt{a^2+b^2}, \quad \hat{\alpha}_d = \hat{\varphi} + \frac{\pi}{2}. \tag{9}$$

It is worth noting that, from the transformation of coordinates relation $\cos\delta\sin h = -\sin\theta\cos\varphi$, the factor $2\langle\sin\theta\rangle/\pi$ can be expressed as well in terms of δ and h as :

$$\frac{2\langle\sin\theta\rangle}{\pi} = \langle\cos\delta\sin h\rangle, \tag{10}$$

where the r.h.s. average is performed by integrating over the eastern and western quadrants.

By comparing Eqn. 9 to Eqn. 8 and using Eqn. 10, it can be seen that the use of the local sidereal time in the modulation search (instead of the right ascension as in the case of the standard Rayleigh analysis), combined to the East-West subtraction, leads to a loss of sensitivity by a factor $\langle\cos\delta\rangle / \langle\cos\delta\sin h\rangle$ (which is typically about two, depending on the experimental conditions) with respect to the performances of the standard Rayleigh analysis. However, this method has the benefit of avoiding the need to implement any corrections of the total counting rates for instrumental and atmospheric effects. Moreover, in some cases those corrections cannot be computed reliably, for instance when they are due to the energy dependence of the trigger efficiency, which can also depend on the unknown composition of the primary CRs. In these cases, only the East-West method can be implemented reliably.

4 Simulations

In this section, we check the behavior of the method through simulations reproducing realistic conditions of a ground experiment subject to artificial modulations at both the diurnal and the seasonal time scales. For definiteness we consider an experiment located at the same Earth latitude $\ell = -35.25°$ as the Pierre Auger Observatory [10] and considering arrival directions up to a maximal zenith angle of 60°, with the following energy independent detection efficiency function :

$$\epsilon(\theta,t) = \frac{1}{1+\exp((\theta-\theta_{ns})/\sigma_{ns})} \cdot g(t), \tag{11}$$

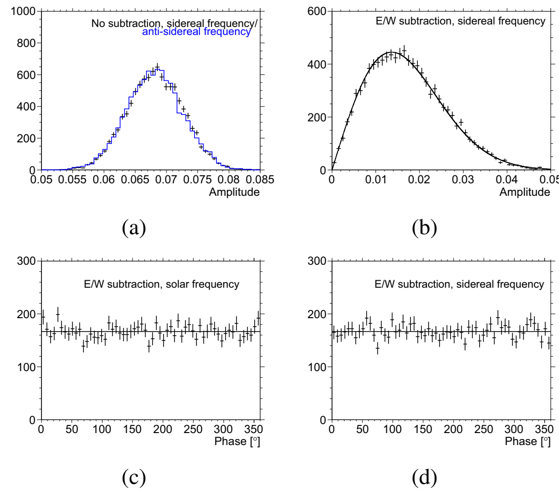
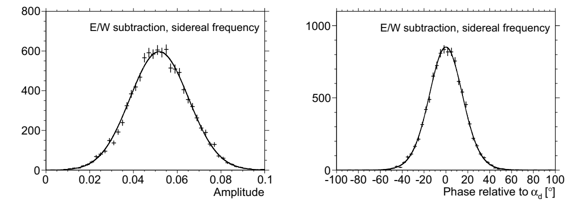


Figure 1: *On the top :* Distributions of the amplitudes of the first harmonic obtained with the standard Rayleigh analysis (Fig. 1(a)) and with the East-West analysis (Fig. 1(b)) in the presence of experimental effects in both sidereal and anti-sidereal times.*On the bottom :* Distributions of the phases obtained from the East-West analysis in the presence of experimental effects in solar (Fig. 1(c)) and in sidereal times (Fig. 1(d)). All the distributions recovered by the East-West method are compared with the isotropic expectations: the subtraction of the spurious effects holds perfectly.

where $\theta_{ns} = 50°$ and $\sigma_{ns} = 5°$. Here, $g(t)$ stands for the spurious modulation, which may differ from unity due to various reasons. For instance, the changes of atmospheric conditions affect the energy estimate of the showers [2]. When such effects are not accounted for, they induce a modulation of the rate of events above any given energy threshold. Hence, we choose the function $g(t)$ to be of the generic form [11]:

$$g(t) = \frac{1+\eta_y c_y(t) + \eta_d\left[1+\eta_\star c_y(t)\right]c_d(t)}{1+\eta_y+\eta_d(1+\eta_\star)}, \tag{12}$$

where $c_x(t) = \cos(2\pi(t-t_x^0)/T_x)$ takes into account the diurnal ($x=d$) and seasonal ($x=y$) mean event rate variations. η_x, t_x^0 and T_x correspond then to the amplitude, the phase and the period of these variations. Finally, $\eta_\star$ stands for the variation of the diurnal amplitude along the year. This last term, combining the diurnal modulation with an annual one, is responsible for the production of sidebands at both the sidereal and the anti-sidereal frequencies, whose amplitudes are given by $0.5\times\eta_d\times\eta_\star$ [11]. To illustrate the power of the East-West method, we choose an extremely high value of $\eta_\star = 90\%$ to guarantee the existence of significant sidebands, while we set $\eta_y = 20\%$ and $\eta_d = 15\%$. We consider here below three different underlying cases



(a) (b)

Figure 2: Distributions of the amplitudes (2(a)) and phases (2(b)) of the first harmonic in local sidereal time obtained with the East-West analysis in the presence of a genuine pattern of 5%. These histograms are in perfect agreement with respect to the expectations.

4.1 Isotropy with spurious effects

We first consider an isotropic distribution of CRs polluted by the spurious effects described above, and analyse 10^4 mock samples generated with a total number of events $N = 10^5$. Applying the East-West analysis at both the solar and sidereal frequencies, it can be seen that the reconstructed amplitudes $\hat{D}_\perp$ and phases $\hat{\alpha}_d$ are now distributed according to the expected distributions: the Rayleigh one for the amplitude, with parameter $\sigma = \pi/2 \langle \sin\theta \rangle \sqrt{2/N}$, and the uniform one for the phase (cf. Fig. 1). Hence, in spite of the strong experimental effects, it turns out that the East-West subtraction allows the removal of possible biases in the estimate of both the amplitude and phase in the case of an underlying isotropic distribution of CRs.

4.2 5% sidereal signal with spurious effects on the acceptance

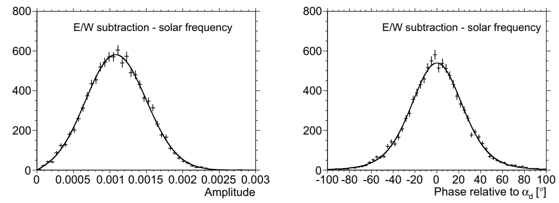
To test now the accuracy of the method in the presence of both a genuine signal at the sidereal frequency and spurious effects, a signal corresponding to a dipolar anisotropy of 5% amplitude is introduced in the simulated samples. For definiteness, we consider the dipole oriented towards the equatorial plane. The reconstructed amplitudes are now expected to follow a Rice distribution with parameters $\mu = 5\%$ and $\sigma = \pi/2 \langle \sin\theta \rangle \sqrt{2/N}$:

$$p_1(\hat{D}_\perp) = \frac{\hat{D}_\perp}{\sigma^2} \exp\left(-\frac{\hat{D}_\perp^2 + \mu^2}{2\sigma^2} \right) I_0\left(\frac{\hat{D}_\perp \mu}{\sigma^2} \right),$$

while the reconstructed phases are expected to follow the distribution described by Linsley in the 2^{nd} alternative in [1]:

$$p_2(\hat{\alpha}_d) = \frac{1}{2\pi} \exp\left(-\frac{\mu^2}{2\sigma^2} \right) + \frac{\mu \cos(\hat{\alpha}_d - \alpha_d)}{2\sqrt{2\pi}\sigma} \times \left[1 + \mathrm{erf}\left(\frac{\mu \cos(\hat{\alpha}_d - \alpha_d)}{\sqrt{2}\sigma} \right) \right] \exp\left(-\frac{\mu^2 \sin^2(\hat{\alpha}_d - \alpha_d)}{2\sigma^2} \right),$$

The results of the simulations are shown in Fig. 2, evidencing a perfect agreement with the expectations.



(a) (b)

Figure 3: Same as Fig. 2, but generating a genuine pattern at the solar frequency.

4.3 0.1% solar signal with spurious effects

We repeat here exactly the same exercise as above, but generating a genuine dipole with an amplitude 0.1% at the *solar* frequency, together with the spurious effects. This kind of feature is expected due to the motion of the terrestrial observer through the frame in which the CR distribution is isotropic. It has been observed by several experiments at low energies, where sufficient statistics has been gathered. To probe such a low amplitude, the number of events has to be greatly increased with respect to the previous cases. Thus, we generated 1,000 samples of $N = 10^8$ events. The results of the simulations are shown in Fig. 3, showing once again perfect agreement with the expectations, even if both the genuine and the artificial modulations are present at the same time scale.

References

[1] J. Linsley 1975, Phys. Rev. Lett., 34, 1530-1533
[2] The Pierre Auger Collaboration 2009, Astropart. Phys., 32, 89-99
[3] K. Nagashima et al. 1989, Il Nuovo Cimento C, 12, 695
[4] M. Amenomori et al. 2005, Ap. J., 626, L29
[5] M. Aglietta et al. 1996, Ap. J., 470, 501
[6] R. Bonino for the Pierre Auger Collaboration 2009, Proc. 31st ICRC, HE.1.4 35
[7] The Pierre Auger Collaboration 2011, Astropart. Phys., 34, 627-639
[8] J. Aublin and E. Parizot 2005, Astron. & Astrophys. 441, 407-415
[9] R. Bonino *et al.* , submitted to ApJ.
[10] The Pierre Auger Collaboration 2004, Nucl. Instr. and Meth., A523 , 50
[11] F.J.M. Farley and J.R. Storey 1954, Proc. Phys. Soc. A, 67, 996-1004