Solar Flare Hard X-ray Polarimetry with the CUbesat Solar Polarimeter (CUSP)

Advances in Space AstroParticle Physics (ASAPP2025)

Sant Feliu de Guíxols, Spain – 15th May 2025

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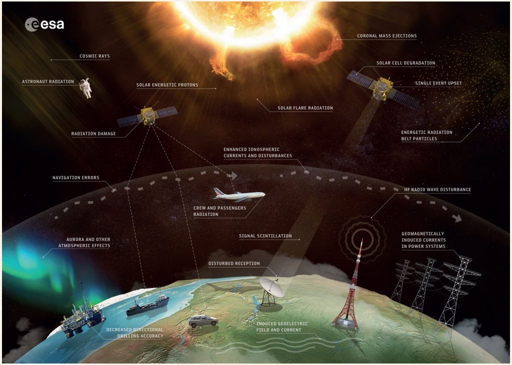
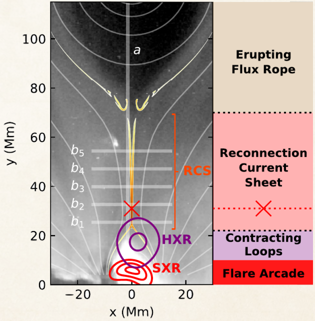
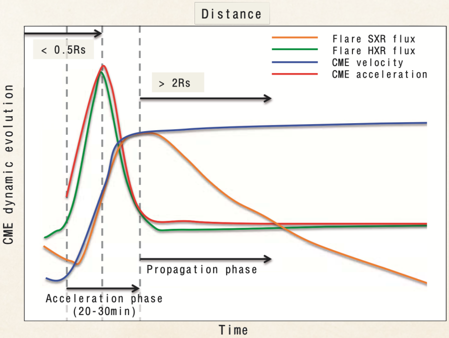
ASI-INAF contract n. 2023-2-R.0

- Solar activity, including **Solar flares (SFs)**, can be disruptive for human technological activities in space and on ground
- The occurrence of SFs is very often associated to **Coronal Mass Ejection (CME)** and **Solar Energetic Particle (SEPs)** events on the ground
- SF **can also occur** alone producing a **direct acceleration** of particles towards the Earth



- Most powerful eruptions associated to powerful flares
- HXRs are related to CME acceleration $\Longrightarrow$ **HXR polarimetry** could improve the knowledge of the **initial conditions** of the eruption of most powerful CME
- SXRs are related to CME velocity
- The rapid CME development in the lower corona during the acceleration phase strongly correlates with the associated flare activity.



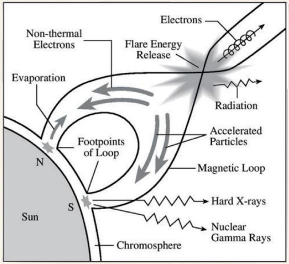


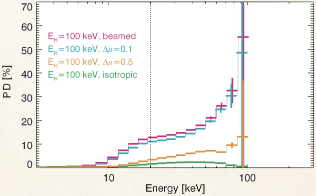
Chen B. et al. (2020), Nat. Astron.

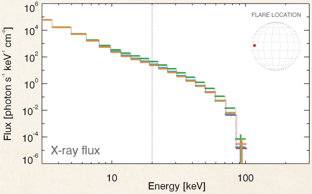
Temmer (2016), Astron. Nachr.

Motivation for X-ray Polarimetry of SFs

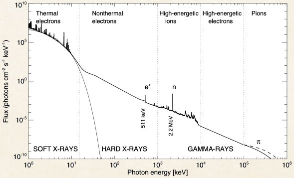
- SFs originate from **magnetic reconnection** in loop structures in solar corona
- SFs energy spectrum in the X-rays is dominated by:
  - **thermal Bremsstrahlung** (due to plasma heating, expected weakly polarized by Emslie&Brown 1980) + emission lines < 10 keV
  - **non-thermal Bremsstrahlung** (at the loop top and footprints, due to particle acceleration along magnetic field lines) expected highly polarized [Zharkova+ 2010] >10-20 keV
- (Linear) **X-ray polarimetry** would allow to **disentangle degeneracies in models** of particle beaming and magnetic field structure (also without imaging of the SF)





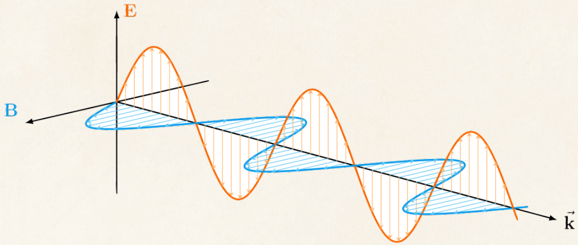


Jeffrey+ 2020 (A&A)



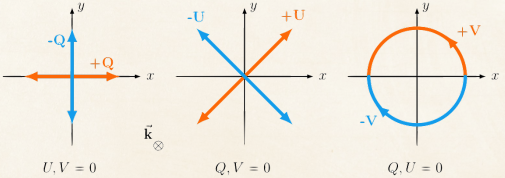
Aschwanden (2005)

Polarization of Electro-Magnetic Waves



A photon consists of the propagation of orthogonal **E** and **B** fields. **E** is taken by convention as the polarization vector.
Stokes parameterization of the polarization state:

$$\vec{S} = \begin{cases} S_0 \equiv I = \langle E_x^2 \rangle + \langle E_y^2 \rangle \\ S_1 \equiv Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle \\ S_2 \equiv U = \langle E_{45^\circ}^2 \rangle - \langle E_{-45^\circ}^2 \rangle \\ S_3 \equiv V = \langle E_R^2 \rangle - \langle E_L^2 \rangle \end{cases}$$

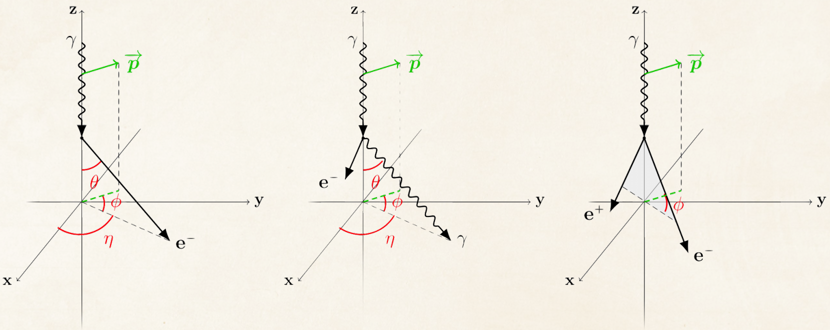


For a linearly polarized wave, polarization fraction and angle are defined by:

$$(PD[\%] \equiv PF \equiv)\ p = \frac{\sqrt{Q^2 + U^2}}{I} \quad ; \qquad (PA \equiv)\ \psi = \frac{1}{2} \arctan \frac{U}{Q}$$

- Photons interact with matter through three processes:

Photo-electric effect Compton scattering Pair production



- Each process is dominant at different energies
- The azimuthal distribution of the secondary products is correlated with the polarization direction of the primary photon: $\frac{d\sigma}{d\Omega} \propto 1+\mu\cos(2\phi)$

Photon interaction with matter

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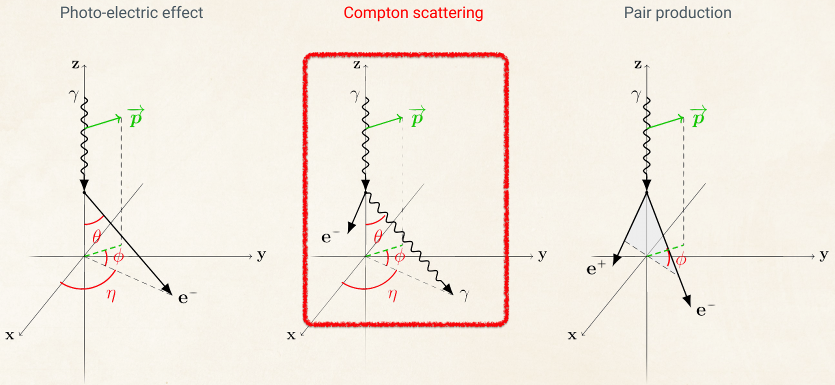


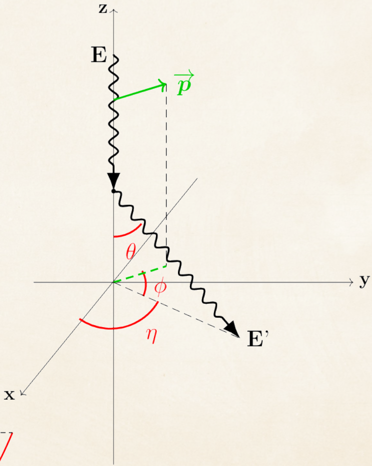
- Each process is dominant at different energies
- The azimuthal distribution of the secondary products is correlated with the polarization direction of the primary photon: $\frac{d\sigma}{d\Omega} \propto 1 + \mu \cos(2\phi)$
- Compton scattering is the dominant process in the energy band where the SF non-thermal emission lies

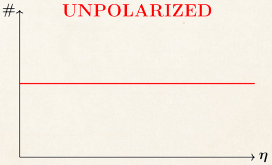
Compton scattering can be used to determine the polarization of a source:

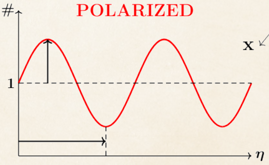
- Azimuthal scattering angle distribution provides information on PD and PA
- Modulation curve parameterized by the Klein-Nishina cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2(\theta)\cos^2(\phi)\right]$$

- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA







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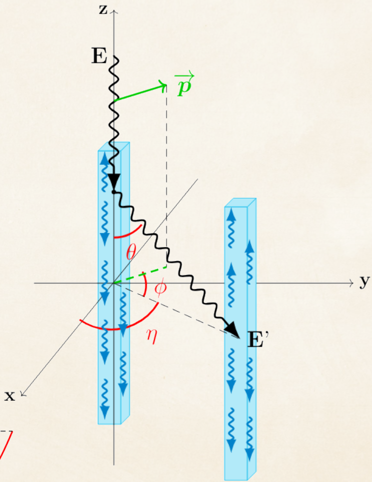
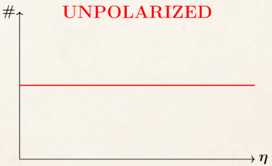
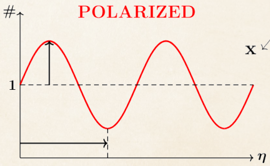
- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA
- **A segmented array of scintillators can be used to measure the scattering angle distribution (aka modulation curve)**

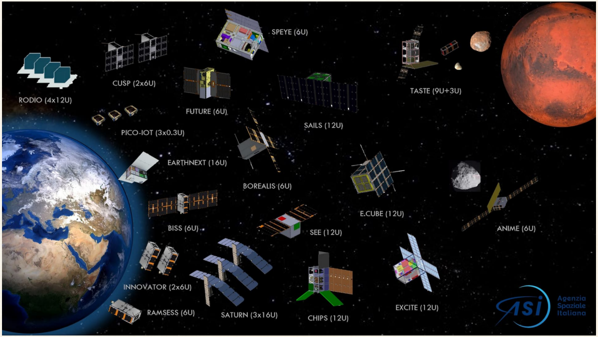






The Project Framework

- The **Italian Space Agency (ASI)** started a new national program named **Alcor** for funding the development of CubeSat technologies and missions
- **CUSP** is one of the 20 selected missions among 49 proposals
- 22 participants from Research Institutes and Universities and 78 companies, mainly Small and medium-sized ones



The CUSP Collaboration

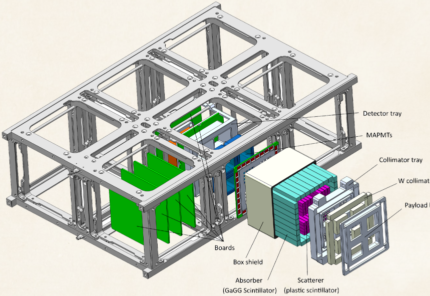
- INAF: **IAPS-Roma:** Prime contractor, PI-ship, and Payload; **OAS-Bologna:** Detector Simulation; **OAR-Roma:** Lab SW Support
- IMT s.r.l.: Satellite Platform
- deda connect s.r.l.: Payload Electronics
- Università di Bologna – CIRI AERO: Mission Analysis
- Università della Tuscia: Ground Segment
- Italian Space Agency (ASI): Project Control

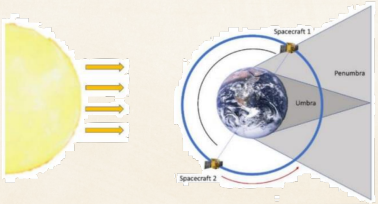
Websites: https://www.iaps.inaf.it/it/missioni-spaziali/cusp

https://www.asi.it/tecnologia-ingegneria-micro-e-nanosatelliti/micro-e-nanosatelliti/il-programma-alcor/cusp/

The CUSP Mission Preliminary Design

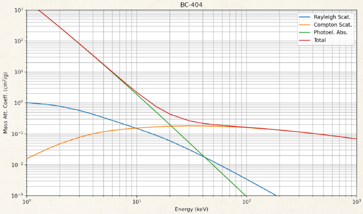
- **Constellation of two 6U-XL CubeSats** orbiting the Earth on SSO orbit (500-600 km) to observe the Sun
- Monitoring of the Sun with a time fraction >68% during the 3 years nominal life-time
- X-ray polarimetry of Solar Flares in the 25-100 keV energy band
- Each satellite hosts a **dual-phase Compton scattering polarimeter** that exploits **coincidence** measurements between plastic (scatterer) and inorganic (absorber) scintillator rods
- **1 RPM rotation** of the spacecraft around the polarimeter symmetry axis pointing the Sun allows to reduce the systematic effect known as spurious polarization



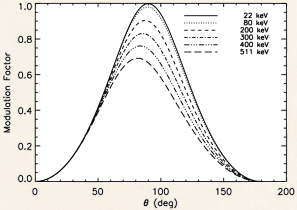


Dual Phase Design

- High probability of **scattering in plastic** material (4 MAPMTs read out with a MAROC-3A ASIC by WEEROC)
- 90° scattering produces maximum modulation of the signal
- @20 keV only 750 eV of Compton energy deposit for scattering at 90°, PMT needed (1-3 optical photons to collect)



NIST XCOM



Fabiani & Muleri 2014

- High probability of **photoelectric absorption** in the absorber (**GAGG**) material (32 APDs read out with a SKIROC-2A ASIC by WEEROC)
- Measurement of **coincidences** Scatterer/Absorber allows effective **background reduction**
- **Fast schedule, no R&D possible,** we need heritage and space proven items as much as possible. We selected APDs from past TSUBAME mission unfortunately lost in 2015 and similar MAPMTs (Y. Yatsu 2014, SPIE Proc.)

Polarimetric Sensitivity

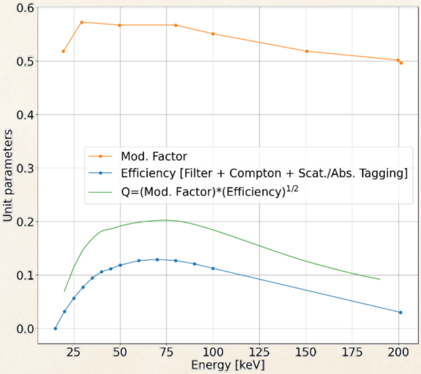
- **Minimum Detectable Polarization** (Weisskopf+ 2010, SPIE, Strohmayer & Kallman 2013, ApJ) in the 25-100 keV energy band (CBE based on benchmark SFs from Saint-Hilaire et al. (2008), Sol. Phys. 250, 53–73)

Flare Class	Integration time (s)	MDP (%) (25-100 keV)
M5.2	284	10.2
X1.2	240	5.0
X10	351	1.1

$$MDP = \frac{4.29}{\mu \cdot R} \cdot \sqrt{\frac{R+B}{T}}$$

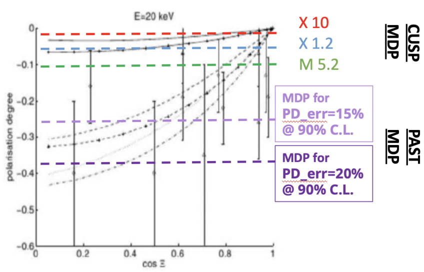
$$Q = \mu\sqrt{\varepsilon}$$

R: source rate
B: background rate
T: integration time
μ: modulation factor
ε: quantum efficiency



Polarimetric Sensitivity

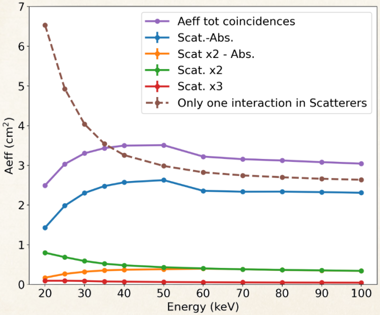
- MDP $\sim 3\sigma$ for 1 parameter measurement (Strohmayer & Kallman 2013, ApJ)
- PD errors of about:
  - 15% with a C.L. of 90% ($\sim 1.645\sigma$) correspond to an MDP $\sim$27%
  - 20% corresponds to an MDP $\sim$37%
- **CUSP will reduce significantly the MDP wrt past observations.**
- Flares are **expected to be polarized at tens of %**, few minutes of integration time allow to measure with high significance their polarization

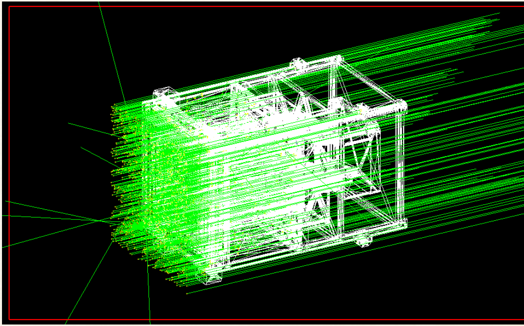


Zharkova+ 2010 (A&A)

Design Optimization: Geant4 Simulations

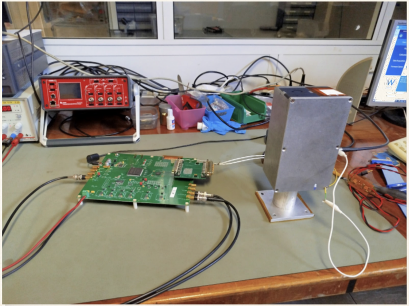
- Analysis of the **effective area** (Aeff) in progress for design and analysis optimization
- We are currently working on getting the **spurious modulation** and **modulation factor** from simulations

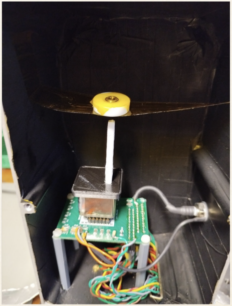


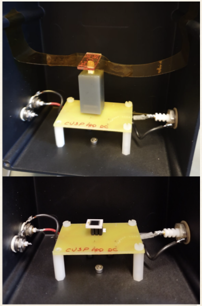


Laboratory Test of the Acquisition Chains

- CUSP is employing **2 acquisition chains** for the **Absorbers** (GAGG + APD + SKIROC-2A) and **Scatterers** (Plastic + MA-PMTs + MAROC-3A)
- Preliminary tests are being conducted based on ASIC Test Boards (WEEROC) and single scintillator bars coupled to sensors







Single Channel Energy Calibration

- CUSP is employing **2 acquisition chains** for the **Absorbers** (GAGG + APD + SKIROC-2A) and **Scatterers** (Plastic + MA-PMTs + MAROC-3A)
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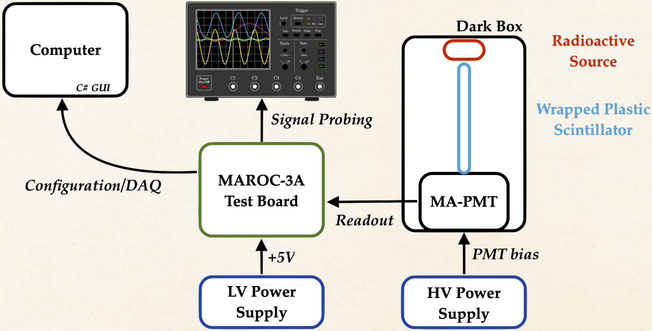
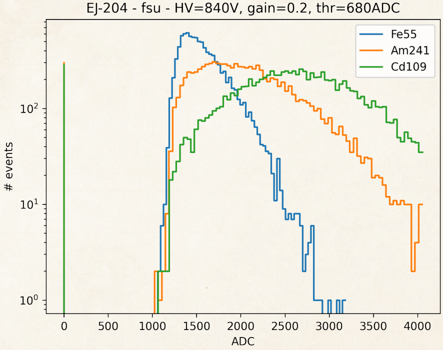
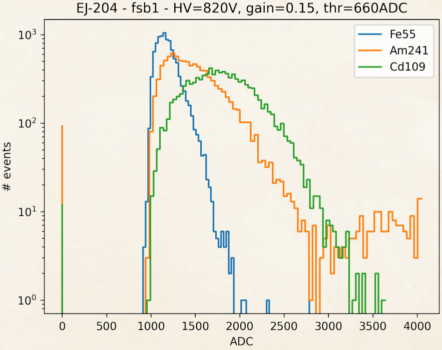
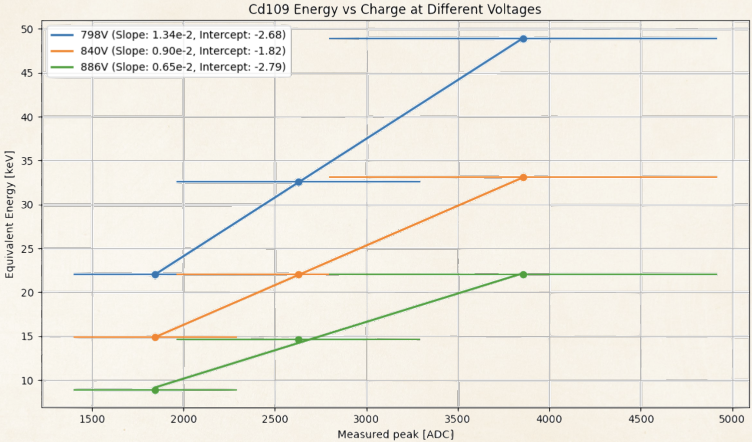


Spectrum of Fe55 (5.9 keV), Cd109 (22 keV), Am241 (18 keV from Compton of 59.5 keV)





Charge [ADC] to Energy [keV] conversion



Real HV [V]	798	840	886
Energy threshold [keV]	7.52	5.07	2.13
Max. Energy (4096 ADC)	52.14	35.24	23.71

Energy Range Requirements

→ from 0.7 keV to 16 keV:

Impinging Energy (keV)	Scattering angle (deg)	Compton energy deposit (keV)
20	90	0.753
25	90	1.17
30	90	1.66
40	90	2.90
50	90	4.46
60	90	6.31
80	90	10.8
100	90	16.4
	65	10.2

Tuning up the preamp gain to reach the 0.7 keV thr.

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Unipolar fast shaper (fsu): **E_{max}=15.2 keV**

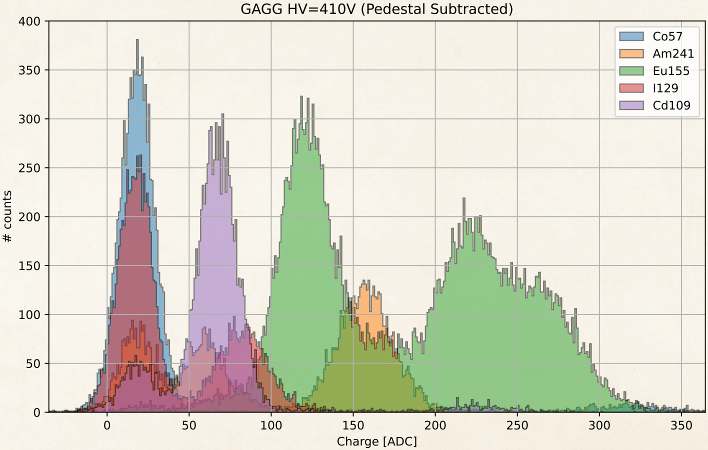
Real HV [V]	798	840	886
Gain ratio to see 0.7keV	2.5345	**1.7125**	1.1394
Max energy for this gain [keV]	15.2287	15.2287	15.2287
Gain ratio to see 20keV	2.3230	1.5696	1.0443
Ratio of the gain ratios	1.0911	1.0911	1.0911

Bipolar fast shaper (fsb1): **E_{max}=17.1 keV**

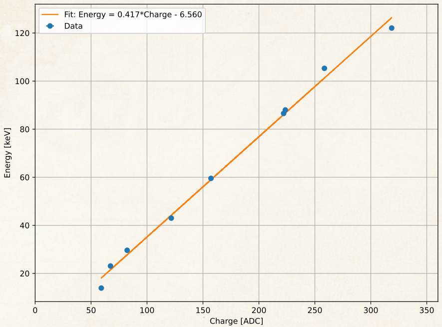
Real HV [V]	798	840	886
Gain ratio to see 0.7keV	2.4002	1.6218	1.0790
Max energy for this gain [keV]	17.1403	17.1403	17.1403
Gain ratio to see 20keV	2.2664	1.5314	1.0189
Ratio of the gain ratios	1.0590	1.0590	1.0590

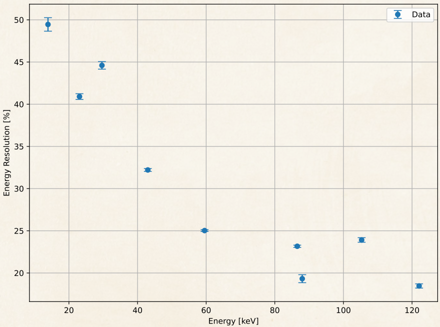
→ these are of course theoretical numbers as the actual energy threshold strongly depends on the light collection efficiency

Spectra of various sources with absorber



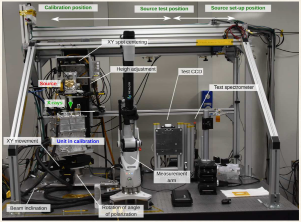
Energy calibration and FWHM resolution





Payload Calibration Plan

- Currently using **calibration sources** (Fe55 – 5.9keV, Cd109 – 22 and 88 keV, Am241 – 59.5 keV, Co57 – 123 keV) with single channel absorber/scatterer read out by ASIC development boards provided by WEEROC
- Soon building a reduced version of the instrument with **4 $\times$ 4 scatterers surrounded by 16 absorbers** to be read out by a **custom FEE** embedding both ASICs and an FPGA to apply the coincidence trigger logic
- This reduced module will be **calibrated in-house using calibration facilities** developed for IXPE's GPD calibration based on X-ray tubes combined with Bragg diffraction crystals to get a highly polarized X-ray flux
- Possibility of **calibration at ESRF** (Grenoble, France) with synchrotron polarized beam in the 20-500 keV range

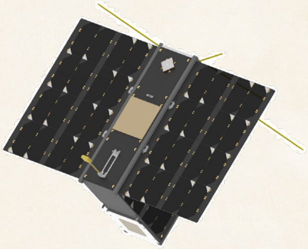


ICE setup @INAF-IAPS

The Satellite Platform

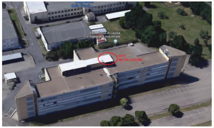
- Designed and produced by **IMT s.r.l.** company
- **6U-XL CubeSat** platform based on the heritage of the HORTA and EOSS platforms (funded by Italian regional POR / FESR 2014-20 projects of Lazio and Puglia regions, respectively).

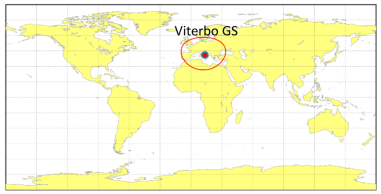
Peak Power	$\sim$ 30 W with Deployable Panels in Sun Pointing
Battery	Up to 84 Wh (baseline 42 Wh)
Pointing accuracy	$\pm 2^\circ$ @ 1σ
Operative frequencies	S-Band downlink; UHF-Band uplink / downlink
Downlink throughput	Up to 5 Mbps
Available interfaces	CAN Bus, I2C, UART, SPI, RS485
Regulated bus	3,3V, 5V e 12V
Not regulated bus	16V (12V-16.8V)
Available volume for the payload	2.5U
Nominal life time	3 years in LEO



The Ground Station

- Located on a building of the Università della Tuscia in Viterbo (Lazio, Italy)
- Built in 2019 for the HORTA project (funds POR/FESR 2014-2020 by Lazio Region)
- Available antennas and bands:
- VHF: Uplink and Downlink
- UHF: Uplink and Downlink
- S-band: Downlink
- UHF/VHF bandwith:
  - Downlink: default 9.6 kbps (available also 1.2/ 2.4 / 4.8 kbps)
  - Uplink: default 1.2 kbps (available also 2.4 / 4.8/ 9.6 kbps)
- S-band bandwith:
  - Downlink: up to 1 Mbps





Project Status

- The 12 months Phase B started last December to define a preliminary design and deliver a representative prototype of the polarimeter
- Next step would be to propose a 15 months combined Phase C/D
- Model Philosophy:
  - 1 detector prototype at the end of Phase B. Representative of the detector front-end (from TRL 3 to TRL 4)
  - 1 payload sub-system Structural Model at the end of Phase B (scintillator bars holding system)
  - 1 payload EQM (design phase B, production and test phase C). Representative of the payload (from TRL 4 to TRL 7)
  - Trade-off assessment to allow ASI to decide if to continue with a 2 CubeSats constellation or with a single CubeSat. Depending on the outcome of the trade-off:
  - 1 Proto-flight Model (PFM). To qualify at proto-qualification level
  - 1 additional Flight Model (FM). To qualify at acceptance level
- Current launch window: late 2027/early 2028