СОФИЙСКИ УНИВЕРСИТЕТ "СВ. КЛИМЕНТ ОХРИДСКИ"

UNISEC GLOBAL
University Space Engineering Consortium

The 6th
Mission Idea Contest
For Achieving Sustainable Development Goals with Human Spaceflight

Gamma-Ray Astronomy Observation as a Subsidiary Function of CubeSat Communication Swarms

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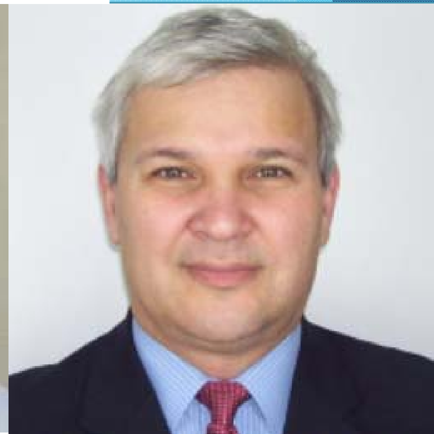

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- satellite swarms
- swarm intelligence
- management of innovations

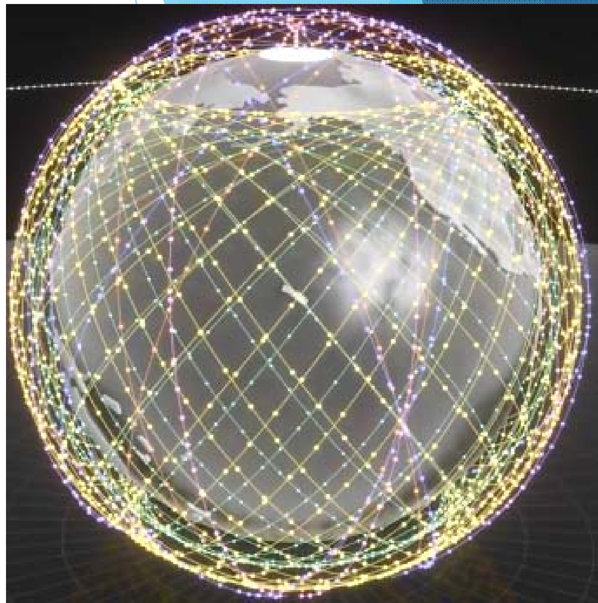
Outline

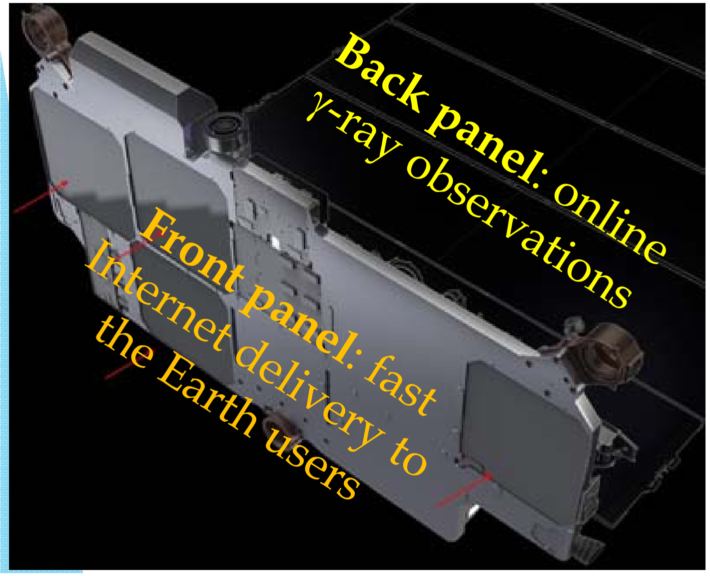
- GAMMA-RAY ASTRONOMY FROM SPACE AND ROLE OF CUBESATS
- MISSION OBJECTIVES
- CONCEPT OF OPERATIONS AND MISSION DESCRIPTION
- SPACE SEGMENTS' DESCRIPTION
- KEY PERFORMANCE PARAMETERS
- IMPLEMENTATION PLAN

<u>Idea</u>: Online Gamma-Ray Observations by LEO Satellite Swarms, Designed for Fast Broadband Internet Delivery

Broadband internet delivery from Space (IoS) through LEO satellites swarms (**primary 5G mission**).

(SpaceX, project Starlink, ~12000 (now up to 42000) LEO satellites, OneWeb, ~3570; Amazon, project Kuiper, ~3236; Samsung, ~4600; Canadian Telesat, ESA space-based 5G network (information from the last week), etc.)





Our idea: to use back "more free" panels of swarm satellites for replacement of gamma-ray detectors for online observation and mapping of gamma-ray burst events (GRBs) from deep space (**subsidiary mission**).

Mission Objectives

- ✓ Our mission idea implementation as a subsidiary function depends on acceptance by owners of big LEO satellite swarms for broadband Internet delivery. Therefore, our first mission objective is to convince (one of) the suppliers of the future 5G Internet of Space (IoS) swarms that γ-ray monitoring could be a feasible and valuable scientific goal.

- ✓ Our project is quite similar to the CRAYFIS project (which proposes synchronized application of smartphone cameras of volunteer users, distributed in mobile-phone networks, to detect ultra-high energy cosmic rays with energy above 10^{18} eV on the Earth surface by applying an algorithm for constructing convolutional neural networks and reliable post processing of weakly activated pixels). We wish to advance even further by transferring such technology to near space (300-1500 km) for really massive and more effective γ-ray observation at lower energies (~MeV) by already proposed small-satellite IoS swarms. This is a typical 5G application of hundred of gamma-ray sensors in a network and we believe that the idea will find enough followers!

Mission Objectives

- ✓ 1) Convince (one of) the suppliers of the future 5G Internet of Space swarms that γ-ray monitoring is a feasible and valuable scientific goal for a *sustainable development* in the area of Science & Technology
- ✓ 2) Develop low-cost, low-weight, low-consumption and sufficiently sensitive γ-ray sensor(s) with accompanying electronics, power supply and coded-aperture imaging technique
- ✓ 3) Verify overall data throughput from detected spectra
- ✓ 4) Verify feasible subsidiary data transfer rate to ground stations that will not interfere with primary function data transfer

Gamma-Ray Radiation in Space

Three main <u>activities</u> for γ-ray observations in Space:

1) Influence over the *human health* in near and deep Space;
2) Influence over the *COTS components*;
3) *Gamma-ray astronomy*: modern knowledge of fundamental processes in the Universe

Physical <u>processes</u> that generate cosmic γ rays:

1) *Collisions* between high-energy particles;
2) *Collisions and annihilation* between pairs of particles and antiparticles;
3) *Radioactive decay* of cosmic radioactive elements (their nuclei);
4) *Accelerated charged particles* that radiate (typically by strong magnetic fields or by electrostatic fields in the nuclei).

Gamma-Ray Astronomy; Flagship Gamma-Ray Telescopes

Astrophysical sources of cosmic γ rays

1) *Nuclear-burning* sites (supernovae, neutron stars, black holes, etc.);
2) *Interstellar space*, where different types of collisions lead to nuclear levels' excitations, followed by de-excitation with accompanied characteristic γ-ray line emission
3) *Places of annihilation* of particles with their antiparticles

Main space-based γ-ray observatories:

1) INTEGRAL (launched 2002 by ESA);
2) FERMI (launched 2008 by NASA);
3) AGILE (launched in 2007, Italy).

Gamma-Ray Astronomy by CubeSat's; why it is possible?

Since 2017, monitoring of X- or γ-rays in near space has received new and very promising support: utilization of CubeSats with incorporated sensitive γ-ray detectors, designed and deployed as space-based single telescopes.

Gamma-ray dedicated missions by CubeSats offer a great variety of valued astrophysical experiments, including:

- *monitoring of selected sources* in deep space for sufficiently long time (weeks or months) such as exoplanets, supernovae stars, black holes and radio transients
- *complementary work* with large flagship space-based instruments for better explanation of observed physical processes.

Gamma-Ray Astronomy by CubeSat's; why it is possible?

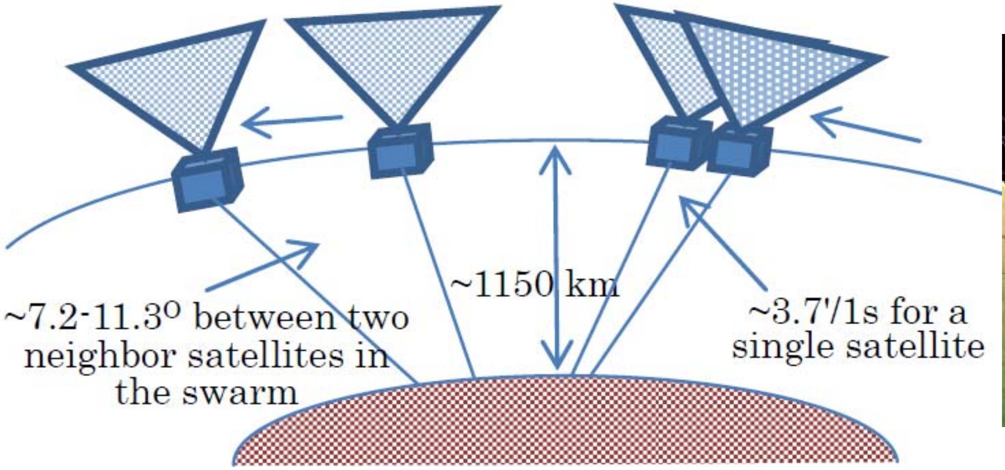
Small observatories housed in CubeSats and primarily prepared for γ-ray research in Space (source: E. L. Shkolnik (2018), "On the verge of an astronomy CubeSat revolution", Nature Astronomy, vol. 2, May 2018, pp. 374-378, www.nature.com/natureastronomy**)**

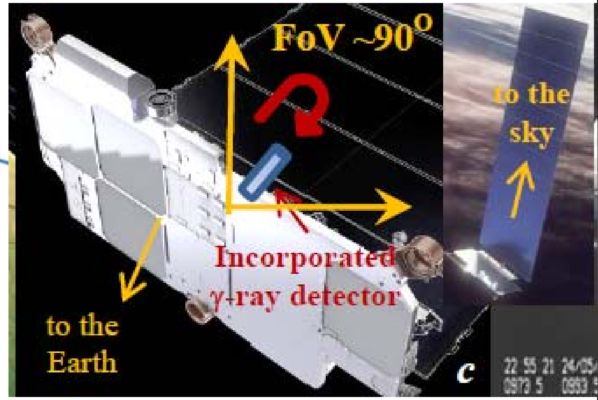
1) ASTERIA (JPL&MIT; 6U, Aug. 2017)
2) CUTE (UColoradoB&NASA, 6U 2020)
3) PicSat (France, 3U, Jan. 2018)
4) HaloSat (UIowa&NASA, 6U, 2021)
5) SPARCS (ArizonaSU&NASA, 6U, 2021)
6) BurstCube (NASA, 6U, 2021) (CsI)

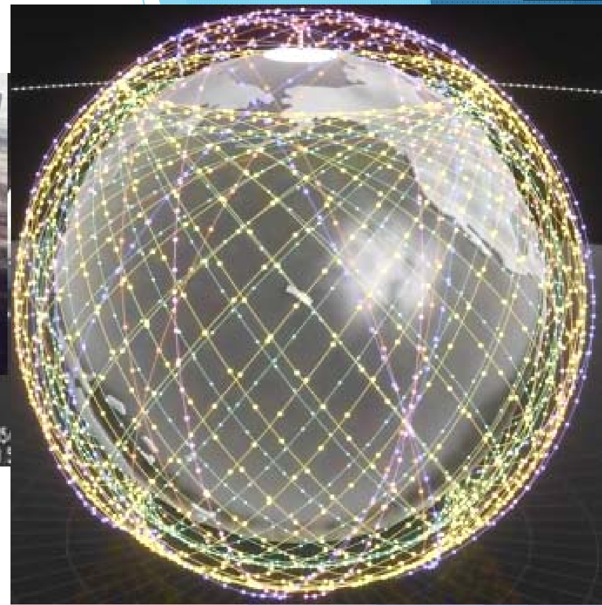
Three important feasibilities of CubeSat-housed γ-ray telescopes, namely:

1) precision pointing (e.g. 5-15" during several minutes of observation);
2) compact sensitive γ-ray low-consumption detectors;
3) incorporated miniature propulsion systems

Gamma-Ray Astronomy by Small Satellite Swarms (*our idea*)







Our concept on the basis of a part of the Starlink project: a constellation of 1600 Ku/Ka-band satellites, flying in 32 orbital planes (50 sat./plane) with 53.8^{o} inclination at ~1150 km altitude. Each satellite has up to 5 laser links for inter-satellite connections to neighbor satellites for execution of their primary function – fast internet delivery (up to 7 Gbps) to Earth-based users. The CzI detectors can be mounted on the top side (inside or outside) of the thin satellite (the solar panels will not disturb the detector operation).

Gamma-Ray Sensors for Small Satellites (Selection)

CsI detectors in protective casing ⇑
Detector systems ⇒

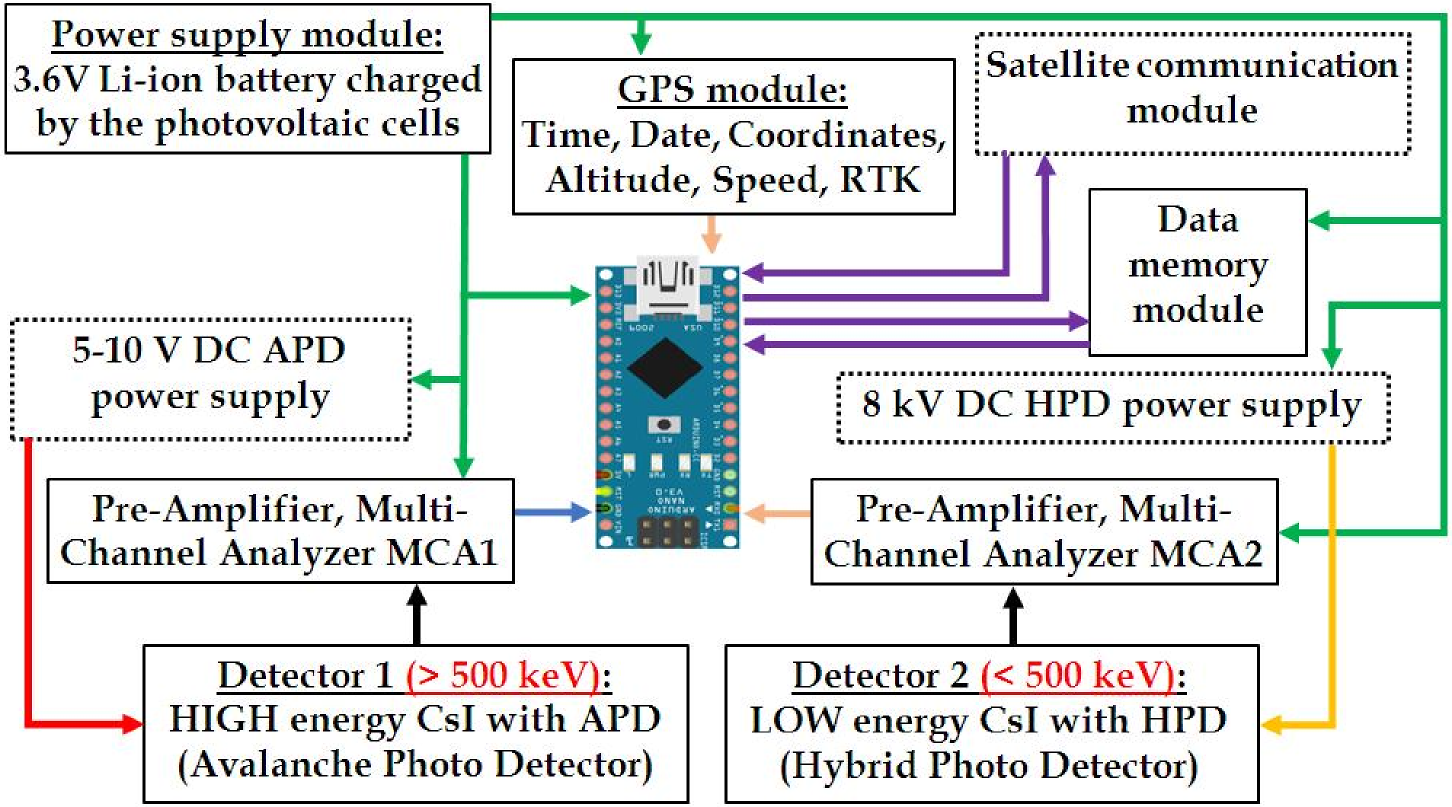
Cylindrical
CsI crystal

Hybrid photo
detector HPD

Table 1. Comparison between some parameters of γ-ray detectors, suitable for CubeSats' incorporation

No.	Type/material	Sizes, mm	Sensitivity, cps/μS/h (Cs-137)	Weight, g
1.	CsI (Tl)	$38 \times \phi 13$	210	40
2.	CZT (CdZnTe)	1000 mm^3	1000	60
3.	NaI	$25 \times \phi 25$	290	120
4.	CsI+Li	$38 \times \phi 35$	1500	550
5.	NaI	$63 \times \phi 63$	4600	1400
6.	Organic scintillator	$75 \times \phi 75$	5800	1400

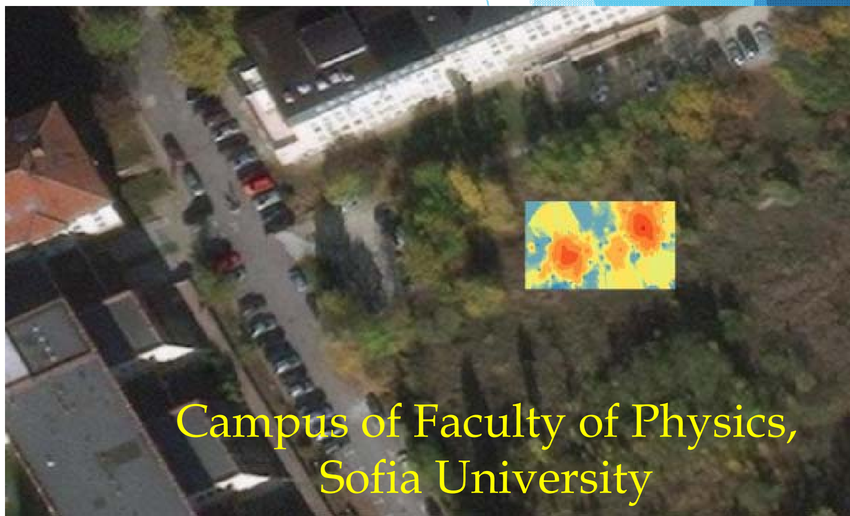
Power and Control Electronic System for On-board Gamma-Ray Detectors



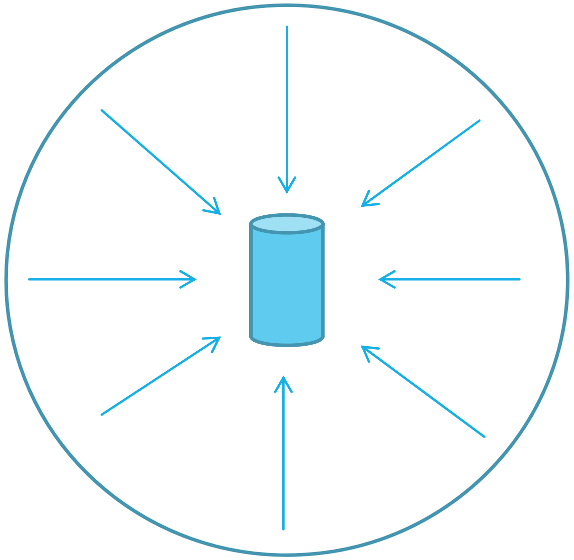
We propose an option with two detectors:

1) High-energy (> 500 keV) CsI detector with Avalanche Photo Detector (APD) (1 Hz repetition frequency)
2) Low-energy (< 500 keV) CsI detector with Hybrid Photo Detector (HPD) (16 Hz repetition frequency)

Test of Detectors and On-Board Electronics by UAV for mapping of radioactive contaminations (already passed)

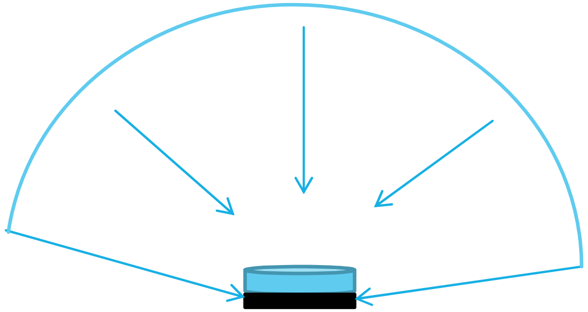


Gamma-Ray Detector Field of View (FoV)



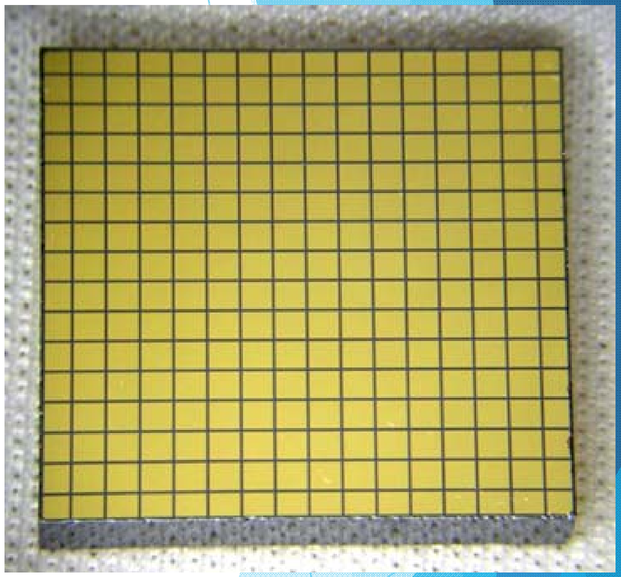
Crystal detectors (scintillators)

FoV ~360 deg



Semiconductor detectors (CZT)

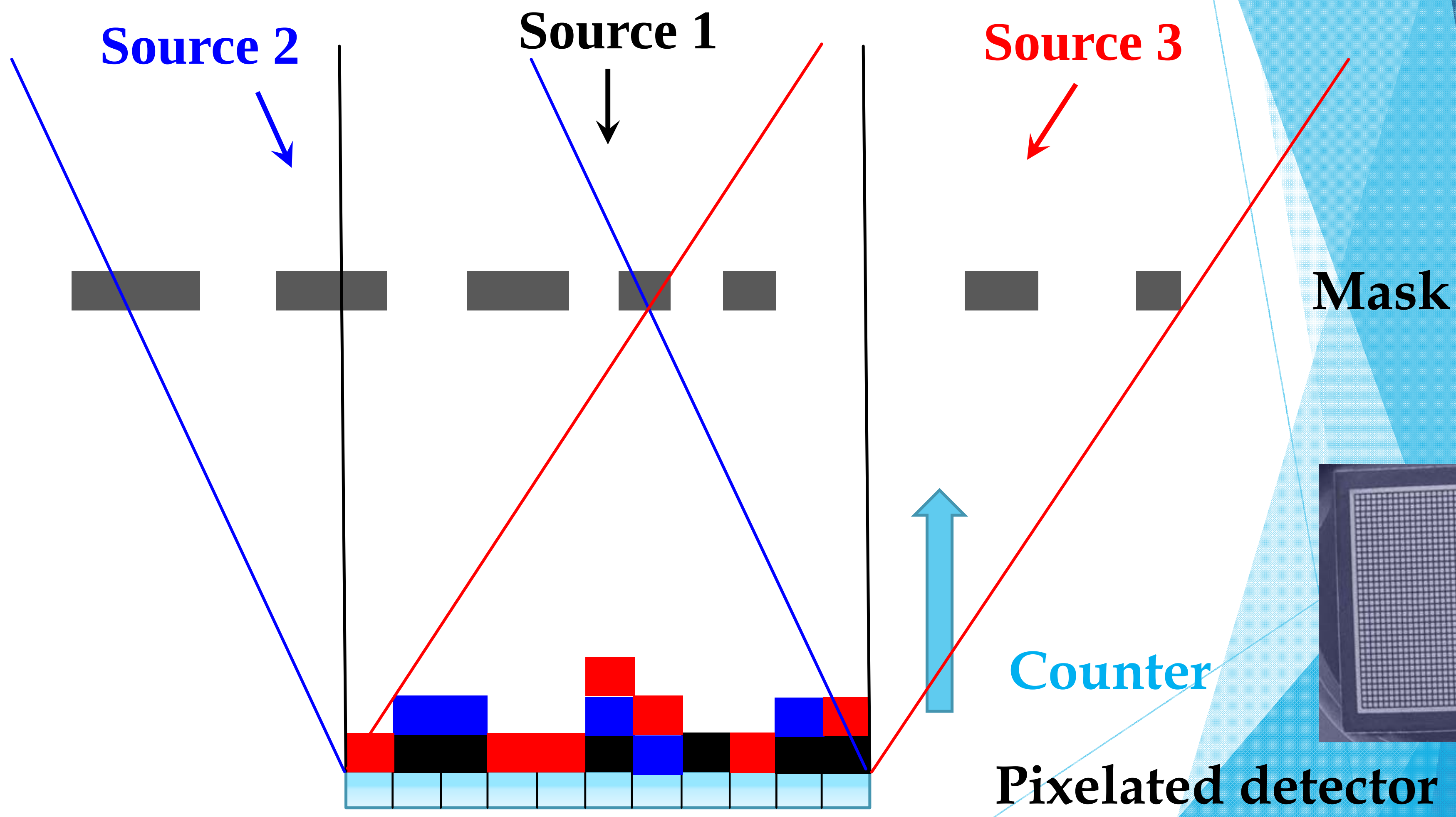
FoV ~90-120 deg

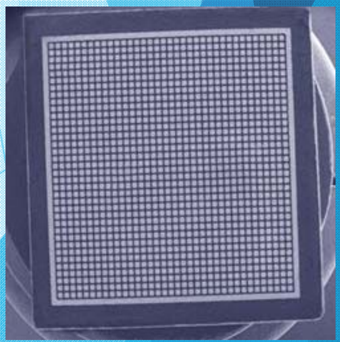


Pixelated detectors

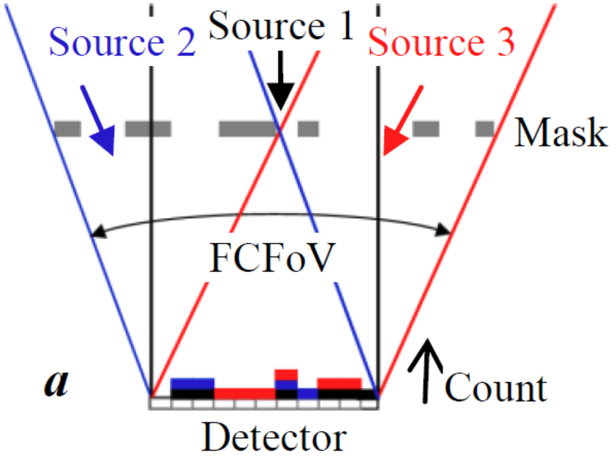
Controlled FoV and resolution angle

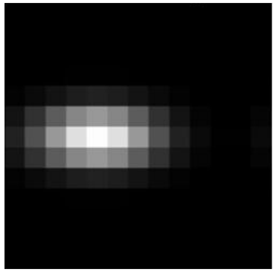
Pixelated Sensors with Appropriate Masks (tungsten)



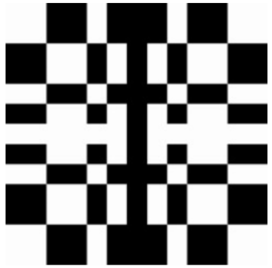


Coded-Aperture Technique for Small-Satellite Swarms with Incorporated Gamma-Ray Pixelated Sensors

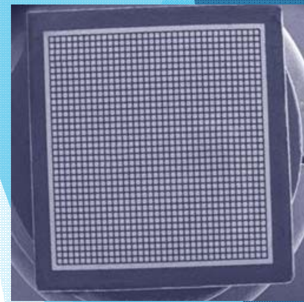




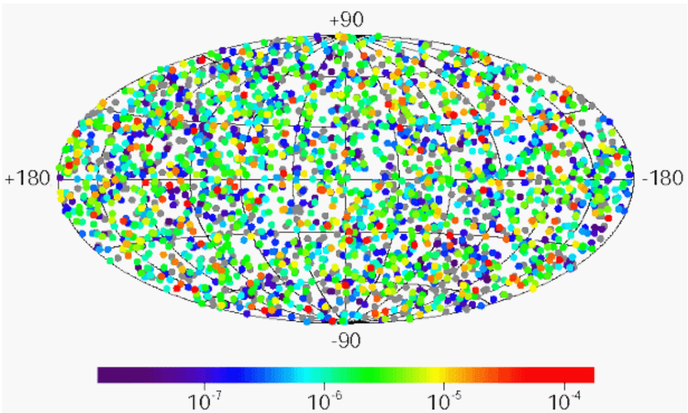
Gamma-ray source



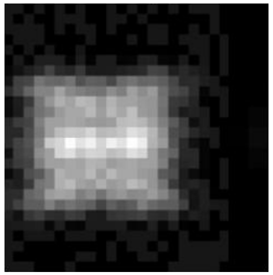
2-mm thick tungsten mask with 21 × 21 mask elements with sizes 1.73 × 1.73 mm at distance ~**7.5 mm** from detector



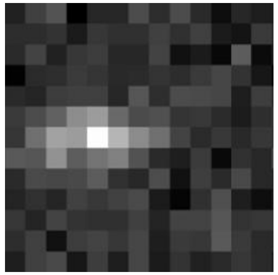
20×20×15 mm^3 CZT detector with 11×11 array of pixels



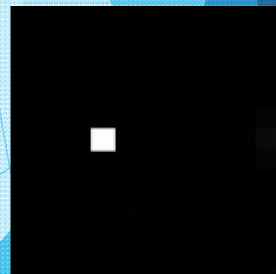
Example of γ-ray events' image of over the star sky (taken from https://apod.nasa.gov/apod/ap000628.html)



CCD image with added noise



Reconstructed image with added noise



Idealized image; achieved **angular resolution of ~13º**

Data Throughput from CsI Gamma-Ray Sensor(s) on LEO

Any γ-ray spectrometric system capable of georeferencing measurement spectra should have a fast communication line for transmitting of:

1) accumulated spectra for 1 second

2) coordinates, altitude, date and time

The question is how big is the data throughput from the onboard gamma-ray detectors?

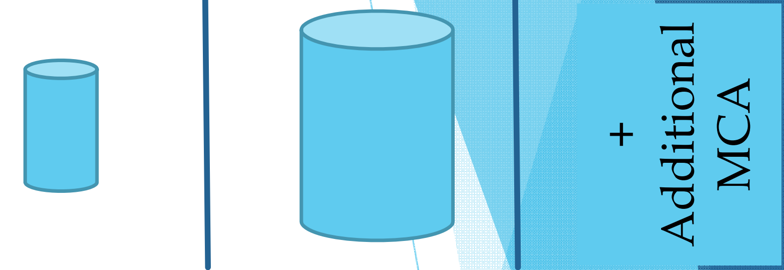
Total number of energy channels in the multi-channel analyzer (MCA):

$$N_{tot} = E_{max}.\mathrm{FWHM}/E_0.R,$$

where E_{max} is the maximal necessity energy in the spectrum [MeV]; E_0 – energy in the peak [MeV]; R – detector resolution; FWHM (full width at half maximum, 5 ch.); N_{tot} = **1340** channels (2048 = 2^{11})

Our choice (2 sensors in 1(2) Sat.):

(0-0.5 MeV) | **(0.5-10 MeV)** | **(10-90 MeV)**

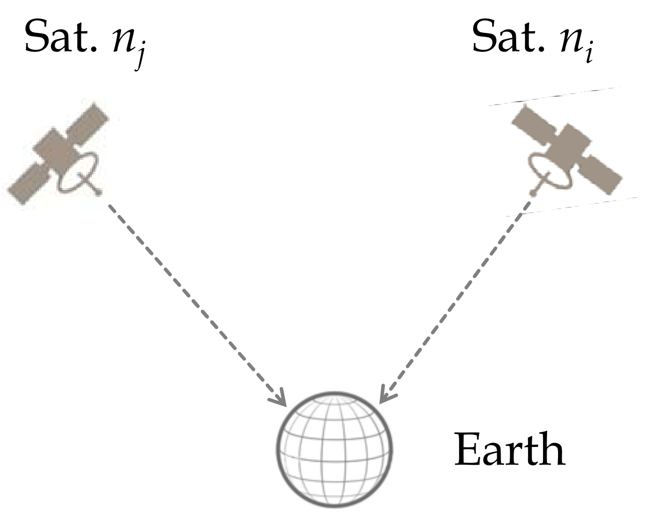


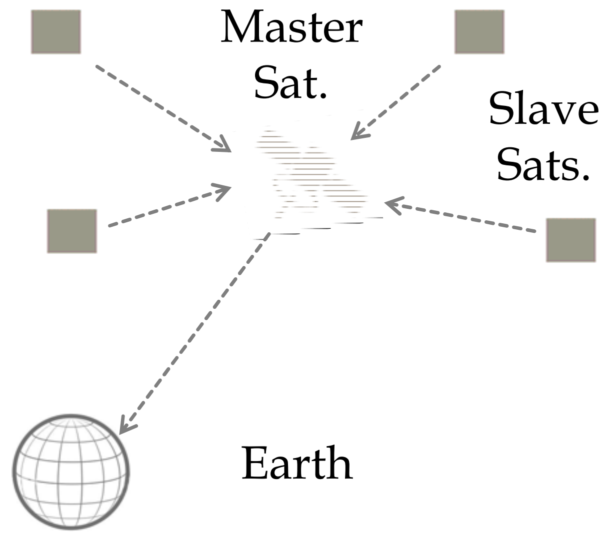
One small sensor with thin input window	One larger sensor with thick input window (0.5-10 MeV) + additional MCA (for 10-90 MeV)

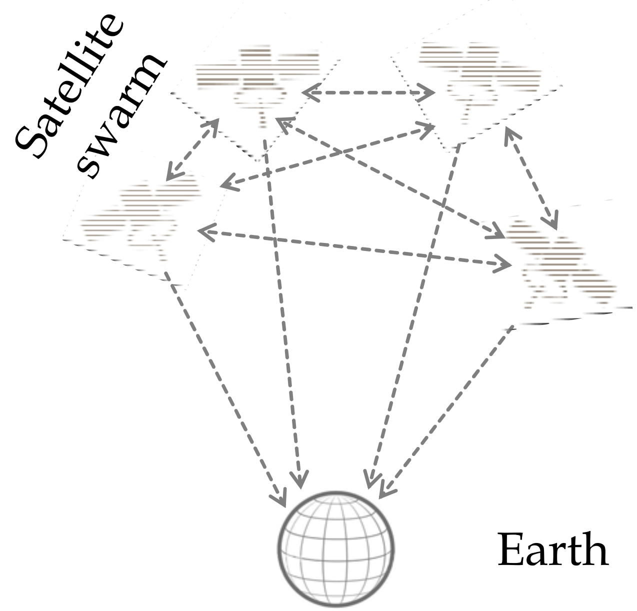
Amount of memory required to record a spectrum for one second: (2048+2048) × 13 bits (8000 counts/channel)+ 16 × [(67×13 bits) + 4 bits] = 67248 + 146 bits (time,date, altitude,coordinate) ⇒ **67.394 kbps**

Data Rate for Gamma-Ray Records' Transfer from LEO

Scenarios:







Option 1: Each LEO satellite directly communicates to Earth:

~0.1 Mbps (150 %)

For 90-min. orbital period: 540 Mb; Necessary DL data rate :

~1.5 Mbps (for 6-min. communication session to Earth)

Option 2: Slave satellites in the swarm (*Ns*) communicate with the Master satellite; only the last one communicates to the Earth. For 90-min. orbital period: 540× *Ns*, Mb; Necessary DL data rate:

~1.5×*Ns* Mbps (for 6-min.)

Option 3: Each satellite in the swarm (*Ng sats. with detectors*) communicates with other swarm satellites and uses the broadband Internet channels to the Earth. Necessary DL data rate: **~0.1×*Ng* Mbps**

Link Budged for LEO to Earth Station Data Transfer

Maximal achievable bit rate $$r_b, \text{bps} = 10^{R_b/10}$$

$$R_b, \text{dBbps} = (C/N_0 - E_b/N_0 - \text{Margin})$$

$$C/N_0 = \text{EIRP}\big|_{Tx} + G/T\big|_{Rx} + 228.6 - \text{Losses}$$

$$\text{EIRP}\big|_{Tx} = G_{Tx} + P_{Tx} \qquad \text{losses} = 20\log(4\pi d/\lambda)$$

Table 2. Maximum achievable bit rate r_b, Mbps for QPSK modulation in an effective bandwidth BW_{eff} reduced due to the Doppler shift and needed gross bit rate R_b, dB.bps

Allocated frequency band, GHz	Max permitted BW, MHz	Max Doppler shift, kHz♣	Min effective BW_{eff}, MHz♣	Max bit rate r_b, Mbps (QPSK)♣	Needed gross bit rate R_b, dB.bps (QPSK)
0.435-0.438	0.02	±10.2/9.3	0.01/0.0011	0.03	44.77
2.427-2.443	10	±57.2/52.1	9.89/9.90	14.8/14.9	71.71
5.83-5.85	10	±101.9/92.8	9.70/9.73	14.5/14.6	71.65
10.37-10.45	10	±244.8/223.0	9.51/9/55	14.3/14.4	71.55
24.05-24.25	10	±568.1/517.6	8.86/8.96	13.3/13.4	71.28
8.025-8.175	50*	±191.5/174.5	49.62/49.65	74.4/74.5	78.72
25.50-27.00	50*	±632.6/576.3	48.73/48.84	73.1/73.3	78.65

* available channel bandwidth for EESS frequency bands; ♣ pair of parameters for 800/1500 km orbit altitudes

Link Budged for LEO to Earth Station Data Transfer

Table 3*a*. Available E_b/N_0 and margin M, dB in the downlink (DL) channels for QPSK modulation for single planar patch on-board antenna with fixed gain +7 dB and equivalent dish antenna of diameter 1.2 m for the ground station (P_{GS} = 2 W)

Central f, GHz / BW, MHz	LEO altitude, km	Path losses, dB♣	C/N_0, dB.Hz♣	Available E_b/N_0; Margin M, dB (P_{sat} = 1 W; P_{GS} = 2 W; 1.2-m diameter for the equivalent dish)♣	Req. P_{sat}, W (E_b/N_0 = 9.6 dB; M = 3.5 dB)♣
2.435/10	800/1500	158.2/163.7	89.3/86.84	(17.60;8.00)/(12.15;2.55)	0.355/1.25
5.84/10	800/1500	163.3/171.2	89.3/86.84	(17.65;8.05)/(12.22;2.63)	0.350/1.23
10.41/10	800/1500	170.9/176/3	89.3/86.84	(17.70;8.10)/(12.30;2.70)	0.346/1.22
8.10/50*	800/1500	168.7/174.1	89.3/86.84	(9.58;0.98)/(5.11; -4.49)	1.785/6.28

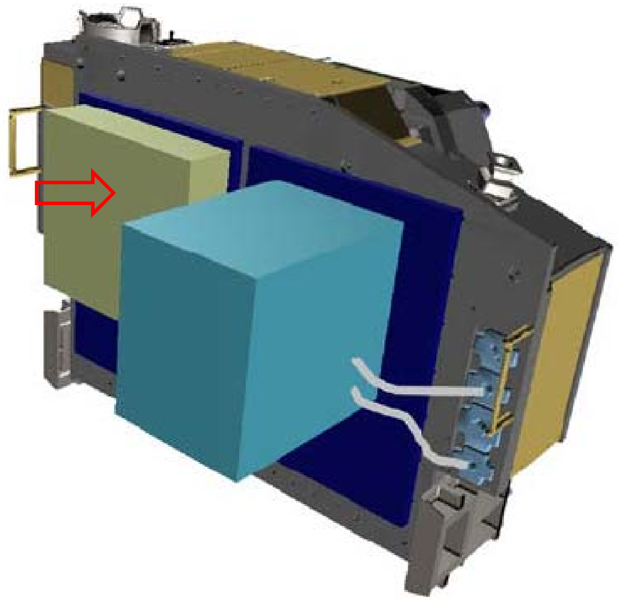
* available channel bandwidth for EESS frequency bands; ♣ pair of parameters for 800/1500 km orbit altitudes

Table 3*b*. Available E_b/N_0 and margin M, dB in the downlink (DL) channels for QPSK modulation in the X band (10.41 GHz/10 MHz) for different on-board antennas (P_{GS} = 4 W; equivalent dish antenna of diameter 1.8 m for the ground station)

On-board antennas	Antenna gain, dB / 3-dB beamwidth Δθ/Δφ, deg	LEO altitude, km	C/N_0, dB.Hz♣	Available E_b/N_0; Margin M, dB (P_{GS} = 4 W; 1.8-m diameter for equivalent dish)♣	Req. P_{sat}, W (E_b/N_0 = 9.6 dB; M = 3.5 dB)♣
Single patch	+9.4/ 61.1/61.1	600/1500	97.6/89.7	(19.3; 9.7)/(10.4; 0.8)	0.24/1.50
2-patch array	+12.7/ 27.5/61.1	600/1500	101.0/93.1	(22.7; 13.1)/(14.8; 5.2)	0.107/0.68
4-patch linear array	+16/ 13.8/61.1	600/1500	104.3/96.4	(26.0; 16.4)/(18.1; 8.5)	0.051/0.317
2x2-patch array	+12.9/ 27.1/27.1	600/1500	101.2/93.2	(22.9; 13.3)/(15.0; 5.4)	0.104/0.65

♣ pair of parameters for 600/1500 km orbit altitudes

Preliminary Test of the Gamma-Ray Detection System on the ISS



Our project is not directly meant for implementation on the ISS. However, we anticipate a preliminary testing period for the proposed γ-ray detectors, which have to be incorporated on satellites in a communication swarm.

The test can be performed first *on the Earth in laboratory conditions* with all detectors and selected γ-ray sources (for effectiveness; test of electronics, software, data throughput, coded-aperture technology and synchronized work of the pair of detectors).

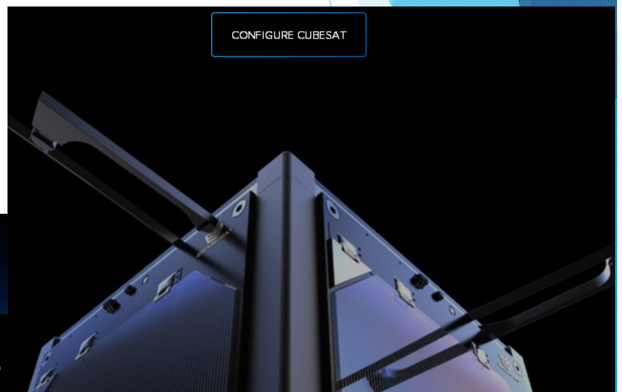
Then, the same set of tests could be performed on the iSEEP platform outside the ISS, thus in real conditions.

In addition, the threshold S/N level could be selected more precisely, and accuracy for source direction determination could be evaluated on-board. We propose three levels of application of on-board detectors (single, pair of detectors and pixelated detector).

Preliminary Test of the Gamma-Ray Detection System on the ISS

Costs of detector systems:

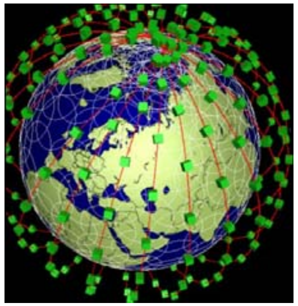
1) Single detector + electronics **~€1650**
2) Pair of detectors +electronics **~€3300**
3) CdZnTe single detector 1600 mm^3 **~€6000**
4) Pixelated detector and mask **~€70000**
5) + 1U satellite (by Endurosat Ltd.) **~€25350**



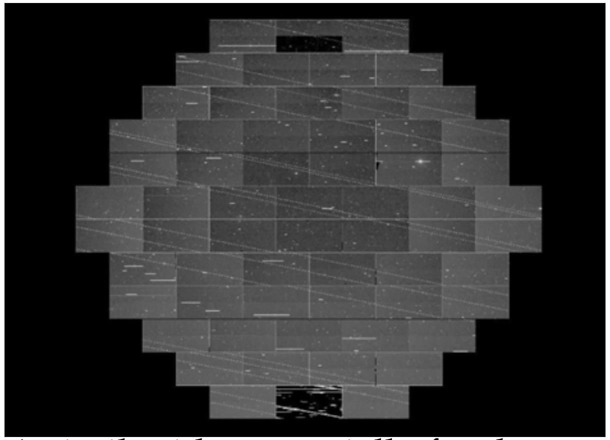
Popularization of the mission and implementation plan

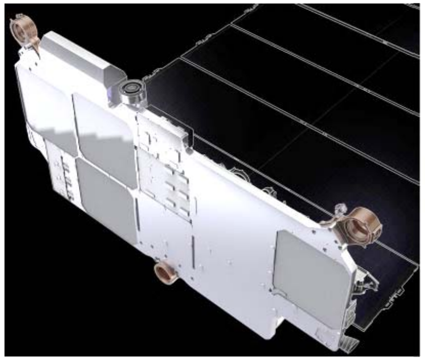
We envisage three phases of project realization:

1) Design of a suitable γ-ray detector(s) and preliminary proof of concept (e.g. by iSEEP Platform outside ISS) (2.5 years);
2) Attracting owners of big swarms for 5G internet delivery to the possibility of γ-ray monitoring with the same satellites, and
3) After initial positive results – launching of several hundred satellites with γ-ray detectors and compiling online a GRB's map of star-sky background (3 years).



Popularization of the mission and implementation plan





A similar idea especially for the Starlink project could be helpful to decrease opposition from astronomers who claim that artificial brightness of satellite swarms would disturb astronomical observations from the Earth.

Main mission risks

The major risk factors for our innovative project are:

(i) Not to be able to **prove the concept** and
(ii) Not to **receive support** from owners of big satellite projects for broadband IoS internet.

The other two technical risk factors are:

Achievement of **insufficient γ-ray detection efficiency** or

(i) Exceeding counting-speed capabilities in situation of unexpected γ-ray intensities.
(ii) Occurrence of **higher data throughput than evaluated** is also risky for the overall implementation of online γ-ray monitoring of deep space as a subsidiary function which does not interfere with the primary one.

Conclusions

- ✓ *Gamma-ray bursts observation* from the space through IoS small satellites in a swarm for future Internet delivery from Space as a subsidiary function is fully possible as a promising 5G application of hundred of gamma-ray sensors working in concert

- ✓ There exist enough flight-proven effective, low-weight, low-consumption and low-cost *gamma-ray sensors*, which are able to ensure reliable really massive gamma-ray observation from the space through small-satellite swarms

- ✓ Effective *codded-aperture technique* can ensure detection of the angle of gamma-ray events with satisfactory accuracy

Conclusions

- ✓ Increased ***data throughput*** due to the synchronised work of hundred of gamma-ray detectors could be minimised by reliable on-board data treatment

- ✓ Necessary overall ***data transfer speed*** is evaluated as ~100×*Ng* kbps, where *Ng* is the total number of satellites with on-board γ-ray detectors; ***will not interfere*** at all the main Internet delivery function!

- ✓ ***Overall cost*** of implemented on-board gamma-ray tools varies between ~€1650, ~€6000, or ~€70,0000 depending on used single, double or pixelated detectors

Thank you for your attention!