Ultra-High Energy Cosmic Particles studies from space: super-EUSO, a possible next-generation experiment.

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Abstract

After the Pierre Auger Observatory, it is likely that space-based experiments might be required for next-generation studies of Ultra-High Energy Cosmic Particles. An overview of this challenging task is presented, emphasizing the main design issues, the criticalities and the intermediate steps required to make this challenging task a reality.

Key words: Ultra-High Energy Cosmic Particles, Cosmic Rays, AirWatch.

1. Introduction

The interpretation of the phenomenology of Ultra-High Energy Cosmic Particles (UHECP) is one of the most challenging topics of modern astro-particle physics.

UHECP reach the Earth with a very low directional intensity of a few particles millennium$^{-1}$ km$^{-2}$ sr$^{-1}$ for particles with an energy $E \gtrsim 10^{20}$ eV [1] and therefore a large, complex and sophisticated experimental apparatus is required to observe them.

The science case of UHECP will not be presented in this paper as it has been extensively discussed elsewhere (for instance see [2, 3, 4, 5] an references therein). This paper will only discuss the experimental apparatus required for space-based experiments for the observation of UHECP in the post Pierre Auger Observatory (PAO) era: perspectives, how-to-do and a roadmap will be identified.

I assume the point of view that, after the PAO south site, which is the present state-of-the-art experiment in the field, the hopefully near future is the full PAO observatory, with the north site added to the already operating Auger-south site. Moreover I assume that the, hopefully not too far, future might be a space-based experiment.

2. The observational technique

EUSO and super-EUSO are implementations of the AirWatch concept, originally proposed by John Linsley more than twenty years ago [6, 7]: to observe from space the Extensive Air Shower (EAS) produced by the interaction of a primary cosmic particle with the atmosphere, as shown in Figure 1.

An EAS can be detected by observing the air scintillation light, produced during the EAS development. The additional observation of the diffusely reflected Cherenkov light (reflected either by land, sea or clouds) provides additional information. It is then possible to estimate the energy and arrival direction of the primary UHECP and to gather information about its nature. The atmosphere is used as a calorimeter. Any given EAS will be seen as a point moving with a direction and angular velocity depending on the EAS direction.

The air scintillation light is mainly emitted in the wavelength range 330 nm ÷ 400 nm, concentrating around three bands at $\lambda_1 \approx 340$ nm, $\lambda_2 \approx 360$ nm and $\lambda_3 \approx 390$ nm. It is isotropic and proportional, at any point along the EAS development, to the number of charged particles in the EAS, largely dominated by electrons and positrons. The total amount of light produced is proportional to the primary particle energy and the shape of the EAS profile (in particular the atmospheric depth of the EAS maximum) contains information about the primary particle identity. In this wavelength range the atmosphere is relatively transparent, down to $\lambda \approx 330$ nm where the ozone absorption becomes strong.

The possible observation of the Cherenkov light diffusely reflected by the Earth (by land, sea or clouds) will help the determination of the EAS parameters. While the amount of observed Cherenkov photons depends on the reflectance and geometry of the impact surface, the directionality of the Cherenkov beam provides a precise extrapolation of the EAS direction to the first reflecting surface.

A selective and efficient trigger is required to distinguish the EAS from the background. Many different kind of backgrounds are expected including: man-made lights, auroras, natural photo-chemical effects (in atmosphere, sea and land), low-energy cosmic rays, reflected moon-light and star-light as well as the most important expected contribution: the random night-glow background. The random night-glow is currently esti-
mated in the range $B \approx (3 \pm 15) \cdot 10^{11}$ photons $\cdot m^{-2} \cdot s^{-1} \cdot sr^{-1}$, in the wavelength range $330 \, \text{nm} \leq \lambda \leq 400 \, \text{nm}$ at $H \approx 400 \, \text{km}$ height, depending on various factors.

The peculiar characteristics of the EAS, including the kinematical ones, allow one to distinguish them from the various backgrounds, because those have a typically different space-time development. The non-random backgrounds, for instance, typically have a time-scale of the order of ms, much longer than an EAS.

The challenging goal can be accomplished from space by observing the Earth atmosphere at night-time, looking down to nadir.

Key points of the observational technique are the following.

1. A large instantaneous geometrical aperture can be obtained, thanks to the large distance, depending on the Field of View (FoV) of the apparatus. A large mass of atmosphere (the calorimeter medium) can therefore be observed.
2. Detection of EAS produced by weakly interacting primary particles, starting to shower deeply in the atmosphere, is possible, by the direct observation of the EAS development and starting point.
3. All sky coverage is possible with one single apparatus.
4. The approach is complementary to the ground-based one. In fact space experiments are best suited for the observation of higher energy UHECP with respect to ground-based experiments. However an overlap of the observed energy spectrum with the one known from ground-based experiments is required for a safe comparison. The systematic effects are largely different in the two approaches.

3. Beyond the Pierre Auger Observatory from space?

Exceeding the PAO performance requires a huge experiment, on a long time-scale, requiring a large amount of preliminary R&D and ancillary studies.

Moreover the challenging goal of a big experiment from space requires intermediate steps some of which are on the way (JEM-EUSO, [8]). Other intermediate steps include some path-finder and/or technological model, as it will be discussed later.

What we are learning from PAO will help to tune the future scientific objectives. A tuning of the scientific objectives is mandatory because the Experiment-For-Everything is, most likely, impossible: a choice of scientific objectives will be needed, to drive trade-offs and choices on the experiment design and performance.

Such a challenging enterprise would require the involvement of a large part of the UHECP physicists community, in a coordinated effort.

Science must be, obviously, the driving force. However, after a careful assessment of the predictable status of UHECP science in some ten/fifteen years from now, based on the exploitation of the full PAO experiment, one needs to consider a realistic implementation of possible experimental apparatus, to avoid dreams which will never become a reality, at least on the time-scale of a human life.

Most new big projects have a long time duration and require a long time for conception, design, commissioning (plus getting funds...). Therefore one must start right now to think about concrete proposals for realistic implementations of post PAO (south+north) experiments. It is not too early, as some ten years are certainly necessary to design and build such a challenging apparatus.

4. The apparatus required for space-based UHECP observation

The AirWatch observational technique was carefully described in [7]. The required apparatus is an Earth-watching large aperture, large Field-Of-View (FoV), fast and highly pixelized digital camera for detecting near-UV single photons superimposed on a huge background and capable of (at least!) five years operation in space [9].

It is made of:

1. a main optics, collecting photons and focusing the EAS image onto its Focal Surface (FS);
2. the photo-detector (PD) on the FS, for registering the EAS image, which is made of: photo-sensors, front-end electronics, back-end electronics, triggering and data analysis systems;
3. possible ancillary instrumentation such as:
(a) a LIDAR for atmospheric monitoring;
(b) an IR camera;
(c) a suitable radio-detection system.

4. system instrumentation.

5. Some order of magnitude estimates

Some order of magnitude estimates are derived in this paragraph, in order to provide figures which are necessary for understanding the concept design.

Assume an apparatus looking down the Earth at night from $H = 400$ km height, with an entrance pupil diameter $D = 5$ m, and half-angle FoV $\gamma = 20^\circ$ and a total apparatus detection efficiency $\epsilon \approx (0.1 \div 0.2)$.

5.1. The EAS signal

Consider an hadron-induced EAS with energy $E \approx 10^{19}$ eV, zenith angle $\theta_z \approx \pi/4$, and azimuth angle with respect to the radial direction on the FoV $\phi = \pm \pi/2$.

Under such hypotheses the time-integrated signal reaching the apparatus (irradiance) is $I \approx 50$ photons $\cdot$ m$^{-2}$, which means that a large entrance pupil is required. This irradiance implies a total number of detected photons from the EAS given by $IA\epsilon \approx 150$, which translates into an energy resolution $\Delta E/E \approx 0.1$ (due to the statistical error only).

The apparent time duration of the visible EAS track is $T \approx 80$ $\mu$s and its typical angular span is $\Delta \xi \approx 1.5^\circ$. These facts imply that a time resolution at the $\mu$s level and a fine granularity of the photo-detector (better than $\approx 0.1^\circ \times 0.1^\circ$) are needed in order to get an angular resolution on the primary EAS particle direction of $\Delta \theta \approx 1^\circ$. This fact and the large FoV require a large number of channels (of the order of $10^5 \div 10^6$).

5.2. The random night-glow background

In the real world background makes the previous estimations too optimistic as the large background must be accounted for.

The reference random night-glow background in the 330 nm$\div$400 nm wavelength range is $B \approx 5 \times 10^{11}$ photons $\cdot$ m$^{-2}$ $\cdot$ s$^{-1}$ $\cdot$ sr$^{-1}$ but current estimates show that it might be up to a factor two larger. Moreover its detailed space-time structure, at the level of the characteristic space-time scales of the EAS development, is not known.

The resulting total random night-glow background rate intercepted (on the whole entrance pupil and full FoV) is then $\approx 4$ THz.

The resulting total random night-glow background rate detected on the PD per pixel (pixel size: $0.1^\circ \times 0.1^\circ$ for a total of $N = 1.2 \times 10^5$ pixels) is then $3$ MHz/pixel.

These figures result in one order of magnitude more random night-glow background than signal photons superimposed on the typical EAS (over all its space-time development) as well as roughly the same number of signal and random night-glow background photons near the EAS maximum. Therefore one needs to find a way to cope with the huge background, taking into account that many other sources of non-random background come into play.

5.3. Extraction of the EAS signal from the random night-glow background

The previous figures show that it is a real challenge to extract the EAS signal from the random night-glow background. This is particularly true if one aims to go down safely in the UHECP energy to $E \approx 10^{19}$ eV, as good physics would demand. In fact the signal and random night-glow background scale proportionally with the entrance pupil area with a signal decreasing when looking at EAS of progressively decreasing energy over a constant random night-glow background.

In order to extract the EAS from the background a precise knowledge of the properties of the background is required, at the space-time level of the EAS kinematics. A continuous monitoring (and subtraction) of the average background on a pixel-by-pixel (or so) basis is thus unavoidable to decrease the energy threshold down to $E \approx 10^{19}$ eV.

The acceptable background level also depends on the energy of the EAS. In order to allow for background dependent observations a precise knowledge of the apparatus sensitivity as a function of the background is required, which requires a precise apparatus calibration.

In order to face the background a clever and powerful triggering and data-handling scheme need to be invented.

Many other types of backgrounds, in addition to the random night-glow one, exist. Most of them appear not to be dangerous as their kinematics very different from the one of an EAS, but it is most likely mandatory a dedicated background measurement to improve our knowledge.

6. EUSO

EUSO was proposed to the European Space Agency (ESA) as a free-flyer with: a main optics diameter of $\approx 3.5$ m; orbit height and inclination as free parameters to be tuned; mass, volume, power, telemetry and other budgets largely unconstrained.

ESA recommended to consider the accommodation on the ESA Columbus module on the International Space Station (ISS) so that many constraints had to be taken into account, including: a fixed orbit and severe limits on mass, volume, power, telemetry and other budgets. In fact the accommodation had to be made compatible with the ISS/Columbus resources including: mass (1.5 ton), volume ($2.5 \times 2.5 \times 4.5$ m$^3$), power (1 kW) and telemetry (180 Mbit/orbit). The volume, in particular, was limited by the envisaged accommodation on the Space Shuttle, not by its capabilities.

Many constraints, mainly due to the ISS, limited the final EUSO performance which was finally put into hibernation by ESA.

6.1. The heritage of EUSO projected into the future

EUSO underwent a detailed phase-A study.

We have learnt a lot about space-based observation of UHECP from the EUSO phase-A studies. The EUSO heritage is exceedingly precious and it is wise to exploit what we learnt from EUSO to develop a second generation experiment.
We can consider EUSO as our prototype exercise in the conception and design of which we have possibly done mistakes!

One of the most important lessons is that one needs a safe design margin on the expected performance already at a design stage.

7. From EUSO to super-EUSO

Aiming at (or dreaming of) an experiment with much better performance than EUSO the following consequences (all relative to the EUSO design [7]) must be faced.

The EUSO efficiency plateau was reached for energies larger than \( E \approx (1 \div 2) \cdot 10^{20} \text{ eV} \): one needs to gain a factor \((10 \div 20)\) - at least - in the energy threshold in order to cross-calibrate with ground-based experiments, to safely observe the GZK region and increase the number of expected neutrino events.

In order to observe fainter events one needs to collect more photons. More collected photons improve the energy resolution and angular resolution on the UHECP as well. However increasing the number of collected photons also increases the background rate: it is not enough to increase the number of photons to improve the performance. In fact at some low-enough energy the EAS will fade away in the background.

The FoV of the optics might be reduced to get better optical efficiency: assume \( \gamma_M = (20 \div 25) \) (half-angle).

After that one has to recover the instantaneous geometrical aperture by higher orbits.

The number of channels is a challenge anyway: if one assumes a maximum of one million channels (it is already very challenging) one finds a angular granularity of 0.06\(^\circ\) (one mrad).

As one needs to account for a higher orbit, this requires smaller pixels to obtain the same granularity at the Earth.

7.1. Optimisation of the orbital parameters

A free-flyer allows many more degrees of freedom in the choice of the orbit than the ISS. One may also think to change the orbit during the mission. Changing the orbit height actually shifts up/down the observational energy range. One can therefore consider tuning of the orbit: either elliptic orbit or orbit altitude change.

A reasonable baseline would be an elliptical orbit with perigee at 400 km and apogee at 1100 km, taking into account the space environment and the experiment requirements.

A tilting of the apparatus in order to increase the instantaneous geometrical aperture is not required. The effect of tilting was carefully described in [9].

It should be stressed that a free-flyer might allow for repetitive passes above specified locations at the Earth (for observing calibration sources, and, possibly for cross-calibration with the PAO sites).

7.2. Technical Developments: from EUSO to super-EUSO

A number of technological developments are indeed mandatory in order to realize the super-EUSO apparatus, including:

- a deployable catadioptric optics (such that a much larger optics is possible); use of better photo-sensors, such as GAPD, (having much better characteristics than photomultiplier-based sensors, including a better expected total detection efficiency); development of low-power instrumentation (sensors, front-end electronics,...); developement of better optical filters allowing separation of the nitrogen scintillation signal from the almost uniform random night-glow background; lightweight materials with low chromatic aberrations for the transparent components of the optics.

All these technological developments are interesting for many other applications so that funding for R&D as well as spin-off is possible. Moreover these R&D are inside a technological road-map, a fact which will help to push the scientific objectives.

7.3. Expected performance [9]

Provided suitable technologies are successfully developed the following performance parameters can be reached.

Area and instantaneous geometrical aperture (depends on orbit and FoV): \( \approx 0.8 \cdot 10^6 \text{ km}^2 \) observed area (at aphelion); \( \approx 2 \cdot 10^6 \text{ km}^2 \cdot sr \) instantaneous geometrical aperture (at aphelion). The duty cycle is not included as measurements are required to properly estimate it.

Threshold energy depends on the optics entrance pupil and total photo-detector efficiency (PDE). However the optics aperture is the only sizeable parameter, to within the external constraints; the PDE can realistically improve by a factor two or so (it is the only factor much smaller than one); a lot of other factors affect the overall efficiency, but all of them are already close to one.

As a guess-estimate: with \( D \approx 6 \) m and PDE doubled with respect to EUSO one can think to reach \( E \approx 10^{19} \text{ eV} \) with \( \Delta E / E \approx 0.1 \) (statistical error only). But background subtraction is not trivial and must be worked out.

Moreover one can expect \( \Delta \theta \approx 1^\circ \) on the reconstructed primary particle direction, limited by the EAS visible track-length and by the affordable number of channels.

On the basis of the previous reasoning the main super-EUSO baselines parameters and design goals are summarized in table[1].

7.4. Main intrinsic critical issues of space-based observation

The large distance implies that: the signal is faint, angular resolution is not excellent and the transverse extent of the EAS is not observable.

Non-random plus random (night-glow) backgrounds implies that the total background is larger than from ground. This huge background calls for an online subtraction for triggering.

Orbit optimisation should account for: observational energy range, man-made background, atmospheric phenomena and day-night effects as well as the very large drag coefficient of such an apparatus requirign a long lifetime.

Stray-light control with such a large FoV and sensitive apparatus is a critical desing issue.

Atmospheric monitoring is a critical and important item as the observed FoV is continuously changing: a continuous monitoring is needed and parameter recording is required.
### Main Physical Parameters

| Parameter                                      | Value                                                                 |
|-----------------------------------------------|----------------------------------------------------------------------|
| Operating Wavelength Range (WR)               | $330 \text{ nm} \lesssim \lambda \lesssim 400 \text{ nm}$          |
| Background (in WR) at $\approx 750 \text{ km}$ | $(3 \div 15) \cdot 10^{11} \text{ photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ |
| Average atmospheric transmission (in WR)      | $K_{\text{atm}} \gtrsim 0.4$                                        |

### Orbital Parameters

| Parameter                              | Value          |
|----------------------------------------|----------------|
| Orbit perigee                          | $r_p \approx 800 \text{ km}$ |
| Orbit apogee                           | $r_A \approx 1100 \text{ km}$ |
| Orbit inclination                      | $i \approx (50^\circ \div 60^\circ)$ |
| Orbital period                         | $T_0 \approx 100 \text{ min}$ |
| Velocity of the ground track           | $v_{\text{GT}} \approx 7.5 \text{ km/s}$ |
| Pointing and pointing accuracy         | Nadir to within $\Delta \xi \approx 3^\circ$ |

### Satellite Parameters

| Parameter                              | Value           |
|----------------------------------------|-----------------|
| Satellite envelope shape               | Frustum of a cone |
| Diameters                              | $D_{\text{MAX}} \approx 11 \text{ m}$ and $D_{\text{MIN}} \approx 7 \text{ m}$ |
| Length                                 | $L \approx 10 \text{ m}$ |
| Operational Lifetime                   | $(5 \div 10)$ years |

### Main Apparatus Parameters and Requirements

| Parameter                              | Value                                      |
|----------------------------------------|--------------------------------------------|
| Type                                    | Deployable catadioptric system             |
| Main mirror                            | $D_M \approx 11 \text{ m}$                  |
| Entrance pupil and corrector plate     | $D_{\text{EP}} \approx 7 \text{ m}$        |
| Angular granularity                    | $\Delta \ell \approx 0.7 \text{ km at the Earth}$ |
| Optics throughput                      | $\epsilon_{\text{O}} \gtrsim 0.7$         |
| $f$/#                                   | $\approx 0.6$                              |
| Optics spot size diameter on the FS    | $3 \text{ mm} \div 5 \text{ mm}$          |
| Apparatus Field of View (FoV), half-angle: | $\gamma_M \approx 20^\circ \div 25^\circ$ |
| Total length of the optics             | $\approx 9 \text{ m}$                      |
| Focal Surface size (diameter)          | $\approx 4 \text{ m}$                      |
| PDE                                     | $\epsilon_{\text{PDE}} \gtrsim 0.25$      |
| Number of detector channels            | $\approx 1.2$ million                      |
| Size of the pixels on the PD           | $\approx 4 \text{ mm}$                     |
| Photo-Sensor                            | GAPD                                       |
| Power consumption                      | less than $2 \text{ mW per channel}$       |

### Main Performance Parameters and Requirements

| Parameter                              | Value                                      |
|----------------------------------------|--------------------------------------------|
| Low Energy Threshold                   | $E_{\text{th}} \approx 10^{19} \text{ eV}$ |
| Instantaneous geometrical aperture     | $A_G \approx 2.0 \cdot 10^6 \text{ km}^2\text{sr}$ |
| Statistical error on the energy measurement | $\Delta E/E \approx 0.1 @ E \approx 10^{19} \text{ eV}$ |
| Angular resolution on the primary direction | $\Delta \chi \approx (1^\circ \div 5^\circ)$ |
| Observation Duty cycle                 | $\eta \approx (0.1 \div 0.2)$              |

### Main Budgets (at the present level of knowledge)

| Parameter                              | Value                                      |
|----------------------------------------|--------------------------------------------|
| Mass                                   | 5 ton                                      |
| Power                                  | 5 kW                                       |
| Telemetry                              | 20 Gbit/orbit                              |

Table 1: The main super-\textit{EUSO} baselines parameters and design goals.
7.5. Main technological critical issues of space-based observation

The main technological critical issues of space-based observation include: the large deployable optics; optimal stray-light control of the large FoV and highly sensitive apparatus; the architecture, design and engineering of the photo-detector with one million channels (front-end and back-end electronics design and power, trigger design); photo-detector protection from intense light (via attitude control and/or a shutter); data-handling and detector calibration of \( \approx \) one million channels on-orbit; power consumption; mass; the need of a suitable (huge) launcher vehicle; ageing of all the components in the harsh space environment; protection from orbital debris of delicate instrumental parts; engineering issues such as thermal control of the large volumes and surfaces and critical mechanical parts; the need for a high-capacity battery system.

8. A large experiment for the ESA Cosmic Vision program (2015-2025)

One possible opportunity to dream for a large future mission is the ESA Cosmic Vision program (2015-2025). The study of UHECP from space entered the ESA road-map (so many other themes too...).

A new call for missions due for implementation in the period 2015-2025 is expected to go out in 2010. The previous selection (2007) judged the super-\textit{EUSO} proposal a scientifically valuable one but technological readiness was judged very low.

All critical points detected by ESA were well known to the community. They point out that a lot of work is required in order to prepare a new proposal.

9. The road-map and the intermediate steps

The demanding requirements impact on resources. This calls for a careful experiment optimisation in order to collect as much as possible information at a preliminary stage via a well defined road-map with intermediate steps.

In fact the challenging goal of a big space experiment does require intermediate steps, some of which are on the way (JEM-\textit{EUSO} [3]).

Intermediate steps might include: balloon flights to test/measure some low-energy cosmic rays: technological tests via stratospheric airplane flights; support activities, including: scintillation yield and Cherenkov albedo measurements; a couple of small missions on a micro-satellite [10].

9.1. Step 1: background measurement

A detailed measurement/characterisation of the background, on the space-time scales characteristics of the EAS development is required to improve our knowledge of it and possibly exploit it to improve background rejection. A low-cost micro-satellite to characterise the background is a fundamental step to prepare such a mission [11].

Moreover such a micro-satellite would allow the estimation of the duty cycle and measurements to improve the stray light control (by measuring the background far-off nadir).

9.2. Step 2: a technological model

A small technological model for validation of the chosen technologies, later on, would be required in order to: perform functional tests on critical parts of the apparatus (optics deployment not-to-scale, for instance); qualify the observational approach (watching, for instance, laser shots at the Earth); test some technological items.

In the meantime JEM-\textit{EUSO} will provide useful information.

10. Conclusions

It is mandatory to clarify the Scientific objectives for post-PAO experiments.

A space-based apparatus is very challenging, also from the political and financial point of view.

From a technical point of view a space-based apparatus is very challenging, as well.

Only a coordinated effort of the world-wide community of UHECP physicists can hope for success.

Planning, R&D and design should start soon, to cope with the long time-scale required for conception, design and construction.

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