Free-flying JEM-EUSO precursor utilizing the InnoSat platform

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Abstract

The JEM-EUSO collaboration is working towards putting a large field of view telescope into orbit to search for the elusive EECRs to identify the origin of such energetic particles. Originally JEM-EUSO was planned to be mounted on the ISS, though given the current lifetime of the space station ending in 2024 there is little possibility that this will be achieved. Therefore, the possibility of using a free-flying satellite for the telescope is becoming more interesting. For the collaboration to reach such a goal at least one pathfinder mission is required. For this reason, the Swedish InnoSat platform, developed by OHB Sweden, has been reviewed as a candidate for such a mission. The findings show that even though small changes to the telescope design can make the scientific case for a Mini-EUSO sized telescope significantly stronger, the mass of such a telescope will most likely be too high for what the InnoSat platform can accommodate.

Keywords: JEM-EUSO, Space Observation, Cosmic Rays, EECR, ISS

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The goal of the JEM-EUSO collaboration [1] has, for a long time, been to place a high resolution, fast, and large field of view telescope in Earth orbit in search of the UV signal generated in the atmosphere when cosmic rays interact with the air molecules during the propagation of an air shower. The aim of the experiment is to identify the origin of the highest energy cosmic rays, events exceeding energies of 1020 eV (or 100 EeV). Such events are usually referred to as Extremely Energetic Cosmic Rays, EECR. One of the main design principles has for a long time been the utilization of Fresnel lenses. The JEM-EUSO collaboration hopes thereby to be able to combine large field of view optics with high photon collection capabilities, and at the same time keeping the total mass of the lens system, and thus the telescope, at bay.

The InnoSat is a highly flexible satellite platform provided by OHB Sweden and ÅAC Microtec. The design of the InnoSat is such that it is classified as a micro-range satellite i.e. in the 10-100 kg range. The platform also allows for three-axis stabilization and high power and downlink capabilities. All of which are crucial for a mission of JEM-EUSO type.

This report will summarize the current status of the JEM-EUSO project as well as exploring the possibilities of utilizing an InnoSat platform for a free-flying JEM-EUSO precursor.

Background

The JEM-EUSO collaboration is currently in the process of completing two pathfinder missions as part of the roadmap to reach the goal of placing a large field of view telescope in orbit around Earth. Key parameters in the design of such a telescope are high photon collection efficiency and large field of view, in order to be able to detect the UV signature of air showers occurring when the rare high energy cosmic rays interact in the atmosphere.

Since the experimental discovery of the cosmic rays in 1912 by Victor Hess [2] a lot of research has been dedicated to the study of cosmic rays. Today we have a good understanding of the energy dependent incoming flux of cosmic rays hitting the earth. This can be seen in Figure 1, where data on the measure flux as a function of energy of the incoming particle has been plotted for several different experiments [3]. In addition, the rate of incoming particles at some energies have also been noted. As one can see already at around 4x1019 eV the rate of incoming cosmic rays is of the order 1 particle/km2/100 years. This highlights the intrinsic difficulty in studying these highest energy particles.

The impinging cosmic rays are nuclei, ranging from protons to iron and beyond. As such they are positively charged and hence, their trajectories in space are affected by magnetic fields through Lorentz forces. Therefore, the origin of cosmic rays cannot be determined by extrapolated a straight line back into space from the direction of the propagating air shower, as can be done for a neutrally charged particle. However, at the highest energies, around 1020 eV and above, the kinetic energy of the incoming particle is high enough that the effect of the magnetic fields in space are small enough that the origin of the particle can be extrapolated like for a neutral particle. The effect of the inter-galactic magnetic field for charged particles at different orders energies is presented in Figure 2.

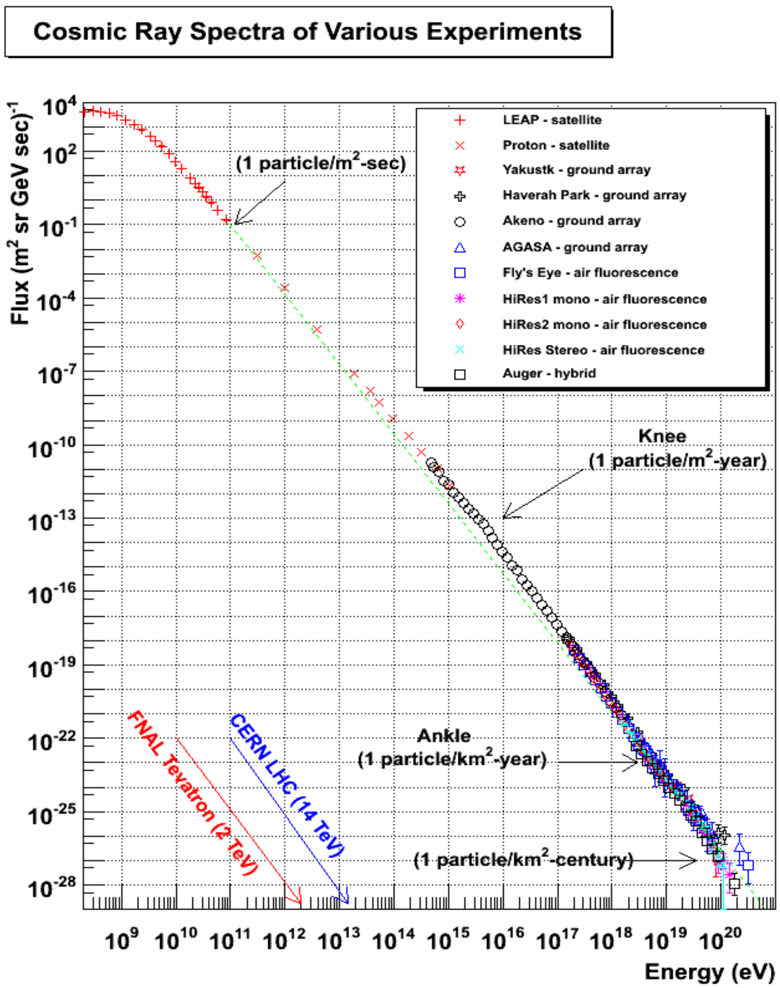


Figure 1 The flux of incoming cosmic rays as a function of the energy

Currently there are two telescopes in operation studying the energy range above 1019 eV; Telescope Array [4] in the desert of Utah in the USA and the Pierre Auger Observatory [5] in Argentina. Employing different techniques, both observatories use a combination of surface detectors and specially dedicated fluorescence telescopes. The fluorescent light is produce as a final result when nitrogen de-excites, after having been given the extra energy by the particles produced in the air shower by the incoming cosmic ray particle. The use of this technique is difficult since the amount of light produced is limited and therefor very strict observational criteria have to be met. Moon phase, cloud coverage, and aerosol contamination are some prominent issues which can reduce the effective observational time. This results in a rather low duty cycle of these ground-based telescopes, of the order 10%.

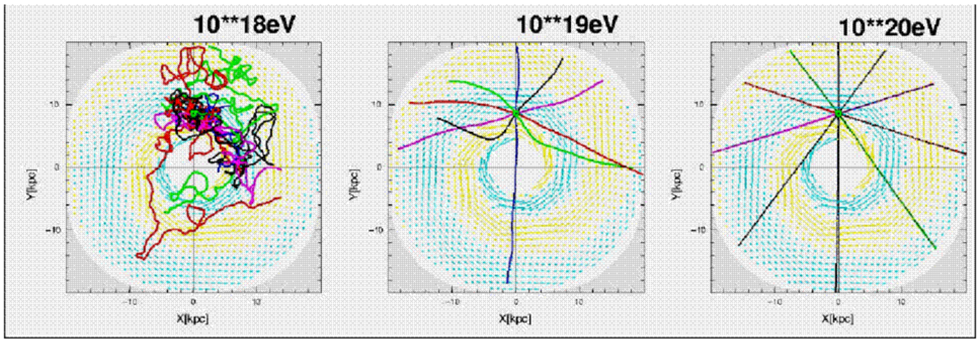


Figure 2 Simulations of how cosmic rays trajectories at different energies are affected by intergalactic magnetic field. At 10^20 eV the particles are more or less un-affected and extrapolated trajectories into space from arrival directions points towards origin.

Yet another limiting factor, which in recent years has gained a lot of importance, is the sky coverage of the telescope. Since the Auger observatory is in the southern hemisphere and the Telescope Array site is in the northern hemisphere, combined they achieve full sky coverage. However, recent results from the separate experiments have shown a discrepancy between the two telescopes as to the flux of cosmic ray particles at the highest energies [6]. It has not yet

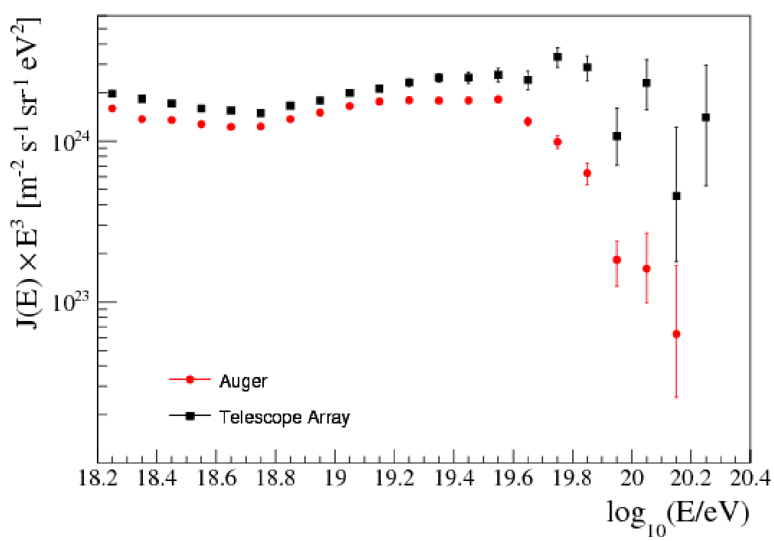


Figure 3 Comparison of the measure incoming flux of cosmic rays by Telescope Array (black) and Pierre Auger observatory (Red)

been determined if this is due to calibration, detector technique difference, or if there actually is a difference in the flux of particles reaching the northern hemisphere compared to the southern hemisphere. A comparison of the measure fluxes by the two experiments are presented in Figure 3.

By launching a telescope into orbit around the earth one would not only be able to observe a much larger part of the atmosphere compared to the ground based telescopes, this can be seen in Figure X, where the observation areas for JEM-EUSO is compared to Auger and other experiments. In addition, the problem of cloud coverage would be mitigated. In addition to this, a telescope orbiting the earth would achieve full sky coverage and thereby be able to answer the question of apparent difference in flux seen in the different hemispheres.

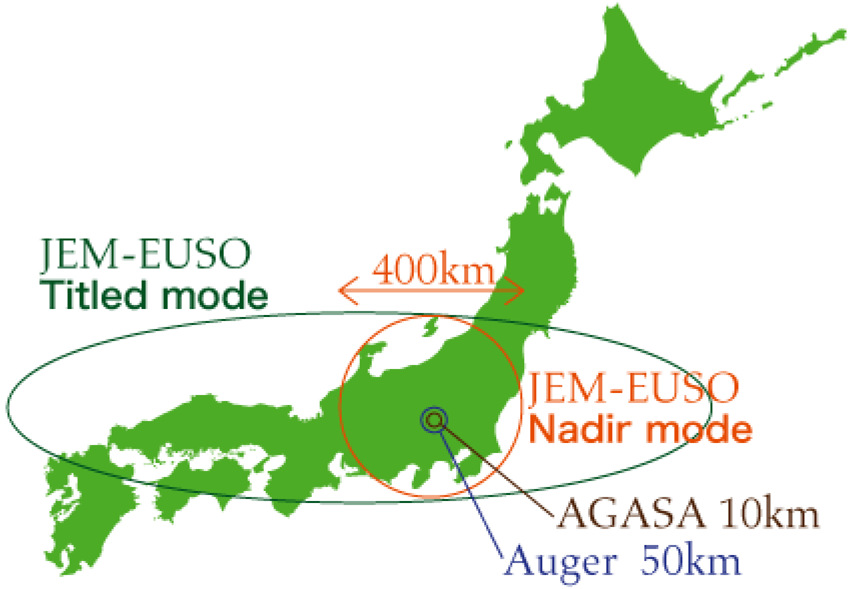


Figure 4 Observation area of the Auger telescope (Blue ring) and JEM-EUSO in Nadir (Red) and Tilted mode (Green)

Current status of the JEM-EUSO collaboration

The main goal of the JEM-EUSO collaboration is to place a large field-of-view telescope with a high photon collection capability in orbit to observe air showers produced by the highest energy cosmic rays. In doing so the data collected will be able to shed light on acceleration origins of the cosmic rays, nuclei composition, and test the GZK-cutoff, but also provide extensive data on atmospheric events, bio-luminesces, strange quark matter and more.

In order to reach this goal a detailed roadmap has been produced containing several pathfinder experiments in order to, step by step, increase the technological readiness level of the collaboration as well as proving the detection principle of the proposed design of the telescope. These pathfinder experiments include both ground-based as well as air and space borne experiments.

EUSO-Balloon

In September of 2014 a short test flight of the first JEM-EUSO hardware was performed in Timmins in Canada. The flight hardware consisted of two Fresnel lenses and a single PDM, photon detection module. A single PDM contains 9 elementary cells, ECs, and each EC consists of 4 Hamamatsu multi-anode photomultiplier tubes, MAPMT. Each MAPMT is in turn divided into 64 pixels. This sums to 36 MAPMTs in a PDM with a total of 2304 pixels. This hardware hierarchy is depicted in Figure 5. While EUSO-Balloon carried a single PDM the design of the main instrument includes a total of 137 PDMs, totaling more than 315 000 pixles.

Given the short flight time (about 6 h) and the low-end energy threshold of the telescope no cosmic ray events were expected to be seen. Therefore, a helicopter had been specially fitted both with a high-powered UV laser as well as a Xenon flasher. The helicopter trailed the balloon, flying in circles underneath firing both the laser and the Xenon flasher when in view of the telescope aloft.

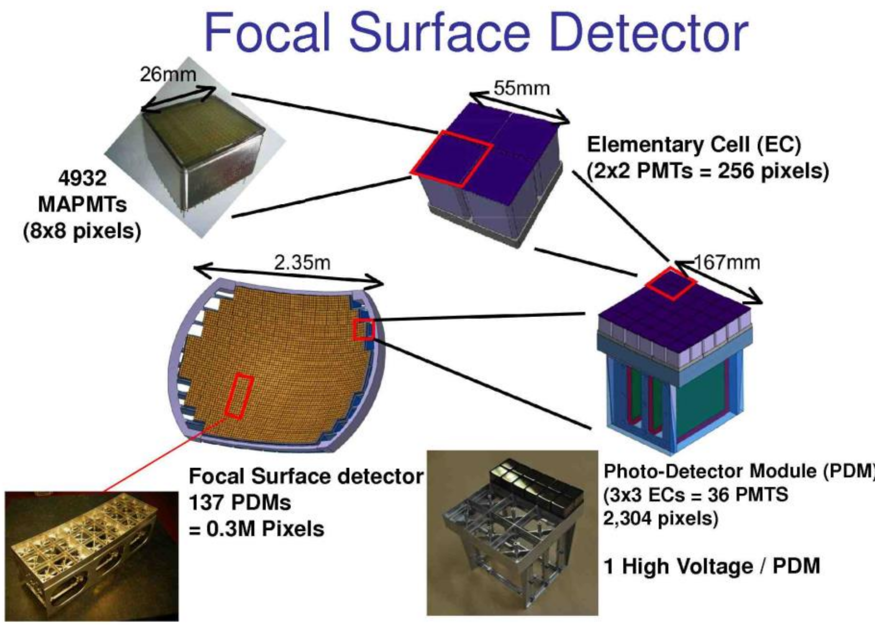


Figure 5 The breakdown of the JEM-EUSO focal surface into PDM, EC, and MAPMTs

EUSO-TA

In parallel to the EUSO-Balloon flight, a permanent test set-up of a single PDM behind a two Fresnel lens configuration had been constructed at the Telescope Array site: Black Rock Mesa, south-west of Delta in the state of Utah. Since March of 2015 observations campaigns have periodically been hosted at the site. In addition to observation of cosmic ray events, the test set-up has proven the capability to observe meteors and meteorites, as well as airplanes. Combined with observational campaigns, test campaigns have also been performed to evaluating different subsystems, such as trigger algorithms as well as sensitivity tests using the high-powered UV laser, and flat-fielding.

The EUSO-TA site constructed such that the field of view of it is covered by the field of view of the Black Rock Mesa Florescent Detector. This allows for comparison of energy calibration of events observed by both telescopes.

EUSO-SPB

EUSO Super Pressurized Balloon (SPB) was a balloon mission in corporation with NASA to fly a single PDM with dual 1 m diameter Fresnel lens setup for a long duration mission, order of 100 days. The flight would launch from Wanaka in New Zeeland and the payload was hoped to circumnavigate the south pole at least once. In contrast with the Timmins flight the EUSO-SPB flight will show that the instrument is capable of autonomous and long duration operations and will capture the first data of ultra-high energy cosmic rays from above.

EUSO-SPB was launched from Wanaka on 24 April. However, due to technical issues experienced by the balloon – not the instrument – the flight terminated on 7 May with an unfortunate splash-down in the middle of the Pacific Ocean. This also, unfortunately, resulted in the loss of the instrument. Data analysis is however ongoing since data was transmitted to ground during the flight. A second EUSO-SPB flight is now in planning.

Mini-EUSO

Mini-EUSO is currently the final single-PDM telescope scheduled in the roadmap. It is also fitted with two Fresnel lenses, though these lenses are much smaller, with a diameter of 25 cm. All in all, Mini-EUSO will measure about 30x30x60 cm^3. This small size is due to the fact that the Mini-EUSO telescope will be launched to the International Space Station (ISS), on a Progress resupply mission, to be placed inside the Russian section of the station. In the Zvezda module there is a UV-transparent window where the telescope will be mounted for observations, window number 9 in Figure 6. The inset in the figure shows a previous experiment mounted at the same window.

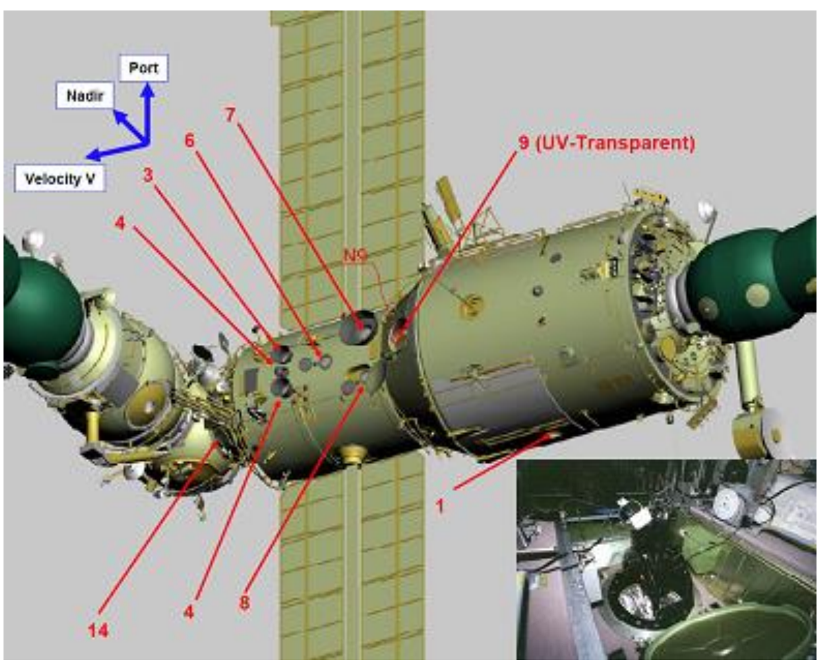


Figure 6 Window number 9 is the UV-transparent window on the Zvezda module of the ISS. The inset shows the Relax experiment, previously mounted at the same window.

In addition to raising the technological readiness level of the collaboration, the Mini-EUSO telescope will be able to produce detailed UV-maps of different regions of the earth, with a resolution at ground level of 5x5 km2/pixel. This will be a vital step in the preparation of the launch of the main, or larger sized, telescope.

However, due to the design of Mini-EUSO, it is highly unlikely to detect air showers from cosmic rays. Even so, Mini-EUSO will provide a lot of data for different fields of research, such as Bioluminesces, Meteoroid observations, Atmospheric events such as Elves and Sprites, and Debris tracking. In addition, the Mini-EUSO mission will be able to assess, in-situ, the performance of the different triggering algorithms which have been developed by the collaboration. Different trigger levels are used for different types of events.

The reason Mini-EUSO is unlikely to detect cosmic rays is due to the size of its aperture, which, among other parameters, affects the lower threshold of detectable cosmic rays. Therefore, with a 25 cm diameter of the photon collection area, the energy of the cosmic ray hitting the atmosphere has to exceed 1021 eV, something yet to be observed. However, such an event can be simulated using a ground-based high-powered UV laser firing into the sky as the ISS passes by.

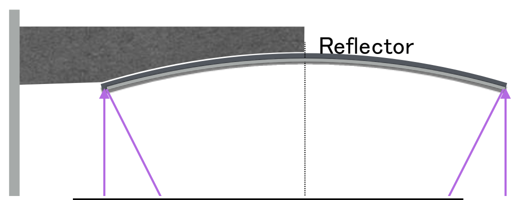
Mini-EUSO will also make pioneering detection trials of orbital debris. The JEM-EUSO collaboration intends to perform orbital debris remediation by combining the full scale telescope with a high-powered CAN laser system to both track the debris and fire laser pulses at it in order to de-orbit the debris through atomic ablation. A ground based laser is planned to be use to illuminate orbital debris and allow for Mini-EUSO to track.

The launch of Mini-EUSO is scheduled for December 2018. With the launch of Mini-EUSO to the ISS the JEM-EUSO collaboration will take its first steps into space.

K-EUSO

Klypve, or K-EUSO, is an intermediate step between Mini-EUSO and the full sized JEM-ESUO telescope. It will consist of a focal surface of 54 PDMs, totaling in over 120 000 pixels, and thereby increasing the ground resolution to between 500 and 750 m2/pixel. The design of the photon collection system has been of a slightly different design than the other precursor missions of the JEM-ESUO collaboration. As seen in Figure 7, the telescope consists of a large reflective mirror focusing the photons onto a corrective Fresnel lens, which in turn focused the photons onto the focal surface. The whole construction would be placed on the outside of the space station as seen in Figure 8.

However, during the course of the collaboration's efforts to compile an application for the ESA Medium sized mission call number 5 (ESA M5), questions regarding the actual proficiency of Fresnel lenses for the collaboration's purpose arose. These uncertainties propagated



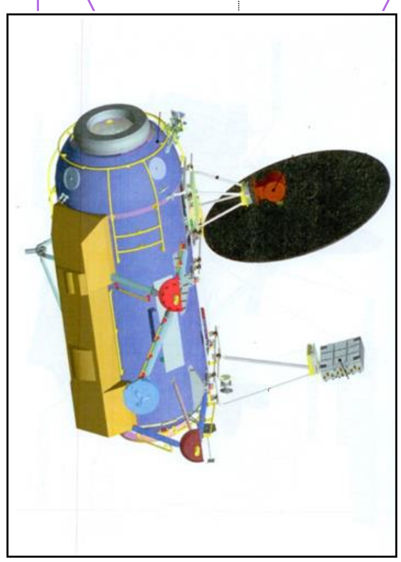


Figure 8 Schematics of the mounting of K-EUSO on the outside of the ISS

throughout the collaboration to such extent that the decision to reevaluate the design principle of the K-EUSO mission was made. As a result of this, a new design of K-EUSO has been proposed and accepted by the collaboration. K-EUSO no longer relies on the Fresnel lens design but on a traditional Schmidt telescope design, seen in Figure 9.

Studies have shown that the new Schmidt type design can give the same performance as the old design, which utilized the Fresnel lens, and as of the 20th collaboration meeting, held in December 2016, the collaboration has now decided to adopt the new design for the K-EUSO mission. During the same collaboration meeting the tentative schedule for the revised K-EUSO telescope was discussed. The current view of Russia is that a launch of such a telescope to the ISS will not be plausible earlier than late 2022 or early 2023.

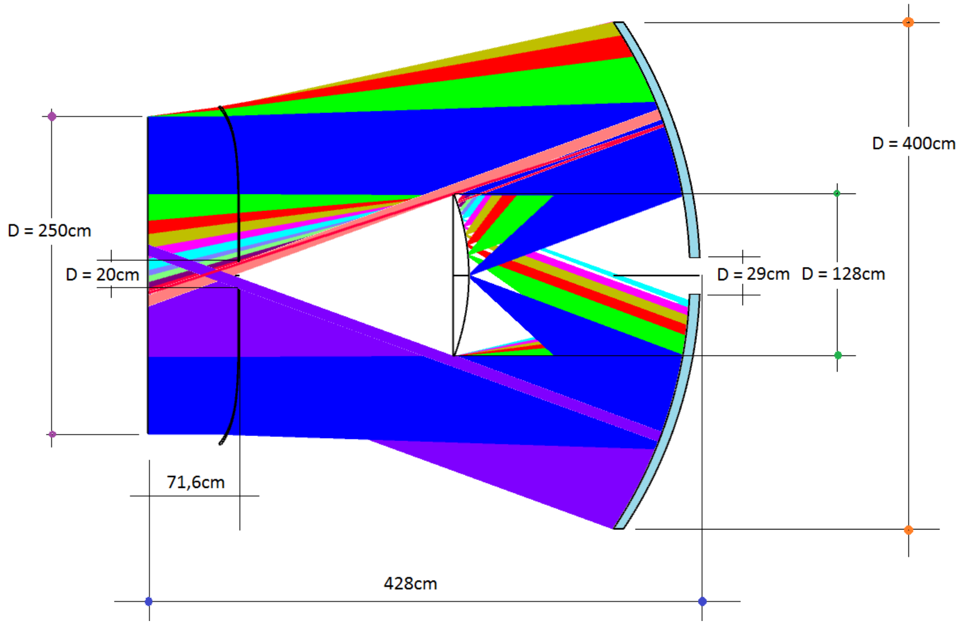


Figure 9 Schematic of the Schmidt telescope design of K-EUSO.

JEM-EUSO telescope

The initial design of the full sized JEM-EUSO telescope included a focal surface of over 130 PDMs, thereby giving it more than 300 000 pixels and a ground resolution of 500x500 m^2/pixel, two Fresnel lenses set up, and field of view of +/- 30 deg. The design also allows for tilting of the telescope from the nadir mode and thereby increasing the total field of view by a factor 2-3.

The future shape of a large field of view high resolution UV-telescope is currently in an undefined state. For several years the aim has been to mount such a telescope on the International Space Station, and once onboard perform observations for at least 5 years in order to acquire data to surpass the accumulated data by Telescope Array and the Pierre Auger Observatory. However, the delay of the JEM-EUSO telescope in combination with the current life time of the ISS, set to end in 2024, it is now an open question if there is time enough to ready the telescope, launch it to the ISS, and have enough observational time to exceed the ground based telescopes. Therefor the collaboration has recently started looking at other options to accommodate a full scale JEM-ESUO telescope. One possible option is to launch the telescope on a dedicated, free-flying mission. A dedicated satellite for the telescope would also give the collaboration the freedom to select orbital parameters most beneficial for the scientific mission. This would also give the collaboration time to develop, launch, and observe with K-EUSO from the ISS.

Future of the JEM-EUSO collaboration

That the need exists for a large field of view telescope in orbit is clear. This in order to be able to collect enough data to statistically be able to determining the origin(s) of the elusive EECRs. It has also recently been shown that full sky coverage is important to distinguish the apparent north/south hemisphere flux difference. And such coverage is only achievable through orbital observations.

With the time plan of K-EUSO being launched to the ISS in 2022/2023 and the retirement of the ISS in 2024, maybe 2028 is it reasonable to assume that K-EUSO will be the last of the JEM-EUSO collaboration's telescopes to be mounted on the space station. Any future planned telescopes, beyond K-EUSO, will have to be considered for a free-flying mission. Such a launch could, however, probably occur in 2030, by the earliest. In preparation for such a mission at least one free-flying precursor mission would be desirable. For such a precursor, technologies such as foldable optics, deployment mechanisms, and improved electronic detection systems (i.e. silicon photomultipliers) would be able to be fully tested and evaluated.

The InnoSat platform

In February of 2015 OHB Sweden and ÅAC Microtec announced that they will be providing a low cost satellite platform for micro-sized missions i.e. total mass of 10-100 kg primarily aimed at scientific missions. The InnoSat satellite platform has been designed with the intent to maximize the usage of the available launcher volume in a piggyback launch opportunity. A market with potential. During the Horizon 2020 project INVEST it was concluded that a lot of the total available launch mass goes unused. In some cases, as much as 50% was not utilised [7]. The Swedish satellite MATS [8], aiming to study Mesospheric Airglow and Aerosol Tomography and Spectroscopy, will be the first operational test of the platform. Currently the launch of MATS is scheduled for 2019. Some key parameters of the InnoSat platform are presented in Table 1.

Table 1: Parameters of the InnoSat platform

Parameter	Value
Max payload size	65x53x48 cm^3
Max payload mass	15 kg
Max payload power	40 W
Downlink	3-5 Mbit (S-band)
Stabilization	3-axis
Orbital determination	On-board GPS
Pointing mode	Earth-, Limb-, or Space-facing

Alternative candidate

Given the relatively low weight constriction of 15 kg for the for the payload mass on an InnoSat platform it is doubtful that it would be feasible to design a Mini-EUSO sized instrument to meet such requirement. Alternative candidates, offered by Surry Satellite Technologies Limited, could be the SSTL-50 or SSTL-100 provided. The SSTL-50 has a payload mass range of 25-80 kg and the SSTL-100 has a mass range of 80-140 kg.

Airbus Defense and Space provides the satellite platform AstroBus XS with a typical payload mass capcaity of less than 70 kg. Test flying during 2017 is the AstroBus S with a payload mass capacity of 150 kg and in contrast to previous three platforms, it offers a lifetime of 10 years instead of 5 years.

In light of recent developments, such a micro-sized platform could provide a valuable opportunity for the JEM-EUSO collaboration.

Even though there is a possibility that the partners in the ISS collaboration (NASA, Roscosmos, JAXA, ESA, and Canada) will come to an agreement to prolong the lifetime of the station until 2028 and given that the current schedule of the JEM-EUSO collaboration will not be compatible with a time limit set at 2024, relying on a further extension of ISS should be considered a too big of a gamble. Therefore, the most likely future of JEM-EUSO is to be mounted on board a free flying satellite. However, this is yet another huge step, technology wise, to take. Hence, at least one additional precursor mission is needed. This is where the InnoSat platform provides a possibility for a dedicated mission.

The basic principle of the mission would be to mount a Mini-EUSO sized telescope, retrofitted with new technologies, on the satellite platform and launch as a piggy-back mission. Such a mission would not only give the collaboration opportunity to select an optimized orbit (providing the availability of piggy-back options), test a new design of the telescope incorporating foldable optics, it would also give the collaboration extremely valuable experience in operating a telescope on a free-flying platform.

Observational criteria

The main observational constriction for observing air showers can be broken down into two categories; background light pollution, and photon collection capability and efficiency. The background light pollution can, in turn, be divided into three main contributions; scattered stray light from the sun, lunar reflected light, and contamination from source on the surface (which includes cities, biological, and naturally occurring emissions in the UV-range). The light collection capability and efficiency is, however, dependent on a multitude of factors, such as orbital height, lens size, and transmittance of the lens material, electronics performance, and quantum efficiencies to name a few.

The following section will cover the basics of how these factors affect the detection capabilities of a JEM-EUSO type telescope in orbit.

Background light pollution

The signal from the fluorescent light from an air shower is very faint and therefor even a small amount of stray light can saturate the detector and thereby hiding the true signal.

Scattered sunlight

The sun is the main contributor to the background and thus measurements can only be performed when the telescope is observing parts of the atmosphere which is totally in the shadow of the sun, i.e. in the Umbra region as seen in Figure 10.
Recent results using the Amon detector have shown that the acceptable levels of background light, measured at ground level, will not be reached until the sun zenith angle is around 15 to 20

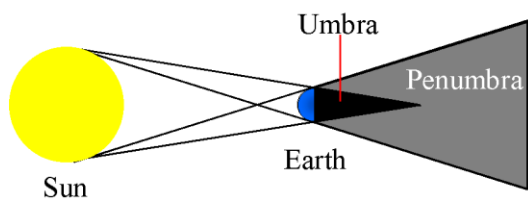


Figure 10 Diagram of the umbra and penumbra regions as a result of the shadow behind the earth.

degrees below the horizon. The Amon measurement data can be seen in Figure 11 [9] as the small red diamonds.

Computer simulations using the libRADtran software [10] have been performed and the simulation results, large blue and green diamonds, are also found in Figure 11. The simulation results are in agreement with the measured data. These results imply that measurements from an ISS-type orbit (approx. 90 min/rev) cannot be performed sooner than approximately 5 minutes after the telescope has passed the terminator, assuming right angle crossing.

Some sunlight sensitive instruments benefits from been flown on sun-synchronous orbits where the orbital plane is close to, or, parallel with the terminator, i.e. a dusk/dawn orbit. However, both the simulated and measured results of the Amon detector highlights the problematics of having a dusk/dawn-type of orbit for a JEM-EUSO type telescope. Therefore, a more desirable orbit would be one in which the satellite spends as much time as possible in the shadow of the earth, and traverses the terminator as close to 90 degrees as possible, in order to reach the observational conditions as fast as possible.

Moonlight

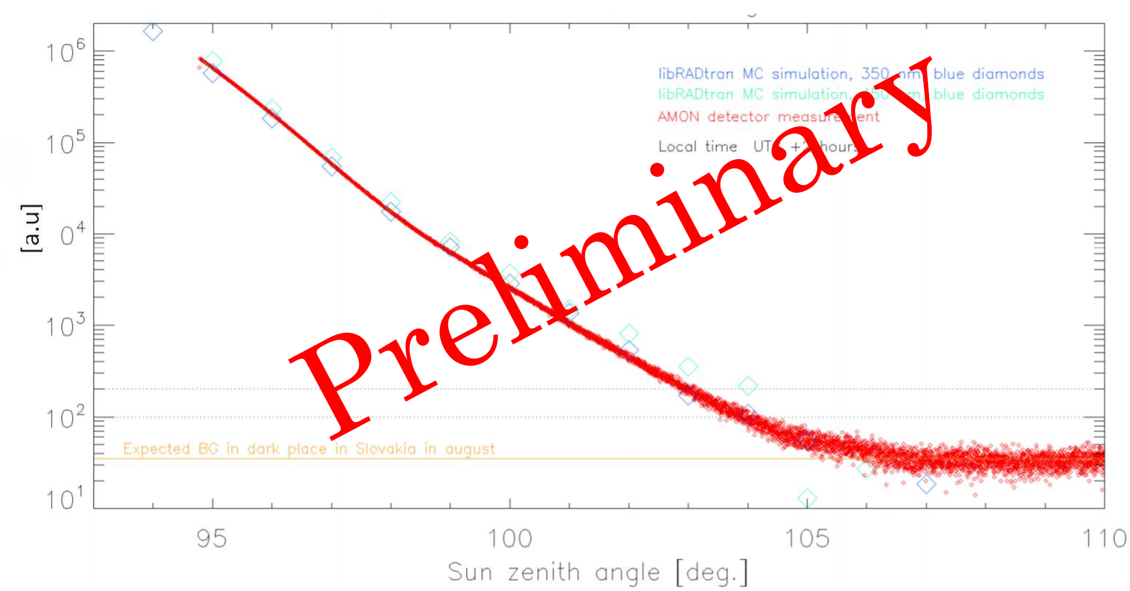


Figure 11 Measured UV background from scattered sunlight as a function of the sun's zenith angle. Diamonds represents simulated values. From Ref. [9]

A second source of light pollution is the Moon phase. The moon phase is, however, predictable and can thus be taken into account into the overall duty cycle of the telescope. Nevertheless, the amount of reflected light depends on additional factors such as ground type (dirt, ice, water etc.) and also on weather conditions such as high/low clouds, fog, clear skies etc.

Additional sources of background are bio-luminescence, and bright lite areas of the earth, both urban and naturally occurring sources of UV-range light. Unfortunately, contrary to the moon phase, these parameters are difficult to accurately take into account during orbital selection and are therefore estimated and included in the efficiency of the duty cycle of the telescope. This is, however, something which the precursor; Mini-EUSO, aims to shed light on by producing UV background maps of the earth for different Moon phases and weather conditions.

Photon Collection Capability

The photon collection capability of the instrument is slightly more convoluted. This depends on multiple parameters, such as observational altitude, lens size, instrumentational efficiency etc.

Orbital Altitude

The fluorescent light produced during the air shower is emitted omnidirectional. Therefore, the number of photons arriving at the telescope is inversely proportional to the distance squared. This is one of the driving parameters for the low end cut-off energy in the detectable energy range of the telescope. This range-dependent detection threshold also gives a radial detection efficiency component. Since the altitude gives the detection efficiency in nadir the radial detection efficiency falls as tan2(α), where α is the angle from nadir to the air shower. For a telescope of JEM-EUSO specifications, with an opening angle of 30 degrees, the incoming cosmic ray has to have three times the energy in the peripheral of the observation area as compared to nadir in order for enough fluorescent light to reach the telescope.

Thus, the orbital altitude is a double-edged sword in the sense that a higher altitude gives a larger footprint area for the telescope and thus larger area-time exposure. Though, at the same time the higher altitude also reduces the number of photons arriving at the telescope.

In addition, given a higher orbital altitude the time spent in the umbra cone will be reduced. However, since this effect will be very small it can be neglected for this case.

Lens size

To compensate for the loss of incoming photons due to the inverse square law, the diameter of the collection area of the telescope can be increased. For the large scale JEM-EUSO the lens diameter is about 2.5 m. With this diameter and an altitude of about 400 km the low-end energy cut-off is just above 1019 eV. The possibility of creating and launching larger sized, single element lenses, is currently up for discussion within the JEM-EUSO collaboration. Nevertheless, the future of large area, space-based optical telescopes will rely on segmented lenses, the James Webb Space Telescope (JWST) being a current example. JWST consists of 18 hexagonal shaped lens elements mounted on a structure with two joints, enabling the two outer columns of mirror segments to be folded in order for the telescope to be fitted into the ferrying compartment of the launcher. This will give JWST a total collection area of about 25 m2 compared to JEM-EUSO’s approximate 5 m2. The JEM-EUSO collaboration has already investigated the possibility of segmenting Fresnel lenses for the K-EUSO mission.

By employing new designs of the JEM-EUSO telescope, incorporating segmentation of lenses, not only for K-EUSO but for the main instrument as well, and utilizing a foldable design to gain collection area, it could be possible to raise the orbital height yet still have the lower-end energy cut-off at just above 1019 eV. This would allow for a larger number of events to be detected without reducing the detectable energy range.

The effect of photon distribution/collection is presented with JEM-EUSO as an example in Figure 12, where the total geometrical aperture (blue) is compared with a cut on the radial distance from nadir (magenta), zenith angle of the incoming particle (green), and the combination of the two cuts (red). When applying both cuts the total exposure equals about 9 times the exposure of the Pierre Auger Observatory [11].

Given the importance of the lens size on the number of photons the telescope is able to collect one would like to have as large lens as possible. Combining the difficulties of producing large-scale, single-piece mirrors with the size constrains by the ferrying compartment of the launch vehicle one arrives at the conclusion that to obtain a (much) larger diameter of the lens one has to use deployable structures.

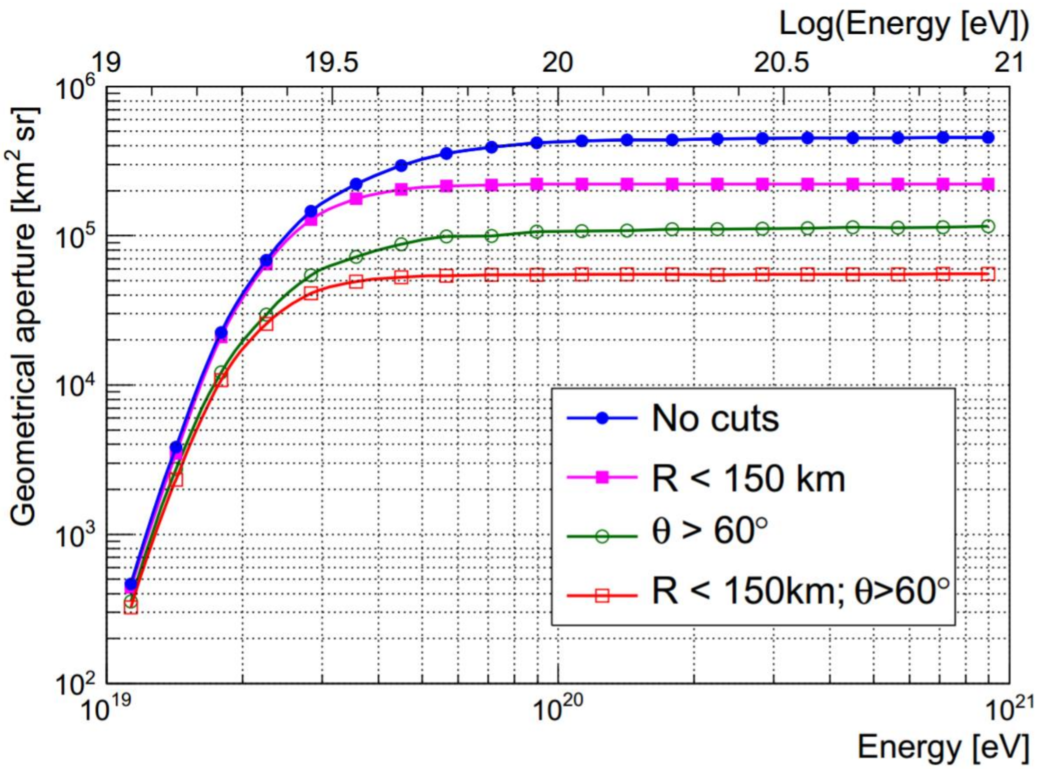


Figure 12 Geometrical Aperture of the JEM-EUSO mission mounted on the International Space Station [11]

Optical performance

The lenses of Mini-EUSO will be constructed out of PMMA plastic, which has been well tested in space. In the UV-range the transmittance of the light in PMMA ranges from about 90% to about 92% between 300 and 400 nm. Thus in a worst case scenario of 90% transmittance the total transmittance of a two-lens system will be about 80% and about 72% for a three-lens Fresnel configuration.

Another possibility for improving the optical throughput is the resurfaced plan of using a Schmidt type telescope, which would improve the total transmittance by reducing the number of lenses to a single Fresnel lens. This type of design is scheduled for the K-EUSO telescope, as described earlier.

The main constraining factor for the optical performance of the telescope is the quantum efficiency of the Multi-Anode Photomultiplier Tubes (MAPMTs), which is of the order 20%. Efforts are currently being put into a test-setup of one elementary cell utilizing silicon photomultipliers (SiMP). This EC will have a sensitive area of 16 by 16 pixels, same as the MAPMT. This experimental setup was flown on the EUSO-SPB mission during the spring of 2017. Unfortunately, the flight suffered technical difficulties of the balloon and the mission was aborted and the payload lost. Data analysis is ongoing.

However, if the SiPM is successfully demonstrated in the future, it is of the greatest interest to push for tests of the SiMP in space. With a quantum efficiency of almost a factor of 2 better than the traditional photo-multiplier tubes, the SiMP would not only improve the overall optical performance of the telescope, it would also reduce mass and volume, and, in addition, negate the need of a high-voltage power supply. The traditional MAPMTs requires a bias voltage of around -1 kV, whereas the SiMP only needs around 55 V for operation.

Test case

For a free-flying pathfinder mission it would be of importance to be able to detect EECRs. This is not the case for Mini-EUSO, as mentioned earlier. Therefore, if a free-flying pathfinder mission is to be considered then such a mission needs to be redesigned, compared to Mini-EUSO. Therefore, when planning such a mission, one must make the following assumptions:

- Low-end energy cut-off in nadir of 10^{20} eV
  This will reduce mass and size of the telescope yet still enable the possibility of detecting cosmic rays, in contrast to Mini-EUSO.
- A duty cycle of 20%
- Implementation of high-efficiency SiPM
  Raising the quantum efficiency from 20% to about 40 %.
- Perfect trigger efficiency
  If an event occurs within the FoV and the energy range of the detector (above 10^{20} eV) the event will be detected.
- An ISS-type orbit
  Approximately 50-degree orbital inclination and an orbital height of about 400 km.
- Lens size
  If taking the full-scale JEM-EUSO telescope size and energy threshold as the base line for comparison (Figure 12), one can arrive at the following scaling parameters when taking higher energy threshold and better quantum efficiency into account.

As describes in earlier sections, the lower end of the energy cut-off is strongly governed by the number of photons hitting the lens and generating a signal in the PMTs. By raising the low-end cut-off by a factor of 10, one allows for a reduction in the lens area by the same factor. In addition, with the quantum efficiency of the SiPMs being a factor of 2 higher than for standard PMTs only half as many photons needs to get to the detector, thereby adding a factor of 2 to the scaling of the lens area. Thus, the total scaling factor would be 20.

The JEM-EUSO lens area is about 20 m^2. Therefore, based on the assumptions stated above, a telescope with a lens size of about 1 m^2 (r = 56 cm) would generate a similar number of detected events above 10^{20} eV as the full-scale JEM-EUSO.

Summary and conclusions

Based on the remaining lifetime of the International Space Station it is clear that there is slim-to-none chance of utilizing the space station as the platform for the full-scale JEM-EUSO telescope. This implies that the K-EUSO telescope will be the collaboration's last telescope to be mounted on the ISS. Therefore, the efforts of the collaboration future development should be focused on transforming the JEM-EUSO full scale telescope from an ISS hosting into a telescope to be mounted on a free flying satellite platform.

The transition from a hosted telescope on the ISS to a free flying satellite provides both opportunities as well as adds difficulties. Opportunities such as the possibility of selecting a desired orbit to optimize the data collection and difficulties such as the data downlink budget, power management, and no possibility of astronaut assistance in case of emergencies.

Using the InnoSat platform

One of the ideas within the collaboration is to turn a Mini-EUSO sized telescope into a free-flying experiment. However, given the relative low weight capacity of the InnoSat platform, a maximum payload capacity of 15 kg, it is unlikely that it would be a good, or even viable, choice of platform for a Mini-EUSO sized free-flyer, given the weight of the Mini-EUSO telescope is 30 kg.

However, by redesigning the Mini-EUSO telescope, for mounting it on a separate platform, one could most likely reduce the mass of the telescope to some degree, though highly unlikely to be able to reduce the mass by 50%. This is mainly due to the mass of the lenses and the fact that the size of the lenses should be increased to make the mission's scientific case stronger. Thus, there is currently little to no possibility of being able to use the InnoSat platform in the foreseeable future.

Nevertheless, a new free-flying pathfinder mission for the JEM-EUSO collaboration is most likely needed to gain the first-hand knowledge of operating a telescope on a stand-alone platform as well as raising the technological readiness level of the whole project. Therefore, the recommendation of this study is to continue working towards a mission profile which includes a free-flying telescope and utilizing more efficient technologies such as SiPMTs as part of the JEM-EUSO road map.

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