# The JEM-EUSO Instruments

F. KAJINO[1,2], M. CASOLINO[2,3], T. EBISUZAKI[2], J. ADAMS[4], P. BALLMOOS[5], M. BERTAINA[6], M. CHRISTL[7], S. DAGORET[8], C. DE LA TAILLE[9], M. FUKUSHIMA[10], P. GORODETZKY[11], A. HAUNGS[12], N. INOUE[13], Y. KAWASAKI[2], K. KUDELA[14], B. KHRENOV[15], G. MEDINA-TANCO[16], A. NERONOV[17], H. OHMORI[2], A. OLINTO[18], G. OSTERIA[19], M. PANASYUK[15], E. PARIZOT[11], I. PARK[20], P. PICOZZA[2,3], M. RICCI[21], M. RODRIGUEZ FRIAS,[22], H. SAGAWA[10], A. SANTANGELO[23], J. SZABELSKI[24], Y. TAKIZAWA[2], K. TSUNO[2], G. VANKOVA-KIRILOVA[25], S. WADA[2], FOR THE JEM-EUSO COLLABORATION.

[1] *Department of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan*
[2] *RIKEN, 2-1 Hirosawa, Wako351-0198, Japan*
[3] *Department of Physics, University of Rome Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy*
[4] *Department of Physics, University of Alabama, Huntsville, AL 35899, USA*
[5] *Institut de Recherche en Astrophysique et Planetologie, France*
[6] *Department of Physics, University of Torino, Via Giuria 1 10125 Torino, Italy*
[7] *NASA Marshall Space Flight Center, Huntsville, AL 35812, USA*
[8] *Laboratoire de Accélérateur Linéaire, University Paris-Sud 11, CNRS/IN2P3, France*
[9] *Institut Omega, LLR Aile 4, 91128 Palaiseau Cedex, France*
[10] *ICRR, University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa, Chiba 277-8582, Japan*
[11] *APC, Univ. of Paris Diderot, CNRS/IN2P3, 10, rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France*
[12] *Karlsruhe Institute of Technology, Germany*
[13] *Graduate School of Science and Engineering, 255 Shimo-Okubo, Sakura-ku, Saitama 338-8570, Japan*
[14] *Institute of Experimental Physics SAS, Watsonova 47, 040 01 Kosice, Slovakia*
[15] *SINP, Lomonosov Moscow State Univ., Leninskie Gory 1 str. 2, Moscow, 119991, Russia*
[16] *Inst. de Ciencias Nucleares, UNAM, AP 70-543 / CP 04510, Mexico D.F.*
[17] *University of Geneva, Sauverny, Switzerland*
[18] *Department of Astronomy and Astrophysics and EFI, University of Chicago, USA*
[19] *INFN Sezione di Napoli, I-80126 Napoli, Italy*
[20] *Department of Physics, Ewha Womans University, Seoul 120-750, Korea*
[21] *INFN Laboratori Nazionali Frascati, Via E. Fermi, 40 00044 Frascati Rome, Italy*
[22] *Space and Astroparticle Group, University of Alcala Ctra. Madrid-Barcelona, km. 33.6, E-28871, Alcala de Henares, Madrid, Spain*
[23] *Institut für Astronomie und Astrophysik, Universitat Tübingen, Sand 1, 72076 Tübingen, Germany*
[24] *Soltan Institute for Nuclear Studies, 90-950 Lodz, Box 447, Poland*
[25] *St. Kliment Ohridski University of Sofia, 5, James Bourchier Boul., SOFIA 1164, Bulgaria*

*kajino@konan-u.ac.jp, casolino.marco@gmail.com, ebisu@postman.riken.jp*

**Abstract:** The Extreme Universe Space Observatory on the Japanese Experiment Module (JEM-EUSO) with a large and wide-angle telescope to be mounted on the International Space Station will open up "particle astronomy" from space. It will characterize Ultra High-Energy Cosmic Rays (UHECR) by detecting fluorescent and Cherenkov photons generated by air showers in the earth's atmosphere. The JEM-EUSO telescope consists of 3 light-weight optical Fresnel lenses with a diameter of about 2.5 m, 300 k channels of MAPMTs, frontend readout electronics, trigger electronics, and system electronics. An infrared camera and a LIDAR system on-board and a global light system on the ground will also be used to monitor the earth's atmosphere and to calibrate the telescope instruments.

**Keywords:** JEM-EUSO, ISS, UHECR, EECR, space instrument, fluorescence

## 1 Introduction

JEM-EUSO on board the International Space Station (ISS) is a new type of observatory that uses the whole Earth as a giant detector to observe transient luminous phenomena in the earth's atmosphere caused by particles and waves coming from space. JEM-EUSO telescope is designed to detect Extreme-Energy Cosmic Rays (EECR) that come into the atmosphere. They collide with atmospheric nuclei and produce extensive air showers (EAS). Charged particles in EAS excite nitrogen molecules and emit near ultra-violet (UV) photons. They also produce Cherenkov photons in a narrow cone of roughly 1° along a trajectory of EAS. The telescope observes these photons from the ISS orbital altitude of about 400 km. Reflected Cherenkov photons at the ground are observed as a strong Cherenkov mark. Viewing from the ISS orbit, the Field-of-View (FoV) of the telescope ($\pm 30°$) corresponds to an observational area on the ground larger than 1.9 $\times 10^5$ km$^2$.

The threshold energy to detect EECRs is as low as several $\times 10^{19}$ eV. As EECRs with such energies will not bend much in the magnetic field of our galaxy and outer galaxy, we will be able to open up "charged particle astronomy" to study origins and acceleration mechanism of EECRs.

An increase in exposure is achieved by inclining the telescope from nadir to tilted mode (Figure 1) . The first half of the mission lifetime will be devoted to observe lower energy cosmic rays with the nadir mode and the second half to observe higher energies using the tilted mode.

JEM-EUSO will be launched by H2B rocket and conveyed by H-II Transfer Vehicle (HTV) to the ISS. The SpaceX Dragon spacecraft is under consideration as an option for the transfer vehicle instead of the HTV [26]. JEM-EUSO will be attached to the Exposure Facility (EF) of the Japanese Experiment Module (JEM).

Details of JEM-EUSO mission[1, 2, 4], its science objectives[6], its requirements and expected performances [5, 10, 11, 12, 13, 14, 16] are reported elsewhere.

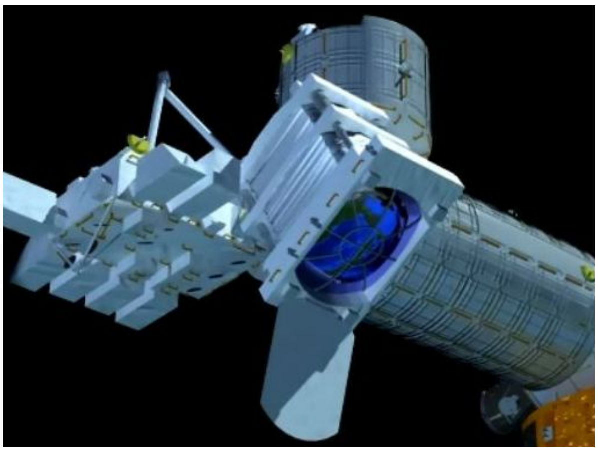

**Figure 1**: Illustrated view of the tilted mode of the JEM-EUSO telescope mounted on the ISS

## 2 JEM-EUSO System

Conceptual view of the whole JEM-EUSO system is shown in Figure 2. The JEM-EUSO system consists of a Flight Segment, Ground Support Equipment (GSE), Ground Segments (GS), a Global Light System (GLS) and a science data center which are shown in Figure 3.

The Flight Segment mainly consists of a Science Instrument System which basically consists of the following elements: 1) The JEM-EUSO telescope which is a large diameter telescope to observe EECR, 2) Atmospheric Monitoring System, 3) Calibration System. Details of these systems are described in the following sections.

GSE consists of mechanical, electrical, optical and calibration GSE. GSE supports the project during the manufacturing of the Flight Segment.

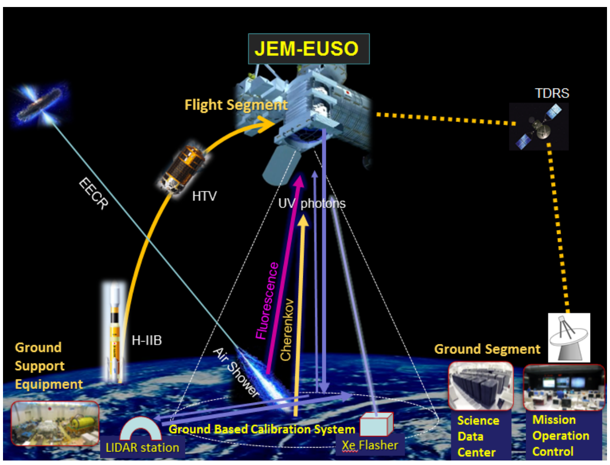


**Figure 2**: Conceptual view of the whole JEM-EUSO system

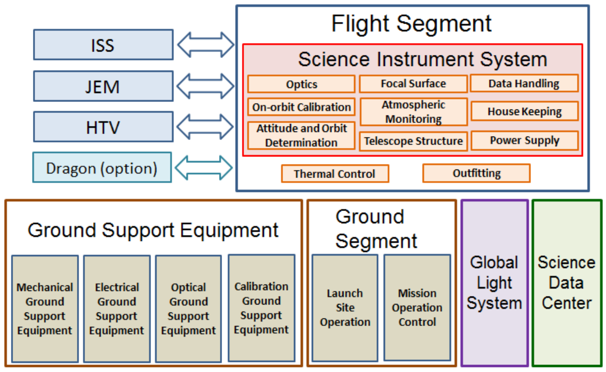


**Figure 3**: Overall JEM-EUSO system

The GS consists of Launch Site Operation and Mission Operation Control and supports launching and mission operation. The GLS is used to calibrate the instruments while the mission is in operation by using a dozen of Xenon flashers installed on the ground. This is done about once a day at each station, when JEM-EUSO passes overhead.

Ultraviolet lasers from the ground LIDAR stations are also used as a part of the GLS. Data taken by the Science Instrument System on the ISS are sent to a Mission Operation Control (MOC) on the ground though a Tracking and Data Relay Satellite (TDRS), and then to a science data center.

### 2.1 The JEM-EUSO telescope

The Flight Segment of the JEM-EUSO mission forms a large aperture telescope. This JEM-EUSO telescope is an extremely-fast, highly-pixelized, large-aperture and large-FoV digital camera, working in near-UV wavelength range (300 - 430 nm) with single photon counting capability. The telescope consists of four main parts: collecting optics with 3 lenses, a focal surface detector, electronics and a structure. (Figure 4)

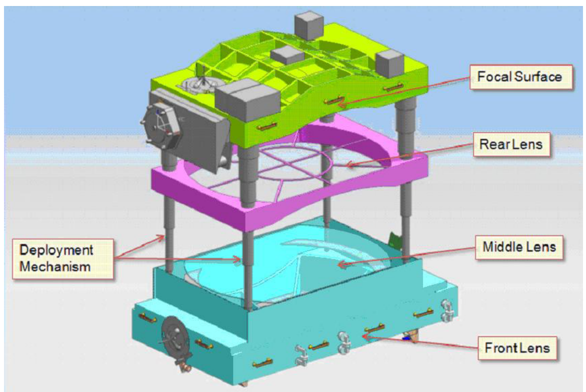


**Figure 4**: Conceptual view of the JEM-EUSO telescope

The optics focuses the incident UV photons onto the focal surface with an angular resolution of 0.1° . The focal surface detector converts the incident photons to electric pulses. The electronics counts the number of the pulses in a period less than 2.5 $\mu$s and records it as a brightness data. When a signal pattern of an EAS is found, a trigger is issued. This starts a sequence to send the brightness data of the triggered and surrounding pixels to the MOC.

The structure encloses all the parts of the instruments and protects them from the outer harmful environment in space. It also preserves the optical lenses and the focal surface detector in the preset place. The telescope is stowed when it is launched and deployed in observation mode.

Main parameters of the JEM-EUSO telescope are summarized in Table 1.

| | |
|---|---|
| Field of View | $\pm 30°$ |
| Observational area | $> 1.4 \times 10^5$ km$^2$ |
| Optical bandwidth | 300 - 430 nm |
| Focal Surface area | 4.5 m$^2$ |
| Number of pixels | $3.2 \times 10^5$ |
| Pixel size | 2.9 mm |
| Pixel size at ground | $\sim 550$ m |
| Spatial resolution | 0.07° |
| Event time sampling | 2.5 $\mu$s |
| Observational duty circle | $\sim 20$ % |

**Table 1**: Parameters of JEM-EUSO telescope

## 2.2 Optics

Two curved double sided Fresnel lenses with 2.65 m external diameter, a precision middle Fresnel lens and a pupil constitute the optics of the JEM-EUSO telescope. The Fresnel lenses can provide a large-aperture, wide FoV optics with low mass and high UV light transmittance. The combination of 3 Fresnel lenses ahieves a full angle FoV of 60° and an angular resolution of 0.07°. This resolution corresponds approximately to 550 m on the earth. The material of the lens is CYTOP and UV transmitting PMMA which has high UV transparency in the wavelength from 330 nm to 400 nm. Precision Fresnel optics adopting a diffractive optic technology is used to suppress the color aberration. Details of the optics are described in [30, 31].

## 2.3 Focal Surface Detector

The focal surface (FS) of JEM-EUSO has a spherical surface of about 2.3 m in diameter with about 2.5 m curvature radius, and it is covered with about 5,000 multi-anode photomultiplier tubes (MAPMTs) [27]. The FS detector consists of Photo-Detector Modules (PDMs), each of which consists of 9 Elementary Cells (ECs). The EC contains 4 MAPMT units [18]. 137 PDMs are arranged in the FS [22].

A Cockcroft-Walton type high-voltage supply will be used to reduce power consumption including a circuit to protect MAPMTs from an instantaneous large light dose, such as a lightning flash [23].

The MAPMTs developed for the JEM-EUSO mission are going to be tested in the TUS detector on a Russian space mission.

## 2.4 Focal Surface Electronics

The FS electronics system records the signals of UV photons generated by EECRs successively in time. A new type of frontend ASIC has been developed for this mission that functions both as a single photon counter and as a charge integrator in a chip with 64 channels [29, 32]. The system is required to keep high trigger efficiency with a flexible trigger algorithm as well as a reasonable linearity over $10^{19} - 10^{21}$ eV range. The requirements of very low power consumption must be fulfilled to manage $3.2 \times 10^5$ signal channels. Radiation tolerance of the electronic circuits in the space environment is also required.

The FS electronics is configured in three levels corresponding to the hierarchy of the FS detector system: frontend electronics at an EC level, PDM electronics common to 9 EC units, and FS electronics to control 137 units of PDM electronics. Anode signals of the MAPMT are digitized and recorded in ring memories for each Gate Time Unit (= 2.5 $\mu$s) to wait for a trigger assertion, after which the data are read and are sent to control boards. JEM-EUSO uses a hierarchical trigger method to reduce the huge original data rate of about 10 GB/s. Cluster Control Boards (CCB) are used at the last stage of the read-out structure and mainly perform further management and reduction of the data to 297 kbps for transmission of data from the ISS to the ground operation center [28].

## 2.5 Data Handling and Housekeeping Electronics

The data acquisition and handling system is designed to maximize detector observation capabilities to meet the various scientific goals, monitor system status, autonomously taking all actions to maintain optimal acquisition capabilities and handle off-nominal situations [24].

The data handling electronics includes Mission Data Processor (MDP), Telemetry Command Unit (TCU), Data Acquisition Interface (IDAQ), Clock & Time Synchronization Board.

Main MDP tasks are: 1) power on/off of all subsystems, 2) perform periodic calibrations, 3) acquire observation data from the FS detector and atmospheric monitor, 4) define trigger mode acquisition, 5) read Housekeeping (HK) data related to the mission system, 6) take care of real time contingency planning, 7) perform periodic Download/Downlink, 8) handle slow control 1553 commands.

The purpose of HK is to monitor and to relay control commands to the several subsystems that constitute the JEM-EUSO instrument [25].

HK tasks include: (a) sensor monitoring of different subsystems, (b) generation of alarms for the MDP, (c) distribution of telecommands to subsystems, (d) telemetry acquisition from subsystems, (e) monitoring of the status of subsystems.

## 2.6 Atmospheric Monitoring System

The Atmospheric Monitoring system (AM) provides information on the distribution and optical properties of the cloud and aerosol layers within the telescope FoV [35, 9, 37, 38]. The intensity of the fluorescent and Cherenkov light emitted from EAS at JEM-EUSO depends on the transparency of the atmosphere, the cloud coverage and the height of cloud top, etc.. These must be determined by the AM.

In case of events above $10^{20}$ eV, the existence of clouds can be directly detected by the signals from the EAS. However, the monitoring of the cloud coverage by the AM is important to estimate the effective observing time with high accuracy and to increase the confidence level of the EECR flux. The AM consists of an infrared camera (IR) and a LIght Detection And Ranging (LIDAR) device. Slow data of FS detector is also useful for monitoring the atmosphere.

## 2.7 Calibration System

The calibration system measures the efficiencies of the optics, the focal surface detector and the data acquisition electronics with a precision necessary to determine energy and arrival direction of EECR. The calibration system consists of the following categories: 1) pre-flight calibration, 2) on-board calibration, 3) calibration in flight with on-ground instruments, 4) atmospheric monitor calibration.

The pre-flight calibration of the detector will be done by measuring detection efficiency, uniformity, gain etc. with UV LED's [17]. To measure efficiencies of FS detector, several diffuse LED light sources with different wavelengths in the near UV region are placed on the support of the rear lens in front of the FS. To measure efficiencies of the lenses a similar light source is placed at the center of the FS. Reflected light at the inner surface of the lid is observed with the FS. In this way, the gain and the detection efficiency of the detector will be calibrated on board [19].

The system can be calibrated with a dozen ground light sources when JEM-EUSO passes over them [21]. The amount of UV absorption in the atmosphere is measured with Xe flasher lamps. The systematic error in energy and direction determination will be empirically estimated, by observing emulated EAS images with a UV laser by the JEM-EUSO telescope. The transmittance of the atmosphere as a function of height will be also obtained.

Absolute in-flight calibration of the JEM-EUSO telescope with Moon light is also studied [20].

The IR camera monitors the FoV by periodically taking pictures during observations. The IR data will help to estimate the effective area.

Studies of the UV night background estimation using simulations are anticipated [34]. The absolute fluorescence spectrum and yield need to be studied in order to determine the energies of EECR events seen by JEM-EUSO [36].

## 3 Pathfinder Experiments : TA-EUSO and EUSO-Balloon

Two pathfinder experiments, TA-EUSO and EUSO-Balloon, are currently being developed that will contribute to the likely success of the JEM-EUSO mission.

TA-EUSO uses a ground-based telescope formed by one PDM and two Fresnel lenses to demonstrate and bring to maturity the technologies used for the JEM-EUSO telescope. The TA-EUSO telescope has been set up and has measured the UV light at the Telescope Array (TA) site in Utah, USA in early 2013[30, 31, 8, 39, 41].

EUSO-Balloon will serve as a demonstrator for technologies and methods featured in the space instrument. This balloon-borne instrument points toward the nadir from a float altitude of about 40 km. With its Fresnel optics and PDM, the instrument monitors a $12 \times 12$ degree wide field of view. The instrument is presently built. A first flight is scheduled in 2014 [7, 15, 30, 31, 40, 41, 33].

## 4 Conclusion

Phase A study (feasibility study and conceptual design) of the JEM-EUSO mission is in progress with an international collaboration of 13 countries at present. Many new technological items have been developed and pathfinder experiments are being performed to realize the JEM-EUSO mission.

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