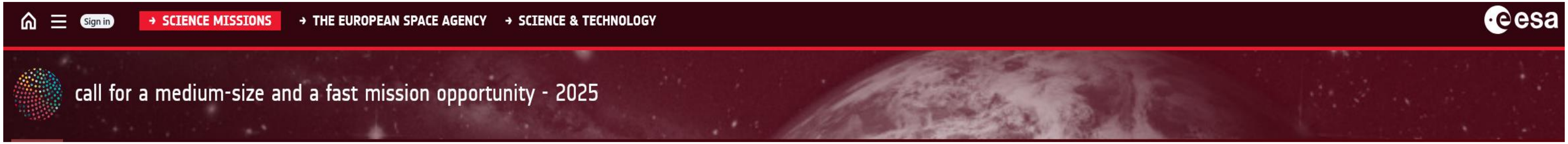


DESIGN STUDY FOR A CHERENKOV-BASED ESA F-CLASS MISSION

G. OSTERIA ON BEHALF OF:

TAKKY, TOBIAS, VALENTINA, MATTEO, MARIO, JOHANNES, ETIENNE, AND SEVERAL OTHER PEOPLE

BOUNDARY CONDITIONS FOR THE F MISSION

ESA UNCLASSIFIED – Releasable to the Public

Mission adoption in 2030, launch around **2034**.

4.2. BOUNDARY CONDITIONS FOR THE F MISSION

Element	Request	Comments or Guidelines
ESA CaC	≤ 205 M€ (2025 e.c.)	Includes all elements to be funded by ESA, including the launch services. Excludes Member State and international partner contributions.
Science objectives and science payload	The science objectives of this mission are open.	The science payload shall be defined in relation with the targeted science objectives. The core science objectives and the proposed concept shall be sufficiently robust for enabling rapid technical convergence by following a design-to-cost approach in the preparation phase.
Launch	around 2034	Mission-dependent
Launcher	The F mission will nominally be launched with the Vega-C/E launcher or small European launcher (as available).	Other schemes may be considered subject to providing evidence of their feasibility. Non-European launchers to be procured by ESA are excluded.
Spacecraft dry mass	Typically ~500 kg	Including payload and all margins
Spacecraft wet mass	Shall be indicated by the proposer	The actual launch mass constraint will depend on the target orbit and the associated Vega-C/E performance. However, a mass constraint is also introduced to limit the spacecraft cost in line with the CaC constraints. The spacecraft wet mass encompasses the platform(s) with its propulsion subsystem(s), the propellant needed for the mission (including disposal, when applicable), and the scientific instrumentation. The launcher adapter is excluded, but any spacecraft dispenser, if needed, shall be included.
Overall science payload mass	Typically ≤ 70 kg	The payload upper mass limit is a recommended guideline with due regard to the overall cost and schedule constraints. The actual allowable payload mass can be lower depending on the mission profile (see sections 5 and 6). The proposers shall keep in mind the need to ensure a fast and reliable payload development and qualification schedule, typically 3 years starting from the mission adoption.

e Public

Platform TRL	TRL ≥ 6 at mission proposal	ISO scale, see Appendix B. Proposers are invited to build their mission proposal by relying on existing platform capabilities, with minimum modifications. The platform is nominally procured by ESA. As a rule, the platform equipment shall be at TRL ≥ 7 (space qualified for the mission needs and available) before the mission adoption. TRL 6 is nominally required at the time of the mission proposal (TRL 5 acceptable) since the Technology Readiness may drive the schedule and will be one important element of the decision process.
Science Payload TRL	TRL ≥ 6 by the mission adoption	The credibility of the payload development and qualification schedule will be an important selection criterion. The proposed payload can be a new development but must rely on significant heritage and fully available technologies. Limited delta-verifications and pre-developments can be envisaged during the definition phase. The payload definition level must reach PDR status before the mission adoption, within ~3 years, and ESA is ready to support the instrument detailed design and pre-developments during this phase for securing the payload development schedule. Proposers are invited to submit in the proposal their views for the payload development plan, including pre-development needs. The role, responsibilities, and heritage of the payload providers must be defined in the proposal.
International collaboration	Can be envisaged, provided a clear support and commitment from the international partner are available.	The F mission must be ESA-led.
Spacecraft operations	The spacecraft operations are nominally under ESA responsibility with contributions from the Member States or partners to the science ground segment. Nominal duration of science operations typically < 2 years	Other collaboration schemes may be considered subject to providing evidence of their feasibility. The contribution to the Science Ground Segment shall be detailed by including the expected contribution from ESA. The nominal duration of science operations does not include the cruise phase, nor the disposal (as applicable).

THE IDEA

A **Cherenkov telescope** pointing towards the Earth's Limb to study:

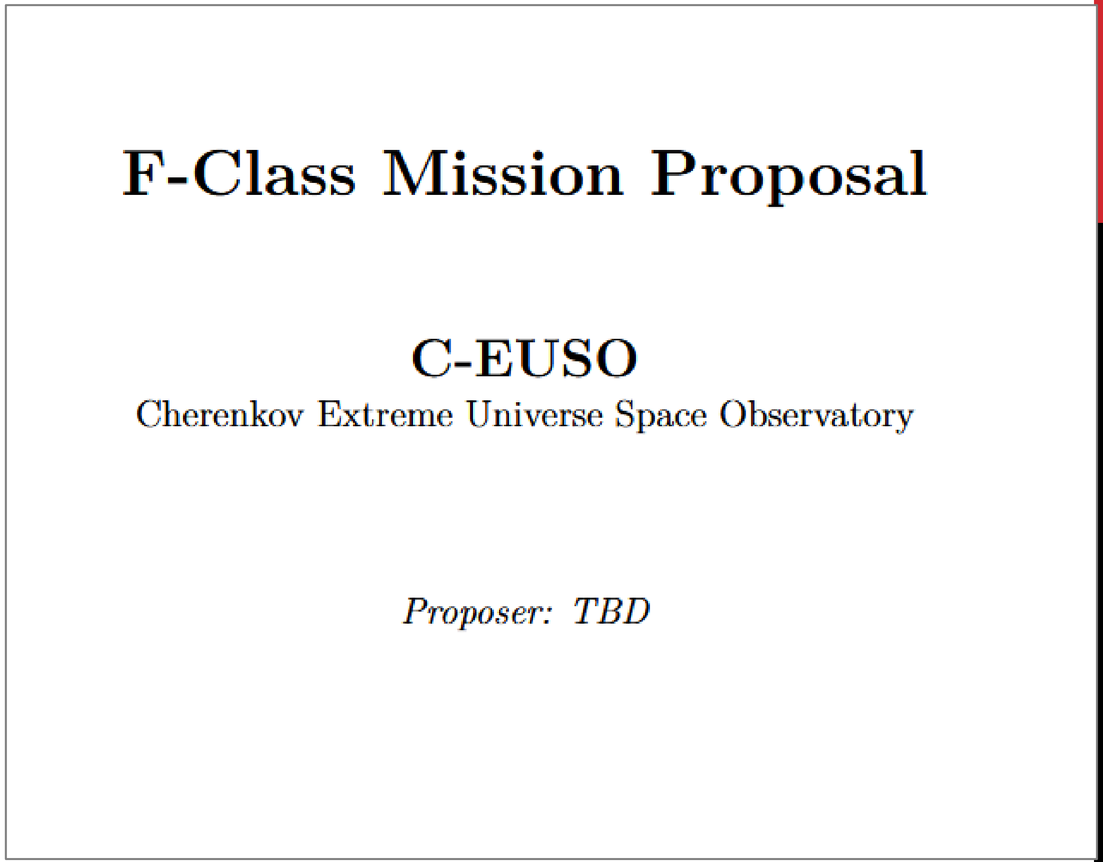
- **Astrophysical neutrinos** from a Target-of-Opportunity (ToO) following multi-messenger events
- **High-Altitude Horizontal Air-showers** (HAHAs)
    - Cosmic ray at PeV energies

Goals:

- Maximum:
    - To get close to the expected results for POEMMA (monocular)
- Minimum:
    - To achieve (significantly) better results than those expected for Terzina and PBR

How:

- Making an instrument bigger (and hopefully better) than Terzina, with ToO capability.
- Compensating for smaller size than POEMMA by studying better orbital parameters (altitude, inclination) or increasing the duty cycle (Sun-synchronous orbit), or …



F-Class Mission Proposal

C-EUSO

Cherenkov Extreme Universe Space Observatory

Proposer: TBD

PRIMARY SCIENCE OBJECTIVES

1.2 Primary Science Objectives

The Cherenkov - Extreme Universe Space Observatory (C-EUSO) mission will address the following open questions:

1. What are the sources of astrophysical neutrinos
2. How do Extensive Air-Showers (EASs) develop at high altitudes (rarefied atmosphere)
3. What is the cosmic ray composition around PeV energies

1) Search for astrophysical neutrinos from a Target-of-Opportunity (ToO) following multi-messenger events
A multi-messenger high-energy transient event generates multi-wavelength photons, gravitational waves, and neutrinos. The C-EUSO primary science goal is to search for astrophysical neutrinos from a Target-of-Opportunity (ToO) following multi-messenger events, such as gamma-ray bursts, tidal disruption events, and binary coalescence of compact objects, with a follow-up time scale of about one orbit (95 min) over the entire dark sky. C-EUSO can follow up these events and reach a neutrino fluence around ?? $E_\nu^2 J_\nu \geq 0.1 GeV/cm^2$?? depending on the location of the sources. C-EUSO can observe the full sky after several months, given the orbit of the Earth around the Sun. To detect the neutrinos, C-EUSO will search for EASs from below the limb of the Earth. C-EUSO will have significant sensitivity over the entire celestial sphere for cosmic neutrinos above 40 PeV?. complementing the new generation of giant ground-based neutrino observatories. In addition, the all-sky coverage may be critical to resolve the tension between the KM3Net observation and the non-observation of similar high-energy events by IceCube.

2) High-Altitude Horizontal Air-showers (HAHAs)
C-EUSO will observe a large number of high-altitude horizontal air-showers (HAHAs) from ultra-high energy cosmic rays by pointing at $\lesssim 2°$ above the limb. The Cherenkov emission of these events can be observed from a small layer of the atmosphere at an altitude above the limb, ranging from 20 km to 50 km. The changing atmospheric density as a function of viewing angle above the limb allows for detailed measurements of the EAS development as a function of traversed slant depth in ways inaccessible to any other ground-based experiments.

3) Cosmic ray at PeV energies
The HAHAs events allow for a completely new approach to the measurement of the cosmic-ray spectrum and the discrimination of the cosmic-ray composition at energies around 10 PeV ? and above. Tobias: Are we going to be able to measure composition? Maybe this could also be

2 Mission Configuration

The **C-EUSO mission** is optimized for measurements, during astronomical night, of EASs from upward-going tau neutrinos via Cherenkov signals in the optical band (300 – 900 nm) with the satellite pointed closer to the Earth's limb. C-EUSO will operate in neutrino target-of-opportunity (ToO) mode. Following a ToO alert, C-EUSO will follow the event position in the sky as it sets or rises below the Earth's limb and search for corresponding EAS events. The scientific operations will be 2 years, with the goal of extending the operations up to a total of 3 years.

2.1 Mission Concept and Detection Technique

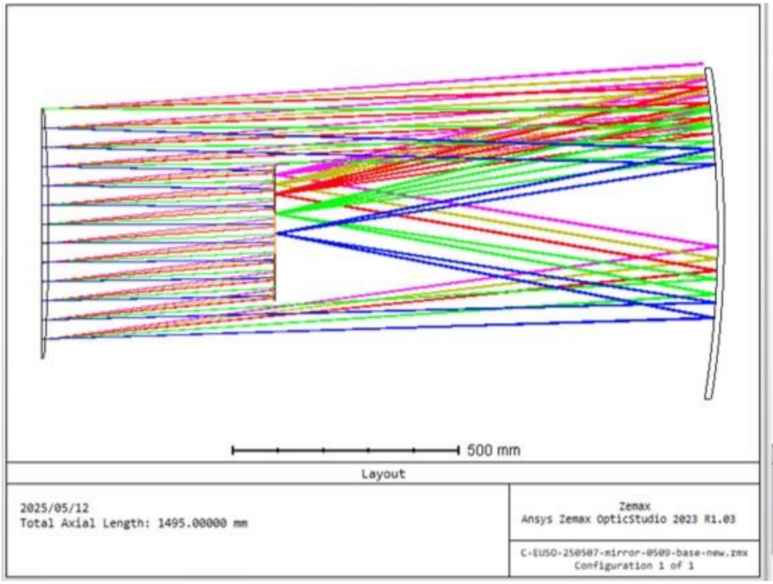
The **C-EUSO** is designed to observe ultra-high-energy cosmic rays (UHECRs) and cosmic neutrinos using space-based measurements of extensive air showers (EASs). C-EUSO will monitor the Earth's atmosphere, pointing in the direction of the Earth's limb located at 67.5° from the nadir for a 525 km orbit's altitude. C-EUSO will cover a viewing area of 12° on azimuth and extending from 9° below the horizon to 3° above it, equivalent to covering τ-lepton trajectories emerging from the Earth with elevation angles xx° while measuring the Cherenkov signal from potential above-the-limb UHECRs. Depending on the origin and direction of the primary particle, C-EUSO will in fact observe two distinct classes of events. When pointing just above the Earth's limb, C-EUSO will observe the Cherenkov signal from high-altitude horizontal air showers (HAHAs) induced by cosmic rays that skim the Earth's atmosphere and traverse the telescope FoV, never intersecting the ground. When pointing just below the Earth's limb, C-EUSO will pioneer the observation of cosmic neutrinos above 20 PeV in particular from astrophysical transient events, by revealing the Cherenkov emissions from EASs induced by τ-leptons produced by cosmic ν_τ interactions in the Earth used as a neutrino converter. In neutrino target-of-opportunity (ToO) operational mode, the C-EUSO telescopes quickly slew to observe and follow transient sources. In ToO mode, C-EUSO will utilize an external alert of transient events from gravitational waves, electromagnetic transients, or signals detected by other neutrino observatories.

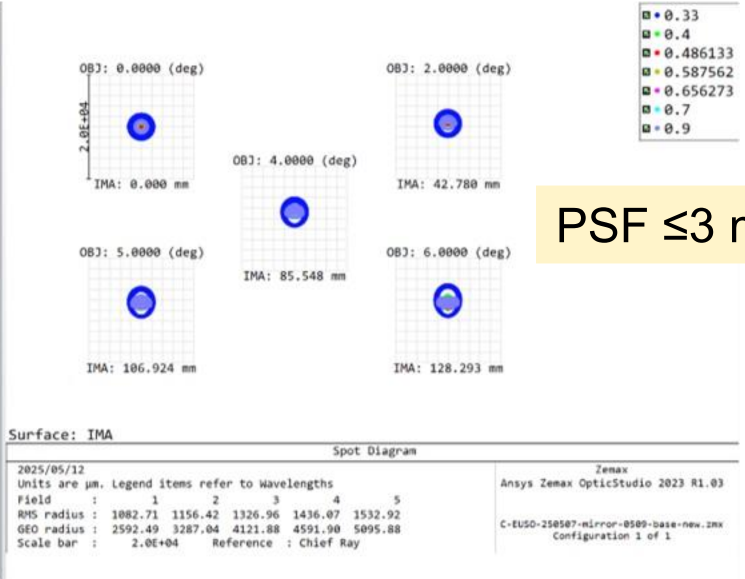
2.2 Instrument Design and Configuration

The central element of the C-EUSO instrument is a high-sensitivity, near-UV sensitive optical system that measures and locates the bright, forward collimated Cherenkov emission from EASs directed at the C-EUSO telescope. The C-EUSO optics and camera are designed to optimize the wavelength coverage, time sampling, and pixel sizes to best reconstruct ultrahigh-energy EASs using the Cherenkov signals. A compact infrared (IR) camera will monitor cloud coverage within and around the main FoV, ensuring accurate exposure determination.
The proposed instrument aims at a simple design, with no moving parts or filter wheels, with already proven technology and minimized risks. The technology has been high-altitude validated through a series of Super Pressure Balloon pathfinder missions, including **EUSO-SPB1**[8] and **EUSO-SPB2**[9] (NASA, in collaboration with ASI and CNES), and will be further validated by the missions that will be launched by 2027, such as **PBR (POEMMA Balloon with Radio)** [10] and **Terzina**[11] (on board the **NUSES** Space mission) currently in development by NASA and ASI, respectively.

THE INSTRUMENT: OPTICAL SYSTEM

After several attempts…
The optical design builds on the successful modified Schmidt design flown on EUSO-SPB2 and adopted for the PBR missions.
(**Thanks to Takizawa san**)





PSF ≤3 mm

The weights of the lens and mirror are **7 kg** and **12 kg**, respectively.

Entrance pupil	550 mm diam.
Mirror	730 mm diam.
Mirror curvature radio	1100 mm
Focal surface	256 mm diam.
FoV	± 6°
Overall lenght	1450 mm

THE INSTRUMENT: CHERENKOV CAMERA

ESA F-Class Proposal C-EUSO

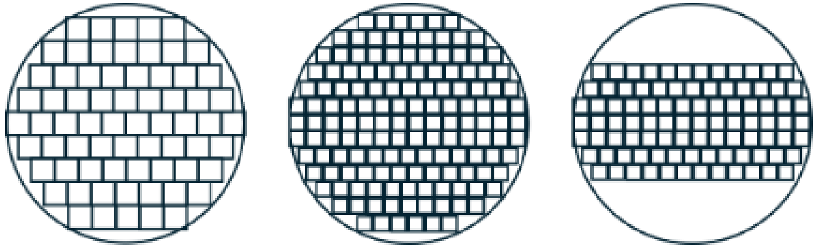


Figure 2: The C-EUSO focal surface: Left: 70 SiPM arrays (3mm $\times$ 3mm pixel size); Center: 144 SiPM arrays (2mm $\times$ 2mm pixel size); Right: 92 SiPM arrays (2mm $\times$ 2mm pixel size), Fov of view $\sim 12° \times 6°$

	Baseline	Adv. Option A	Adv. Option B	PBR	POEMMA	TERZINA
SiPM arrays	70	144	92	32	180	10
Pixels size	3 x 3 mm^2	2 x 2 mm^2	2 x 2 mm^2	3 x 3 mm^2	3 x 3 mm^2	3 x 3 mm^2
Total pixels	4480	9216	5888	2192	11520	640
FoV	12°x12°	12°x12°	12°x6°	12°x6°	30°x9°	7.20°x2.88°
Instant. FoV	0.14°	0.09°	0.09°	0.2°	0.08°	0,18°

OBSERVATION STRATEGY

C-EUSO will fly into **Low Earth Orbit (LEO)** with the **instrument pointing toward the dark side of the Earth's limb.**

C-EUSO will operate in neutrino target-of-opportunity (ToO) mode, so, in case of an external alert of transient events from gravitational waves, electromagnetic transients, or signals detected by other neutrino observatories, the telescope has to quickly slew (90° in <500 s) to observe and follow transient sources.

We decided to discard my first proposal of using a **Sun-synchronous orbit** (>98°) with solar panels exposed to the sun and the telescope pointing toward the dark side of Earth's Limb. This orbit simplifies the thermics and ensures constant power availability, and I was hoping that it could also improve the duty cycle of the measurement. (Terzina quotes a **40% duty cycle** operating on this kind of orbit).

The unanswered question: How dark is the telescope FoV in this orbit?

The mission will fly in a Low Earth Orbit at an **altitude between 450-550 km**. The altitude and inclination will have a significant impact on the energy threshold and effective area of EAS measurements. A full orbital study will be presented before mission adoption.

MISSION FEASIBILITY & RESOURCE ENVELOPE

F-EUSO builds on extensive flight heritage, with mass, power, and telemetry requirements grounded in hardware already developed and flown on EUSO-SPB2, and the upcoming NASA-led PBR balloon mission. We derive the following requirements from the proposed mission and payload configuration:

	Instrument		Spacecraft	
Optics	Schmidt	12° full FoV	Slew rate	$\leq$0.5°/s
	Primary Mirror	0.73 m diam.	Pointing Res.	0.1°
	Corrector Lens	0.55 m diam.	Pointing Know.	0.01°
	Focal Surface	0.257 m diam.	Clock synch.	10 ns
	Pixel size	3×3 mm^2	Data Storage	5 days
	Pixel FoV	0.14°	Dry Mass	500 kg
	Mass	60 kg	Wet Mass	700 kg
FS	SiPM	4928 pixels	Power	100 W
	Instrument + Telescope		Mission	
	Mass	500 kg	Lifetime	2 years
	Power	150 W	Orbit	525 km 98°
	Data	1 GB/day	Orbit period	95 min

All current projections confirm that C-EUSO fits comfortably within the €205M Cost-at-Completion for F-class missions.

WHAT WAS MISSING

In a word:

The expected results

More in details:

Performance of the apparatus in terms of:

- **Neutrino energy threshold (40 PeV??)**
- **Neutrino fluence sensitivity to sources ($E_\nu^2 J_\nu \geq$?? GeV /cm^2)**
  - Expected number of neutrino events seen by C-EUSO see in a two-year-long mission
- **Energy threshold, energy resolution, and expected number of HAHAs for different choices of the orbital parameters.**

CONCLUSION

The work done to try to propose C-EUSO leaves us with doubts about how unrealistic the proposal was.

The goal was to determine if, with a small mission, it is possible to make a significant contribution to the study of high-energy neutrinos, HAHAs, or other topics (the spectrum or composition of cosmic rays or particle physics, etc.).

We should have verified how and if we could get close to the scientific objectives of POEMMA on these topics by optimizing the performance of the telescope, the satellite platform (or constellation of platforms), and the orbital parameters.

The path has only just begun, but, considering that calls for small (or fast) missions are more frequent (and affordable) than those for medium or large ones, we must ask ourselves if it is worth continuing it while waiting for M-EUSO and POEMMA missions.