EUSO
Extreme Universe Space Observatory
Data Simulation and Analysis Tree

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EUSO Collaboration

ADA III, Sant’Agata sui due Golfi, Napoli, Italy, 28 April – 1st May 2004
**EUSO, the “Extreme Universe Space Observatory”**

**What**

*EUSO* is the first Space Mission devoted to the exploration of the outermost bounds of the Universe through the investigation of Extremely-High Energy Cosmic Rays (EECR), using the Earth atmosphere as a giant detector.

**Why**

The objective is to obtain a detailed description of the Cosmic Ray energy spectrum above $5 \times 10^{19}$ eV together with a map of the arrival directions, and to possibly open the channel of Cosmic Neutrino Astronomy.

**Where**

*EUSO* will be accommodated, as an external payload, on the ISS International Space Station.

**When**

The program foresees a goal for a three year mission starting in 2010 (the *EUSO* Phase A study is now, May 2004, under completion).

**Who**

*EUSO*, with Italian leadership, is a mission of the European Space Agency ESA supported by an International Consortium: more than 150 researchers in 50 Institutions in 6 countries in Europe, Brazil, Japan and USA.
The EUSO Collaboration (Spring 2004)

Participant Nations and Institutions

Brazil
- IAG, Univ Sao Paulo
- APC, Paris
- CdF, Paris
- IAP, Paris
- LPSC, Grenoble
- LPTHE, Paris
- OdP, Paris

France
- APC, Paris
- CdF, Paris
- IAP, Paris
- LPSC, Grenoble
- LPTHE, Paris
- LPTHE, Paris
- OdP, Paris

Italy
- MIP, Munich
- MPIHLL, Munich
- MPIfRA, Bonn
- Univ. Wuerzburg

Germany
- LIP, Lisbon

Portugal
- Obs. Neuchatel

Spain
- IAA-CSIC, Granada
- Dpt.FTC & CAFPE, Univ. Granada

Switzerland
- MSFC & NSSTC, Huntsville
- UAH, Huntsville
- UCB, Berkeley
- UCLA, Los Angeles
- Vanderbilt Univ.

USA
- RIKEN
- ICRR
- Konan Univ.
- ISAS
- Rikkyo
- KEK
- NAO
- Tokyo Univ.
- Saytama
- Aoyama
- Kinki
- Seikei
- Kanazawa

Japan
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The atmosphere is the “natural” High-Energy CR's detector

A Primary High-Energy Cosmic Ray, interacting with the Earth atmosphere, give rise to propagating Extensive Air Showers, EAS, of secondary particles.

The **EUSO** observational approach is based on the detection of the isotropic UV fluorescence light emitted by EAS along its passage through the atmosphere, and of the diffuse reflected UV light due to the impact of the Čerenkov beam, accompanying the EAS, on clouds, land or sea.
**EUSO – basic parameters**

**Fluorescence from Space – advantages:**
- Huge mass of atmosphere \((10^{12} \text{ ton})\)
- All-sky coverage (North and South)
- Observation of the reflected Čerenkov light
- High observational statistics: \(E_0 > 10^{20} \text{ eV}\)

**Electronics** fast, modular, able to manage more than 250,000 channels

**Detectors** fast MAPMT (10 ns resolution time)

**Field of View** wide angle FoV ±30°

**Optics** Fresnel lenses ~2.5 m Ø

**Atmosphere Sounding** Lidar and IR camera

**Wavelength Range** 330÷400 nm (337, 357, 391)

**Ground-based observatories:**
- ~40 years of operation
- ~25 EECR events detected at \(E_0 > 10^{20} \text{ eV}\)
- >100 EECRs per year (GZK hypothesis)
- >1000 EECRs per year (Super-GZK extension)

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**EUSO – the observation mode**

**STEP 0** - The EECR primary particle, interacting with the Earth's atmosphere, give rise to propagating Extensive Air Shower (EAS) of secondary particles accompanied by isotropic emission of UV fluorescence induced in air Nitrogen as result of a complex relativistic cascade process.

An EAS corresponding to a Primary with energy $\sim 10^{20}$ eV forms a significant streak of fluorescence light over 10-100 km along its passage in the atmosphere, depending on the nature of the Primary and on the pitch angle with the vertical.

**STEP 1** – The isotropic UV fluorescence light is registered by the EECR/ν telescope.

**STEP 2** – Highly collimated Čerenkov photons are produced along the shower axial direction. When the Čerenkov beam impacts on the top of a cloud, or on the sea or land, its reflected isotropic UV light is seen by the EECR/ν telescope.

**STEP 3** – The EECR/ν telescope continuously registers and, whenever the signal intensity is greater than a proper threshold, the electronics system understands that the signal could be the "good" one and then "triggers". A photograph of the FoV is then taken by the IR camera at the trigger time.

**STEP 4** – The atmosphere sounding is then performed by the Lidar device along the shower direction.

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Meteors, lightning, ... and EUSO

By using atmosphere as a natural detector for the fluorescence induced by EECRs, EUSO will systematically survey a large portion of space providing a complete dataset of UV measurement in the 300÷400 nm band. Besides the Cosmic Rays events, this dataset will contain information about all atmospheric UV-phenomena that occurred during the observation time (meteors, elves, lightning, elves, ...)

Ref. EUSO RedBook, 2004

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The various peculiarities of the **EUSO** space-based observational approach imply a dedicated effort for the evaluation of the expected features of the detected signals and for the reconstruction of its space-time development, energy and composition, namely from the simulation and data analysis point of view.

**Physics Process Simulation**
- Event generators:
  - fast generator, bulk event generator, 2nd order effect simulation
  - EECR, EEν, meteors, lightning

**Active Target Simulation**
- Fluorescence yield
- Čerenkov light production
- Atmosphere description
- Atmospheric transmission
- Pressure, temperature, clouds effect

**Detector Simulation**
- Geometry description
- Optics description
- Focal surface description
- Electronics description
- Trigger simulation

**Event Reconstruction**
- Event Type (EECR, EEν, Meteor,..)
- Direction Reconstruction
- Energy Reconstruction
- Particle identification

**Expected results**
- Experimental resolution
- Acceptance and aperture
- Expected flux sensitivity

First goal was to obtain an end-to-end simulation chain finalized to study the **EUSO** detector response function.
The trade-off of EAS generation is between

- the desirable detailed description given by the most common and sophisticated Montecarlo programs, but paid with a very high computing time, even in the “thinning” version, and

- a less detailed simulation, focused on the correct treatment of the longitudinal EAS profile, the fluorescence yield and Čerenkov light emission with less emphasis on the tracking of all the secondary particles produced in the shower.

At each relevant step of the generation process, a cross-check of the results with CORSIKA is performed.

Ref. EUSO RedBook, 2004
Active target simulation - the Earth atmosphere

The atmosphere plays a twofold major role in EUSO: it is

- the light emission medium (yield of fluorescence from Nitrogen, and associated Čerenkov light), and

- the transmission medium where the light (fluorescence, diffuse and reflected Čerenkov UV light) propagates and attenuates from its source location to the telescope site.

Atmosphere as a light emission medium

Fluorescence yield ⇐ Energy, Altitude, Air Density, Temperature, Humidity (Kakimoto, 1995; Nagano, 2003)

Čerenkov light production ⇐ Energy, Refraction Index (Wavelength, Air Dens.) (Hillas, 1982; Baltrusaitis 1987)

Density of molecular Nitrogen (on ground) around Earth in winter. A fast 10% variation is present along the ISS trajectory (black curve).

Black curve (left axis): fluorescence yield. Coloured curves (right): relative abundance of the three main lines (337, 357, 391 nm)

Expected UV light from an EAS generated by a $10^{20}$ eV primary proton, 45° incl.
Atmosphere as a Transmission Medium

The transmission of the photons from their source location to the telescope is affected both by scattering and absorption effects, all of them depending on the altitude of the starting point:

- **Rayleigh scattering**: by the air molecules, dominant in high atmosphere and for low wavelength values, mainly acts on Čerenkov light reflected from ground.
- **Mie scattering**: by aerosols (dust, smoke...) and droplets (clouds).
- **Absorption by Ozone**: rather transparent for large wavelength, sharp cut-off below 330 nm, influences Čerenkov photons more than fluorescence ones.

In the EUSO Simulation chain:
- **Atmosphere transmission** → LOWTRAN7 s/w package for different atmospheric models.

Graph: Vertical transmission (%) across the atmosphere - 1976 U.S. Standard Model, “Navy maritime”

- λ = 337 nm
- λ = 391 nm
- Total
- Rayleigh
- Mie

Ref. EUSO RedBook, 2004

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### Clouds and EUSO

**Clouds can:**
- hide the signal (fluorescence and/or Cerenkov)
- hide the maximum of fluorescence
- affect the proportionality between detected signal and shower energy

**depending on:**
- the height of the cloud top
- the optical depth of the cloud
- the shower inclination (arrival direction)

In the EUSO Simulation chain, top height and optical depth are currently derived from:

**Meteorological Databases** → **ISCCP and TOVs**

At the EUSO operation time, this basic info will be directly derived from the EUSO Atmosphere Sounding devices (see poster on IR images by A. Anzalone & F. Isgrò)

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**ISS latitude = ±51°**

15 orbits/day

**Clouds:D**

- cirrus
- stratus
- altocumulus
- nimbostratus
- cumulonimbus or stormy clouds

**Meteorological Databases (ISCCP and TOVs)**

**Clouds:**
- clear
- no trigger
**Background**

Looking at nadir, *EUSO* will be sensitive to:
- any source of UV light located in upper atmosphere below its altitude location (~400 km), and to the
- light coming from space and upward reflected through Earth albedo.

The level of background depends on various parameters as moon phase, geographical position, seasonal and meteorological conditions. UV background in the Earth atmosphere includes:

- **Man-made sources**
  - Ships
  - Airplanes
    - very slow moving sources
  - City Lights
    - attitude ISS information, geographical databases and maps

- **Transitory natural phenomena**
  - Lightning
    - meteorological conditions
  - Aurora
    - scattered light from high latitude

- **Constant sources**
  - "Airglow"
    - Chemical reactions
    - local oxygen density, seasons
  - Stars and Moon
    - reflected star- and moon-light

In the EUSO Simulation chain:

- **Background level** $\rightarrow$ programmable
- **“natural” background reference level** $\rightarrow$ 500 photons m$^{-2}$ s$^{-1}$ sr$^{-1}$
The shower will appear as a single track event (embedded in the background) whose duration, position and intensity are related to the arrival direction, energy and nature of the Primary EECR/ν. The space-time image is given in terms of X-T and Y-T projections of the collected photoelectrons, X and Y being the coordinates inside the field-of-view; the time coordinate T measures the shower development in depth, providing info about the shower length in the third direction, the height in the atmosphere.
Event reconstruction – basic scheme

Background subtraction, pattern recognition, ...

X-T, Y-T ↔ θ, φ
EECR Arrival Direction

pixel track

$S_{\text{max}} \propto$ EECR energy

$S_{\text{max}} \propto$ EECR energy

... but atmospheric correction ...

$S_{\text{max}} \propto$ EECR energy

Ref. EUSO RedBook, 2004
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During the **EUSO** Phase A study, a set of parallel s/w modules were built to perform a fast end-to-end simulation chain finalized to the detector design and optimization. Only part of the involved variables were used. At the same time, a project started to define a sophisticated framework on which to develop a complete data simulation and analysis system, **ESAF**.

The end-to-end simulation chain: separated s/w tools (before ESAF)

**Physics Process Simulation**
- Event generation
  - ECal, IT-simulations, lightning

**Active Target Simulation**
- Fluorescence yield
- ECal-light production
- Atmospheric description
- Atmospheric transmission
- Pressure, temperature, clouds effects

**Detector Simulation**
- Geometry description
- Optics description
- Focal surface description
- Electronics description
- Trigger simulation

**Event Reconstruction**
- Event type (ECal, IT-simulations, Effective energy, etc.)
- Energy Reconstruction
- Particle Identification

**Shower Source**
- SLAST parametric
- ~ Kakimoto + SLAST Čerenkov

**Light Source**
- UNISIM Čerenkov
- Paris Čerenkov

**Radiative Transfer**
- LOWTRAN
- LOWTRAN + clouds

**EUSO Detector**
- SLAST parametric
- UNISIM parametric
- Paris parametric
- Palermo parametric

**Reconstruction**
- STAR
- UNISIM reco
- Paris reco
- Palermo reco
ESAF – EUSO Simulation and Analysis Framework

… integrated software framework designed to handle the complete event simulation chain and the reconstruction and analysis of both simulated and real events …

**ESAF**

- written in C++ and Fortran
- currently implemented on Linux
- able to handle external packages, even if written in different languages
- Object Oriented → high modularity
- built with an “onion-like” structure: outer layers are more general and abstract than the inner ones which become step by step more and more real and specialised.
- Located in the CVS official repository
- based on the ROOT package

**ROOT**

- Object Oriented programming
- implemented on various platforms: Linux, Windows, ...
- interfaces towards standard formats as FITS and IDL
- adopted in particular items of ground- and space-based observatories

Scientists from astrophysics, physics of particles, and atmosphere science, form the EUSO community.

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ESAF – the “simulation” structure – top level

- ShowerSource
- LightSource
- Atmosphere
- Rayleigh
- Lowtran
- RadiativeTransfer
- EusoApplication (various configuration files)
- EusoDetector
- Telemetry Data (ROOT/ASCII file)
- Electronics
- Focal Plane
- θ-φ and X-Y layouts
- Optics
- M36 MAPMT
- fV1.0-2.3mEP
- UNISIM
- SLAST
- CORSIKA
- Trigger Engine
- Atmospheric

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ESAF – the “reconstruction” proposed structure

**Simulation**

- **RootFile**
- **InputModule**
- **RecoEvent**

**Real Data**

- **External Data Bases:**
  - ISS Orbital Attitude
  - Atmosphere DB
  - Meteorological DB
  - Geographical DB
  - Astrophysical Catalogues

**EUSO specific Data Bases related to housekeeping, engineering and calibration info:**
- Detector Configuration (including AnglePixelMap)
- Instrument Calibration

**RecoFramework**

- (various configuration files)
- BackgroundAnalysis
- SlowFastSelection
- TrackPatternReco
- ČerenkovFootprint
- ArrivalDirection
- HmaxXmax
- EnergyReconstruction
- Particle Identification
- Neutrinos
- InfraRedImages
- LidarAnalysis
- SlowEventsAnalysis

**Analysis and interpretation of “certified” EECR/ν events**
ESAF – status of the project (Spring 2004)

**Simulation**
- Showers:
  - UNISIM, SLAST, CORSIKA, AIRES
- Other physics of interest:
  - meteors, lightning
- Fluorescence and Čerenkov:
  - Kakimoto ref., directly from shower
- Atmosphere:
  - MSISE models, clouds and DB
- Radiative Transfer:
  - no clouds, with clouds
- Detector Simulation:
  - Optics
  - Focal Surface
  - Electronics
  - Trigger
- Output:
  - Root file
  - Other formats

**Reconstruction**
- Pattern recognition
- Čerenkov footprint
- Track fitting
- Hmax finding
- Xmax reco
- Energy reco
- Particle ID
- Neutrino selection

- Done or in advanced state
- Under development or optimization
- To Be Done

Autumn 2004
Epilogue …

… for more details about EUSO …

"Starry Night"

Vincent Van Gogh
June 1889

Van Gogh painted the night sky with great whirling stars that seemed to express his feelings of the great cosmic energy that rules human lives with both malice and benevolence. The sight of the stars had a strong impact on him: it made him contemplate whether "the whole of life was visible to us, or do we in fact know only the one hemisphere before we die"?

Similarly to his great connatural Erasmus from Rotterdam, who wrote "Stultitiae Laws" (Praising of Folly), the vision of life of Vincent Van Gogh expresses the struggle to reach beyond the conventional.

In its own, EUSO represents the non conventional way to look beyond at the Extreme Universe using the largest available detector for the Extraterrestrial Energetic Radiation, as represented by the Earth Atmosphere.

www.euso-mission.org


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