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The Angular Resolution of the JEM-EUSO Mission: an Updated View

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The Extreme Universe Observatory onboard the Japanese Experiment Module (JEM-EUSO) is a mission being developed to observe ultra high energy cosmic rays (UHECRs) from space. JEM-EUSO consists of a wide field of view UV-telescope, assisted by an atmospheric monitoring system, designed to be mounted oboard the International Space Station. JEM-EUSO will observe the extensive air showers (EAS) induced by UHE cosmic particles with energies above 3×10^{19} eV by using the earth's atmosphere as a large detector. Due to the amount of monitored target volume JEM-EUSO is expected to reach an effective aperture of approx. 2×10^5 km^2 sr. During its lifetime, the mission will measure several hundred events with $E > 5 \times 10^{19}$ eV significantly improving the statistics of the most energetic part of the spectrum above the observed cut-off.

In the context of the JEM-EUSO Collaboration different mission profiles are being explored. A configuration actively investigated is a telescope, mainly based on the same technologies already employed in the baseline instrument, which can be launched with the SpaceX Falcon 9 rocket and transported to the ISS by the Dragon spacecraft. This new mission configuration allows a circular design of the optics which improves the performances. In this paper we present a brief study of the expected angular resolution of this new configuration.

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1. The JEM-EUSO Mission

The *Extreme Universe Space Observatory on board the Japanese Experiment Module* (JEM-EUSO) is a space borne UHECR observatory under construction. Currently it is designed to be attached to the International Space Station (ISS) before 2020 [1]. Using the fluorescence technique it will observe EAS generated by UHECR from an altitude of about 400 km. JEM-EUSO will yield a large aperture of approximately $2{\times}10^5$ km^2 sr [2]. Hence, it will improve the statistics in the ultra high energy regime of the cosmic ray spectrum with several hundred events $> 5 \times 10^{19}$ eV [3]. At the same time, its lower energy threshold at 3×10^{19} eV allows for cross-calibration with nowadays UHECR observatories. The main objectives of the mission are to identify the sources and to measure the composition of the cosmic ray flux at highest energies. The planned lifetime of the mission will be 3 + 2 years.

In the development phase of the mission we explore a number of different detector designs and evaluate their specific advantages. The baseline design is a refractive telescope which employs three Fresnel lenses to focus the UV photons on a focal surface detector. This instrument is proposed to be launched by a Japanese H2B rocket and to be transferred to the Japanese module by means of the HTV spacecraft – *JEM-HTV*. The shape of the HTV requires the circular shaped instrument to be cut at two sides. Using ESAF - the *EUSO Simulation and Analysis Framework*[1] [4], we simulate the JEM-EUSO mission and implement different choices for detector designs. One potential alternative to the baseline design is the *JEM-Dragon* design. This completely circular shaped instrument is supposed to be launched by the Falcon rocket of SpaceX. Then it is transferred to the ISS using the Dragon spacecraft.

In the scope of this paper we present this updated instrument design of the JEM-EUSO mission. Using the ESAF package, we evaluate the expected angular resolution of the instrument.

1.1 The Dragon Update

SpaceX is a commercial space contractor [5] and the first private company to deliver supplies to the ISS [6] (Fig. 1). Currently a manned variant of the spacecraft is under development. The Dragon spacecraft of SpaceX has a payload capacity of 6 t. It is combining a pressurized with an unpressurized part. The JEM-EUSO telescope can be stored in the unpressurized section (the Trunk) of the craft. A number of design changes of the telescope arise to comply to the different designs of the Trunk compared to the storage bay of the Japanese HTV.

The baseline instrument has been envisaged with a circular optics having a diameter of 2.65m with the sides cut to fit in the hatch of the HTV. However, the SpaceX Dragon allows for an entirely circular optics design thanks to its annular shape. This would enable us to maintain the same aperture and to decrease the diameter of the optics at the same time. While one advantage is certainly less weight and increased stability, the optics performance is expected to benefit from this design improvement. A second improvement is the attachment of the payload in the Trunk, where the telescope could be fixed at its focal surface end, the most heavy part of the instrument. This improvement leads to less forces imposed on the instrument's tube structure during the launch phase. This saves additional mass [7].

[1]ESAF is a software designed to simulate space based UHECR detectors. It has been developed during the time of the (ESA-)EUSO project

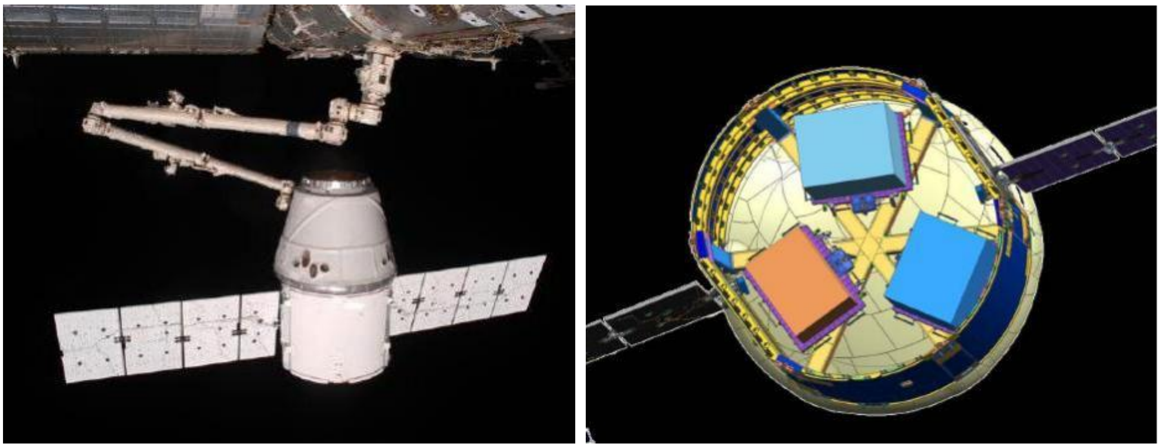

Figure 1: The Dragon spacecraft of SpaceX at the ISS (left) and the unpressurized part of the craft's payload bay (right) [7, and references therein].

In general, payloads transferred with the Dragon are delivered by using the flight releasable attachment mechanism (FRAM). However, since the mass of JEM-EUSO exceeds the capacity of the FRAM, a custom made solution is proposed [7]. The design changes briefly described above lead to a significant reduction of payload mass. At the same time, some design changes are expected to have an impact on the expected performance of the telescope. This refers to changes in the optics as well as in the electronics (Tab. 1). For the new focal surface, we have rearranged some of the

	JEM-EUSO	
	JEM-HTV	JEM-Dragon
Lens dimensions	2650×1900 mm	2500 mm circular
Lens area	4.4 m^2	4.9 m^2
Pixel-angle-map	accordingly	accordingly
Focal surface diameter	2650×1900 mm	2200 mm circular shape
Lens thickness	10 mm	7 mm

Table 1: Key parameter of JEM-HTV and JEM-Dragon simulations [8].

outermost PDMs (Fig. 2).

2. The Dragon Studies

2.1 Signal Behaviour

To assess whether or not the expected angular reconstruction quality reflects any of the instrument's design changes we have to consider the optical components in detail. First of all, the circular FOV is expected to have a more homogeneous throughput efficiency than the side-cut counterpart. To verify this behaviour, we have placed many thousand air showers (Energy = 10^{20}, $\Theta = 60^{\circ}$) as standard candles inside the FOV of the telescope. From each of the showers we compare the number of photons arriving at the entrance pupil of the telescope, reaching the focal surface and

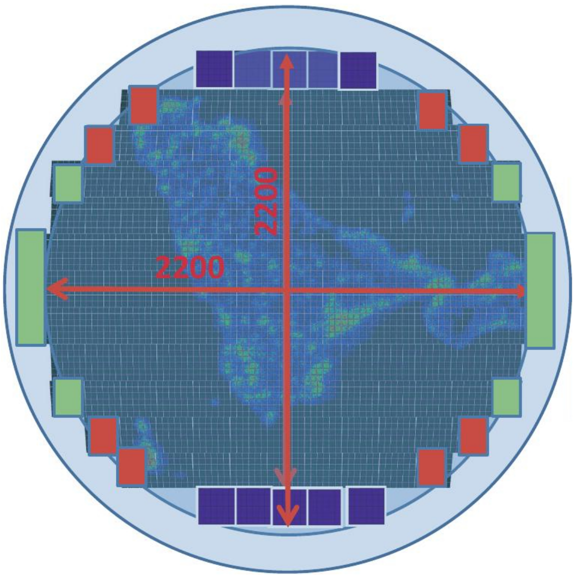

Figure 2: The focal surface of JEM-EUSO in the circular configuration [8]. Some of the outermost PDMs have been reassembled (green into blue).

eventually create a signal in the readout electronics. A very relevant number to compare in between the two different designs are the ratios between the number of photons crossing the focal surface and the ones coming to the first lens of the telescope — the throughput efficiency. (Fig. 3) In the centre, the throughput efficiency yields about 0.3 for both detector variants, while at the outer parts of the field of view, the ratio drops down to about 0.15 - 0.2. Since the number of photons per shower is vital for the event reconstruction accuracy, we try to design the telescope as efficient as possible keeping the mind the optical system as the major contribution.

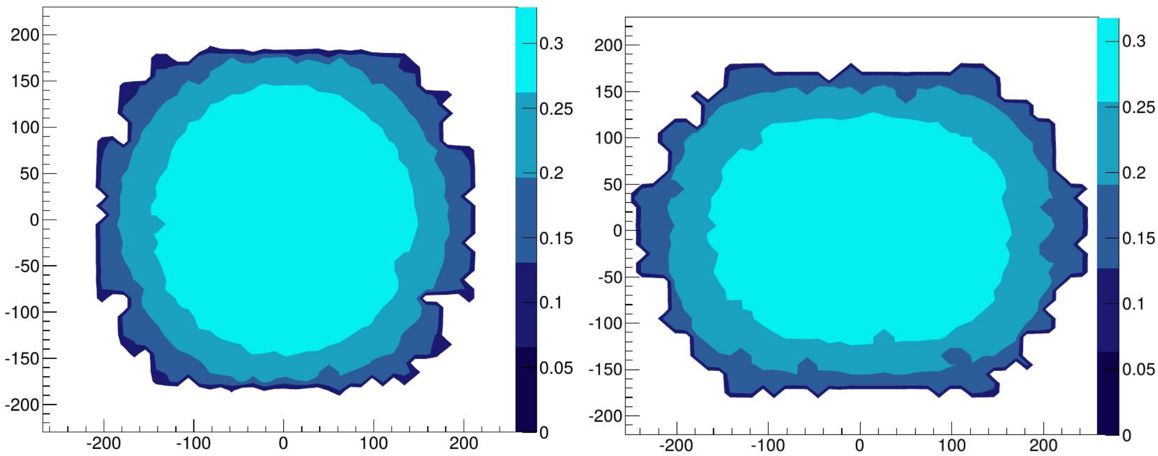

Figure 3: Comparison of the optics throughput efficiency of the JEM-Dragon instrument (left) and the JEM-HTV design (right).

Changing the side-cut design to a purely circular shape obviously changes the pattern how the observed events appear in the FOV. Even though the total amount of events observed remains constant, on average they now appear closer to the nadir point of the detector.

2.2 Angular Resolution

To study the angular resolution performance of both detector set-ups we have simulated and reconstructed a collection of UHECR event within the field of view of the telescope. We have limited ourselves to pure proton induced events. The zenith angles of the incoming cosmic rays are set to 30°, 45°, 60° and 75°, whereas the Φ directions of the showers are randomly distributed between 0 and 360°. The events have fixed energies of 5×10^{19} eV, 7×10^{19} eV, 1×10^{20} eV, 3×10^{20} eV and 10^{21} eV for the JEM-HTV version. (Fig. 4) The air showers have been injected within a rectangular area of x: $\pm$ 270 km $\times$ y: $\pm$ 190 km. In the JEM-Dragon set-up we have replaced the highest

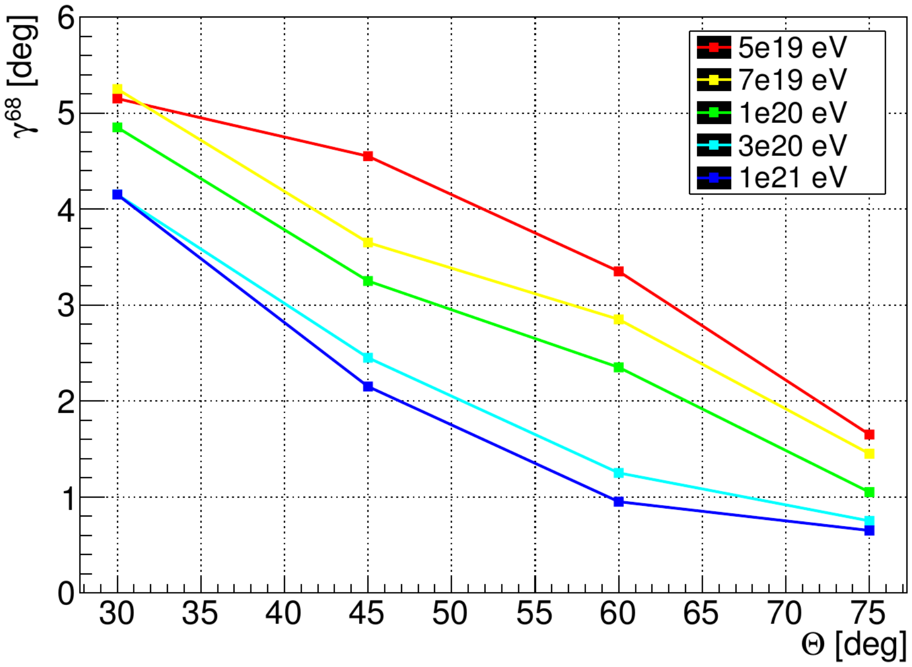

Figure 4: The angular resolution of the JEM-HTV instrument [9]. γ denotes the angle between the true and the reconstructed direction. γ^{68} indicates the cumulative distribution.

energy 10^{21} eV by 5×10^{20} eV. (Fig. 5) Here, all air showers have been injected within a square of x: $\pm$ 240 km $\times$ y: $\pm$ 240 km.

When we compare the obtained angular resolution of the JEM-Dragon we can confirm a clear improvement with respect to the JEM-HTV detector (Fig. 5). For the 75° case and higher we cannot observe any improvement compared to the side-cut instrument. For all lower zenith angles we can see a strong improvement of the resolution. It must be noted that especially at low energies the reconstruction efficiency remains at about 50 %, whereas in the other configurations about 80 % of the events are reconstructed successfully. Especially the higher energies benefit more than a factor of 2, but also the lower energies gain between 1° and 1.5° in resolution.

We have applied different angular reconstruction methods (AA1, AA2, NE1,NE2,AE1)[2] and checked the performance of the individual Θ and Φ determination. We can confirm that all of the

[2] for details on the algorithms please refer to [9, and references therein]

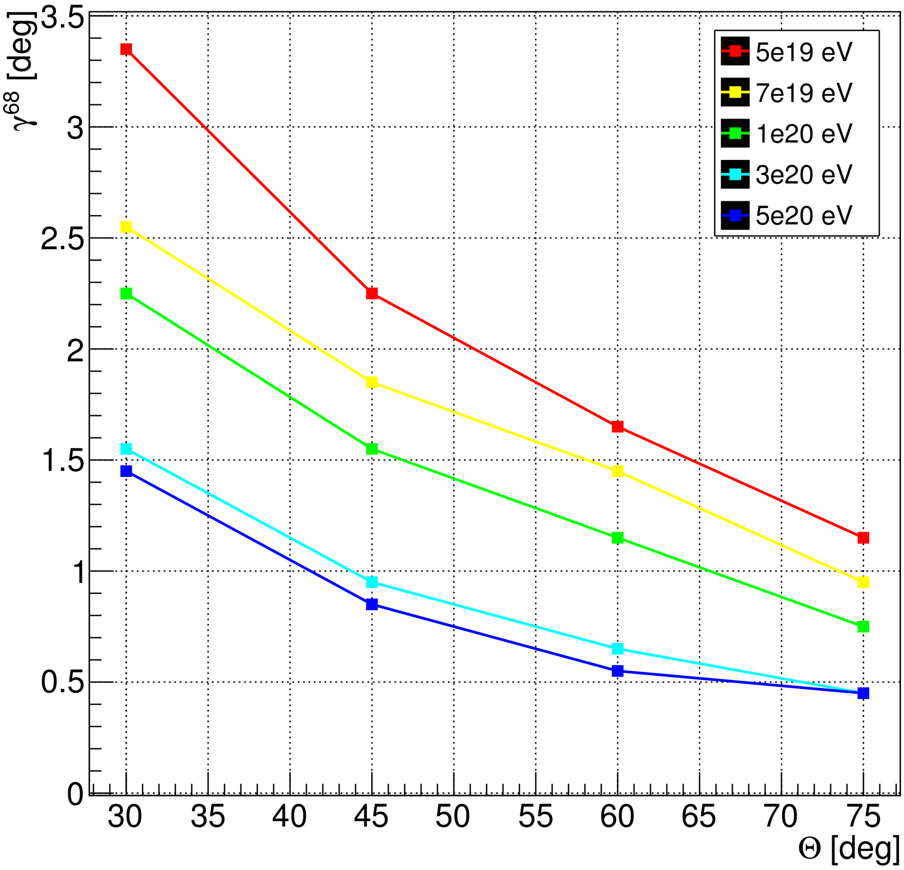

Figure 5: The angular resolution of the JEM-Dragon instrument [9]. γ denotes the angle between the true and the reconstructed direction. γ^{68} indicates the cumulative distribution.

single algorithms agree to a good extent in their angular determination and the errors are small. (Fig. 6)

3. Conclusion and Outlook

The JEM-EUSO instrument in the circular JEM-Dragon version yields an improved and satisfactory resolution compared to the JEM-HTV instrument (side-cut). It delivers at least the same or better performance as the baseline instrument in the central part of its field of view. At the same time it does not see those events (harder to reconstruct) occurring in the outer FOV parts of JEM-HTV. This behaviour is not surprising since the new geometry of the field of view bears several advantages. The distance of the air shower to the telescope can be regarded as the main factor determining the angular resolution performance. The circular JEM-Dragon observes events which on average occur closer to the detector compared to the JEM-HTV (Fig. 3). Hence, its significantly higher reconstruction quality benefits in a threefold way.

At first, due to the purely geometrical factor the number of photons from a air shower diminishes by a factor of 1/distance^2. Thus, the more distant a shower appears to the detector, the less photons arrive at all to the telescope. Secondly, the optics throughput efficiency is higher for the

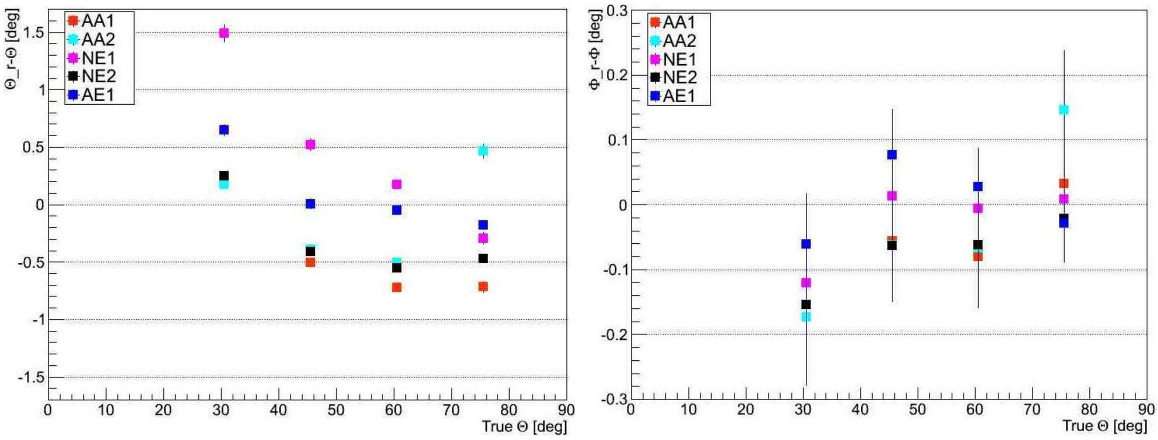

Figure 6: JEM-Dragon: reconstructed $\langle\Delta\Theta\rangle$ (left) and $\langle\Delta\Phi\rangle$ distributions (right) for cumulative energies [9]. The colours represent the five different algorithms to show their individual performance. The error bars indicate the standard deviations.

events closer to the nadir point. Now, events that appear brighter already due to the shower-detector geometry are less attenuated or defocussed due to the lenses. And third, showers far out in the FOV are observed by pixels whose projection on ground is much larger than the ones of their counterparts in the centre of the FOV. Of course, the resolution of the shower image on the focal surface is the base for any reconstruction algorithm applied. Moreover, in a circular field of view, showers are less likely to touch the border of the FOV, since the ratio of surface to circumference is optimal.

Altogether, we can conclude that in the new detector design showers appear brighter and with a better resolution on the focal surface. Hence, the the pattern recognition as well as the angular reconstruction algorithms can perform better in comparison to the side cut instrument.

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