Presentation of the R&D work and the future needs for IR detectors at ESA

Brian Shortt/Nick Nelms

07/12/2022

ESA Detector Development – Strategy

- For Science detector developments are typically mission driven, with some longer term strategic
- Development roadmaps and technology harmonisation –

Achieved through both dedicated roadmap development for major technology streams e.g.

- **NIR Large Format Sensor Array Technology Development Plan (ALFA)**
  - Development programme aimed at developing 2K x 2K, very low noise, very low DC, MCT array + supporting ASIC. (TEC-MME/2008/100)
- **Low Dark Current 2D MWIR to VLWIR MCT Detectors Technology Development Plan**
  - Coordination and synergy of detector development activities at ESA aiming towards the next generation of MCT 2D IR detectors. (TEC-MME/2012/290)
- **European CMOS Image Sensor Technology Development Plan**
  - Two phase programme aimed at investigating and supporting European CMOS foundry interest and capability for development of high-performance image sensors. (EUROCIS-TDP-01032011MZ-NN)

and via technology harmonisation with industry

- **ESA Technology Harmonisation**
  - ESA/Industry approved roadmap of Technologies for Optical Detectors (ESA/IPC/THAG(2022)5). Revision 4.2
- **Detector Working Group**
  - Endorsed by Component Technology Board, as part of the Policy and Standards

ESA Technology Development

(Detector) technology developments are initiated through several dedicated programs:

Technology Development Element (TDE, formerly TRP)
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/About_the_Technology_Development_Element_programme_TDE

General Support Technology Programme (GSTP)
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/About_the_General_Support_Technology_Programme_GSTP

Science Core Technology Programme (CTP)
https://www.esa.int/About_Us/Business_with_ESA/Business_Opportunities/Science_Core_Technology_Programme

Earth Observation Envelope Programme (EOEP)
http://www.esa.int/About_Us/Business_with_ESA/Business_Opportunities/Earth_Observation_Envelope_Programme

European Component Initiative (ECI)
http://www.esa.int/Enabling_Support/Space_Engineering_Technology/European_Component_Initiative_ECI

Open Space Innovation Platform (OSIP)
https://ideas.esa.int/

Secure and Laser Communication Technology Program (Scylight)
https://artes.esa.int/scylight

The scope of these programs varies by domain (e.g. EO, Science) and by Technology Readiness Level.

OSIP also provides support for PhD and Post-doctoral research posts

ESA Detector Development

Detector developments covered in this presentation

1. ALFA-N – Large-format NIR MCT hybrid array development
2. ALFA-C – Control ASIC development
3. LAPD – Large-format NIR avalanche photodiode array development

NIR Astronomy Large Format Array (ALFA) Development

The ALFA development program was formulated in 2008 with the aim to develop a European large-format MCT hybrid array and dedicated control ASIC for astronomy applications.

Phase 1 (Not discussed here)

Optimise MCT material – parallel activities with CEA-LETI (FR), Leonardo (UK), Qinetiq (UK)

Prototype Control ASIC development activity was initiated with Caeleste (BE)

Phase 2

Prototype ROIC development hybridized to optimized MCT material from Phase 1 – parallel activities with CEA-LETI (F) and Leonardo (UK)

ALFA-C Optimised Control ASIC development - activity with Caeleste (BE)

Phase 3

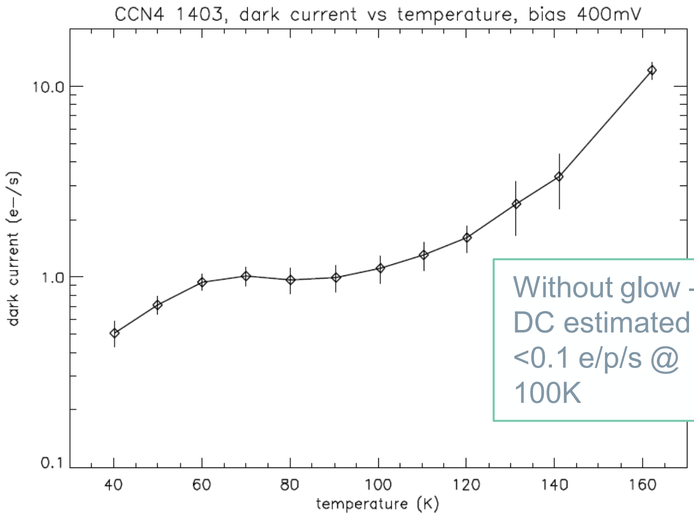
ALFA-N 2k x 2k Hybrid MCT array development – activity with Lynred (F)/CEA-LETI (FR)

Phase 2 – Prototype hybrid array

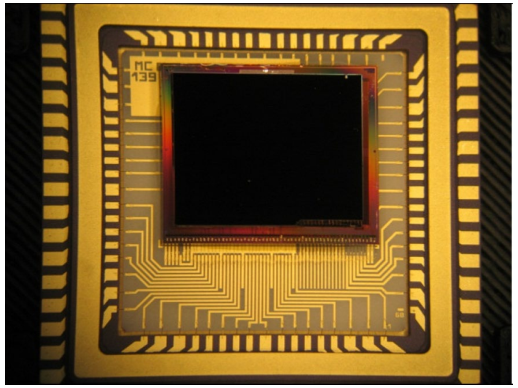
New ROIC developed – 640 x 512 pixels
15 um pitch, SFD
Optimised MCT

Very good performance achieved -

Dark current limited by ROIC glow

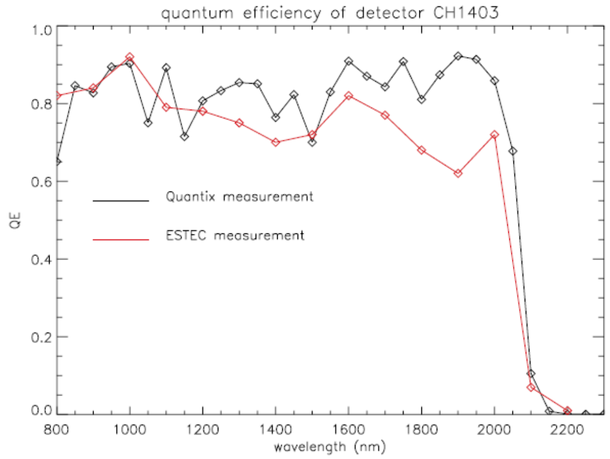


Without glow – DC estimated at <0.1 e/p/s @ 100K

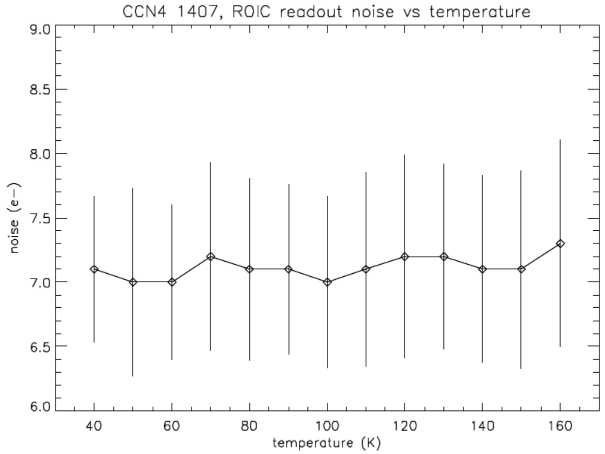


CH1407 Hybrid Array

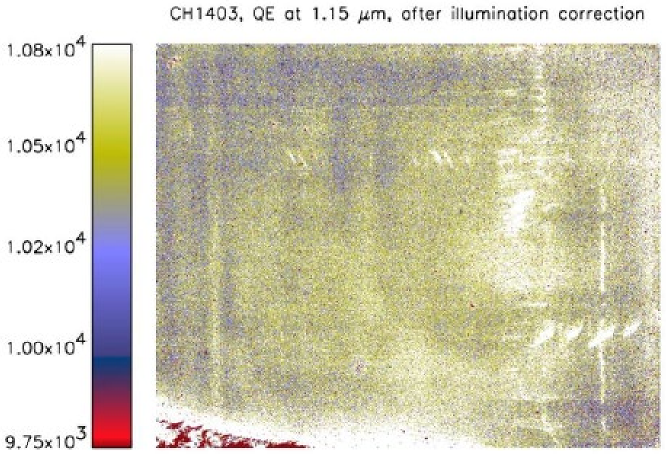
QE ~80%, cut-off 2.1 um



ROIC read-noise ~7 e-rms



PRNU ~2.5%



ALFA-N Phase 3 - Specification

Challenging activity – new 2k x 2k pixel ROIC, large format MCT (3 x 3 cm2), custom package with flex connector

Target Specification

Parameter	Value	Comment
Array size	2k x 2k	
Pixel pitch	15 um	
QE	>70%	
Read-out mode	Rolling shutter	Non-destructive readout
CHC	60 ke-	
Dark current	0.1 e-/p/s	At 100 K
Read noise	18 e-rms	Single CDS
Frame rate	>1 Hz	
Operating temperature	100 K	Nominal
Cut-off wavelength	> 2.1 um	
Cut-on wavelength	< 0.8 um	

7 e-rms Up-the-ramp (150 samples)

Schedule

- Kick-off: Nov. 2016
- TRR part 1 Dec 2019
- Final TRR November 2022
- Planned completion: Q1 2023

ALFA-N Phase 3 – ROIC

ROIC Status

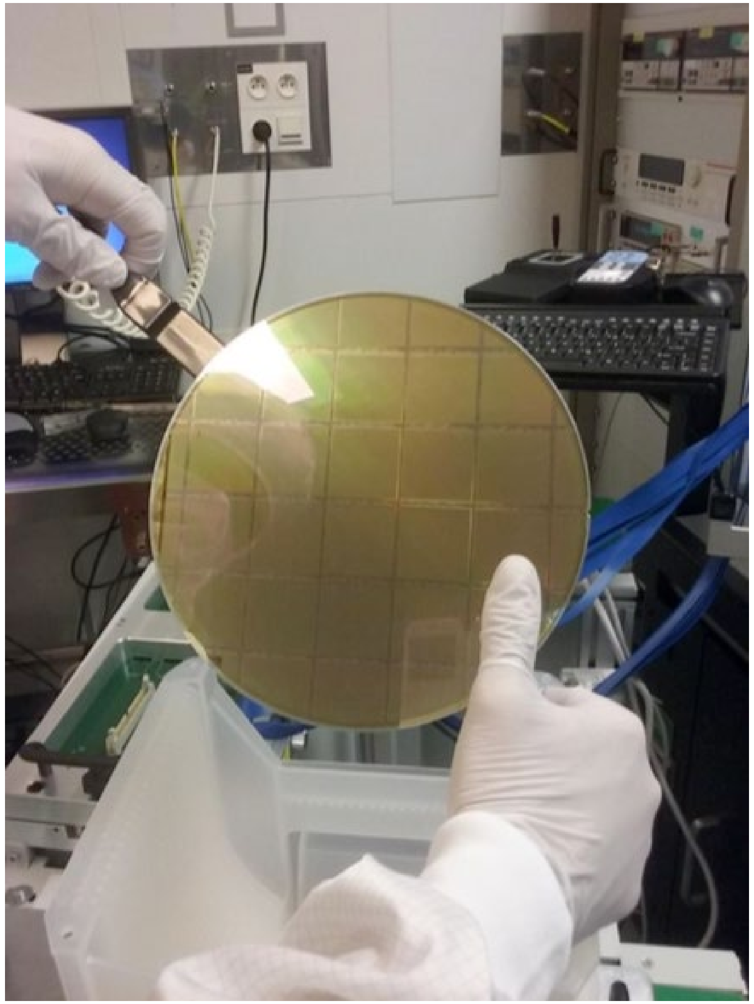
Rad-hard ROIC design and manufacture completed – ROIC delivery Q2 2018

ROIC operational and suitable for detector hybridization and characterisation, but

Several design issues identified –

- Global reset mode not operational
- Reference pixels operation and grey mode affected
- Rower consumption affected
- High read-noise (28 e-rms)
- Row-reset behaviour
- Window addressing

ROIC functional at Top (100K)
ROIC glow minimized



ALFA-N Phase 3 – MCT hybrid

Hybrid detector status

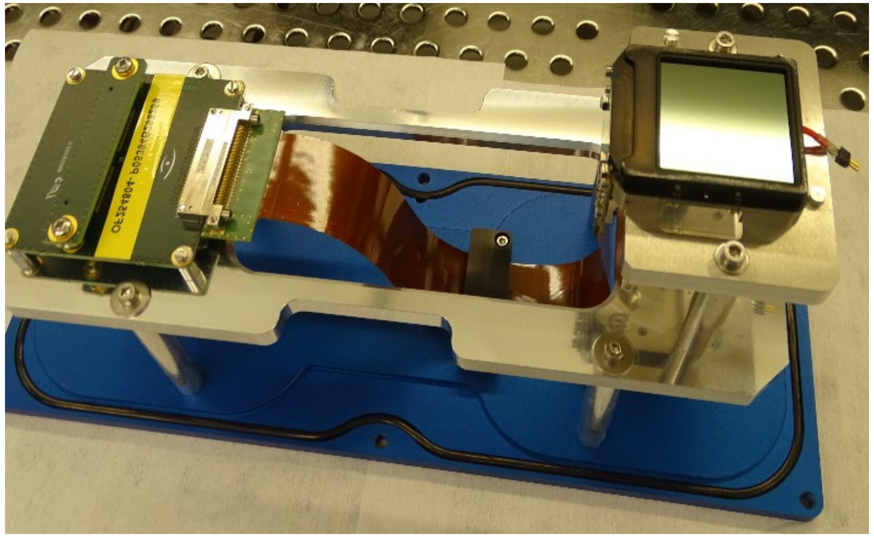
- 3x batches of 4 MCT wafers grown at CEA-LETI – 1x 2k x 2k array site per wafer
- Hybridisation, ARC and packaging performed at Lynred
- 4 detectors hybridized – 3 selected for characterisation

MCT hybrid 3 x 3 cm^2

2x ROIC packaged and delivered to ESTEC

1x Hybrid Array packaged and delivered to ESTEC

3x Hybrid Array packaged and delivered to CEA-IRFU



Packaged ROIC

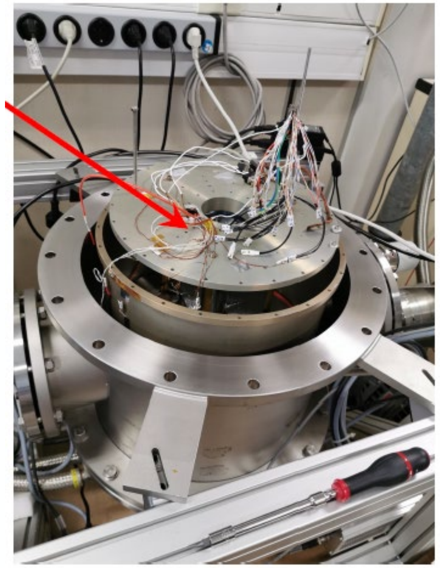
ALFA-N Phase 3 – Characterisation

Detector characterisation

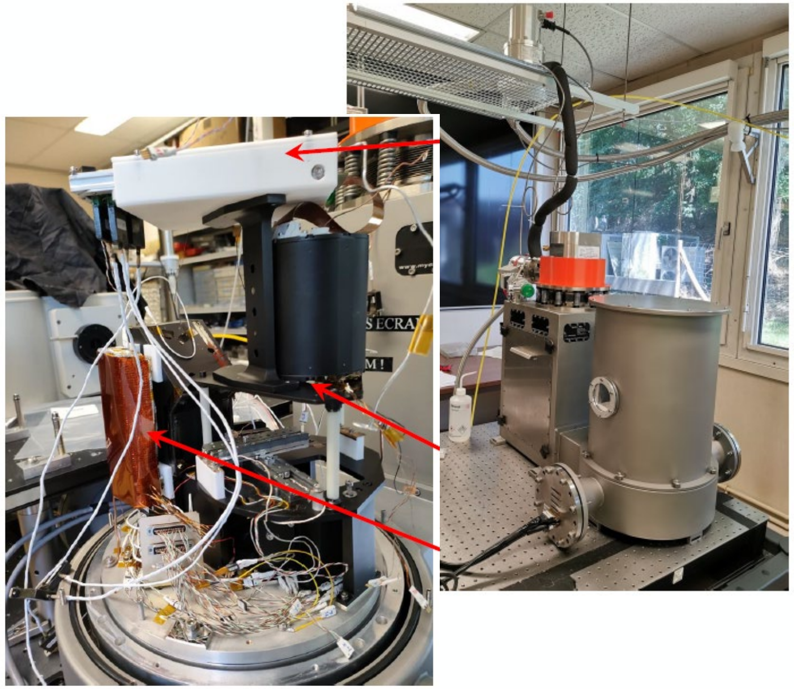
3 test benches utilised at CEA-IRFU

- Verticalix – dark measurements
- Quantix – QE measurements
- Intrapix – intrapixel responsivity

Verticalix



Quantix



ALFA-N Phase 3 – Performance CEA-IRFU

3 Hybrid MCT detector arrays characterised

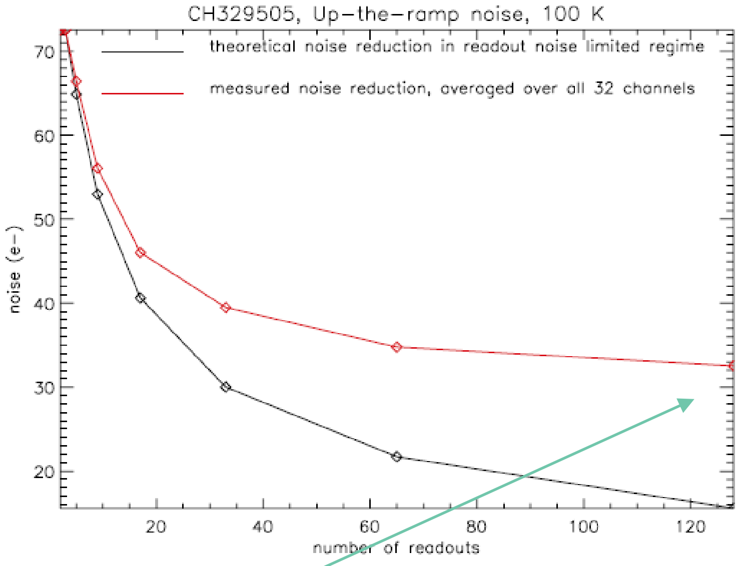
2 fully characterised, 1 not fully functional

Overall performance reasonable –

- Good dark current measured (~1 e/p/s)
- No ROIC glow evident
- QE~60% but not matching performance of prototype arrays

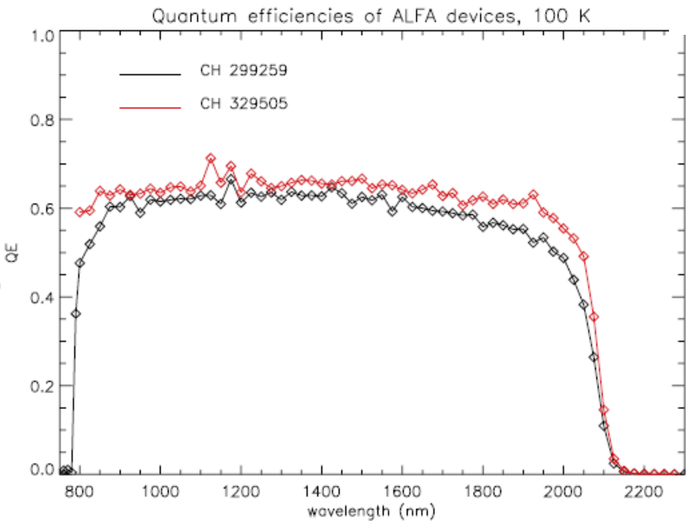
Read-noise high, even with up-the-ramp

Up-the-ramp read-noise



Detector array noise >30 e-rms after 120 up-the-ramp samples

QE ~60%, (80% measured for prototype)



ALFA-N Phase 3 – Summary

Summary

- ✓ Functional 2k x2k ROIC developed and characterised
- ✓ Large-format MCT layers produced and hybridized
- ✓ Cryogenic package developed
- ✓ 2x packaged ROICs
- ✓ 4x hybrid arrays packaged
  - -> 3 for characterisation
    - -> 2 with good performance

- ❖ ROIC design issues identified – full re-spin required
- ❖ MCT performance does not match prototype performance

Deliverables

2x functioning and packaged ROIC – delivered to ESTEC

2x fully functioning packaged and characterised devices – planned Q1 2023

- -> 1x delivery to FOCUS/Labex Cagire/Colibri project
- -> 1x delivery to ESTEC

Outlook

- Phase 3 initially planned to implement a ROIC re-spin and validation of the large-format array through build and characterisation of a number of full hybrid arrays.
- Unfortunately, due to a number of factors including required/available budget, business strategy and activity priorities (EO) at Lynred and lack of large scale procurement from SCI, Phase 3 of the ALFA-N development has been cancelled.

ALFA-C Control ASIC – Caeleste [BE]

Development of a universal readout and control ASIC for CMOS ROIC based detectors

Target Specification

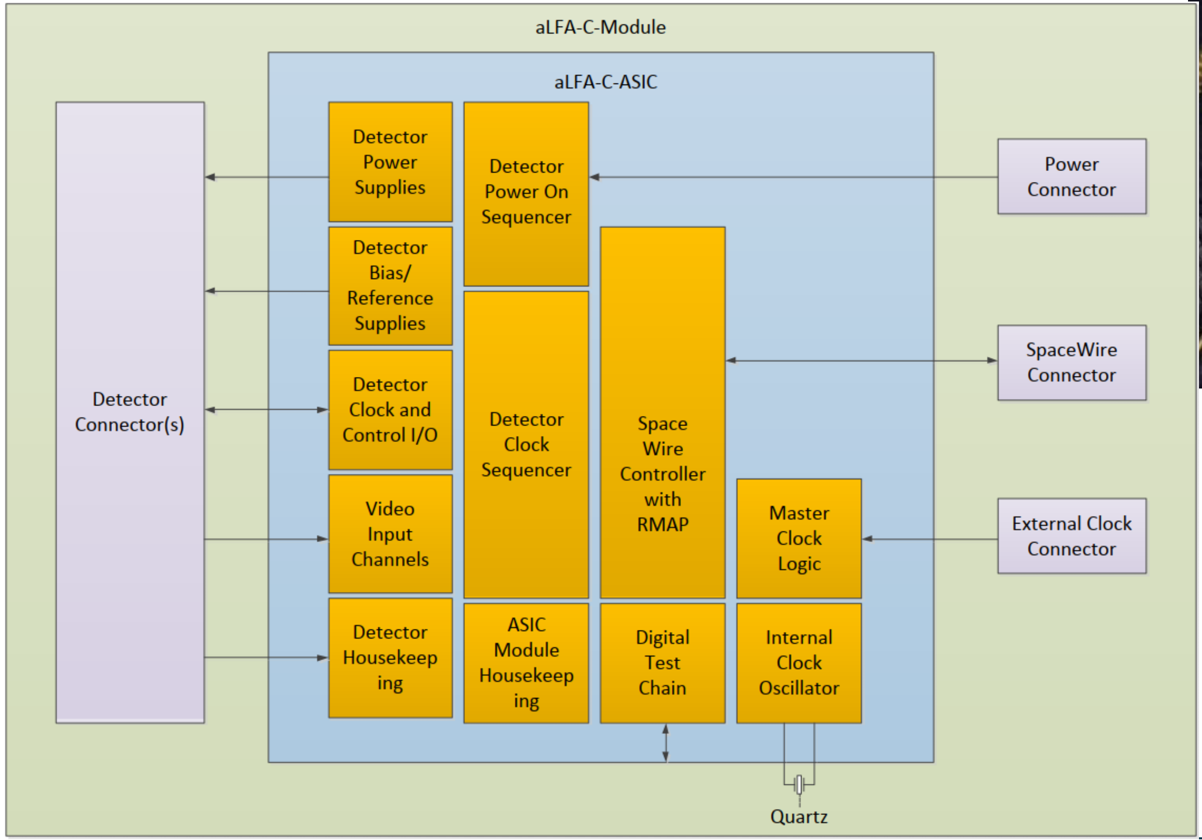
Parameter	Value	Comment
Video channels	32 + 4 reference channels	16 bit, 100 kHz nominal sample rate, with programmable pre-amp
Programmable LDOs	12	0 – 3.3V
Programmable bias voltage sources	32	0 – 3.3V
Programmable bias current sources	8	10 nA – 1 mA
Detector clocks	32 SE or 16 LVDS pairs	Single ended logic level adjustable
Digital inputs	16 SE or 8 LVDS pairs	
Detector SPI	1	
Housekeeping ADC	2	For voltages, currents, temperature
Interface	SpaceWire	
Operating temperature range	35 – 300 K	Operation and start-up down to 24.5 K demonstrated
TID	100 krad	

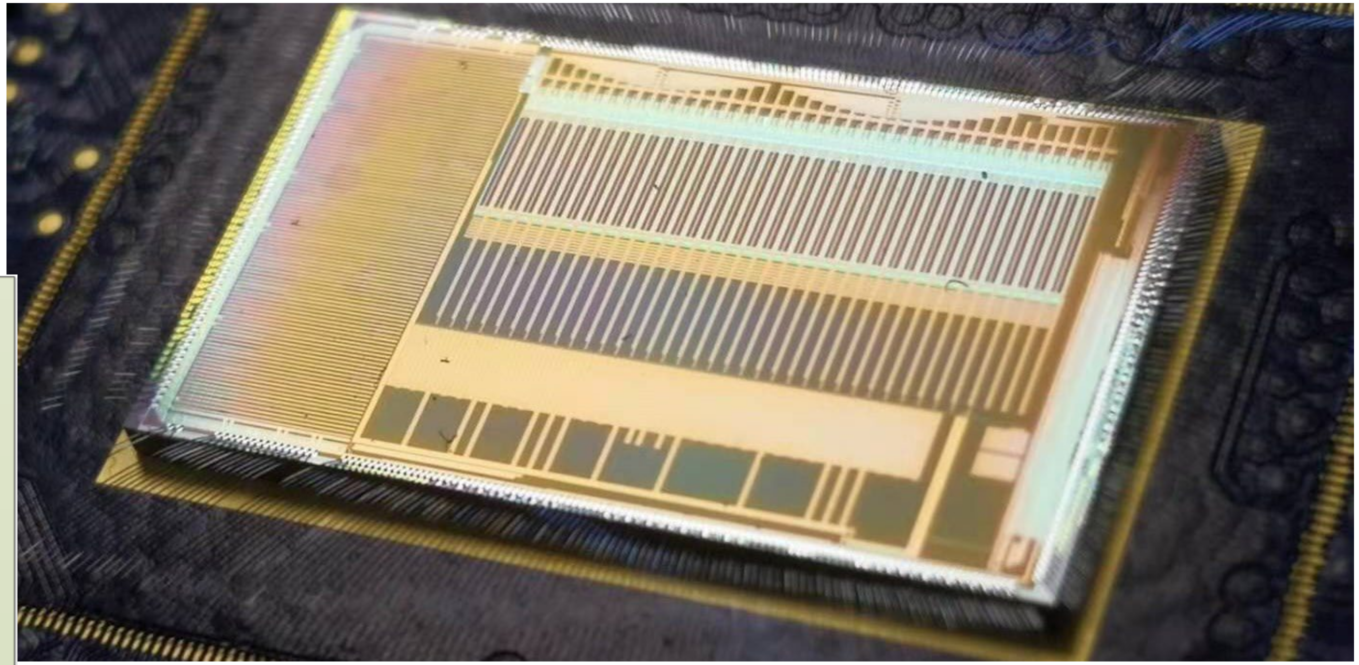
Schedule

- Kick-off: June 2018
- Final Presentation February 2022
- Planned metal redesign: KO Q1 2023

ALFA-C Controller ASIC – Design and Manufacturing

Block Diagram





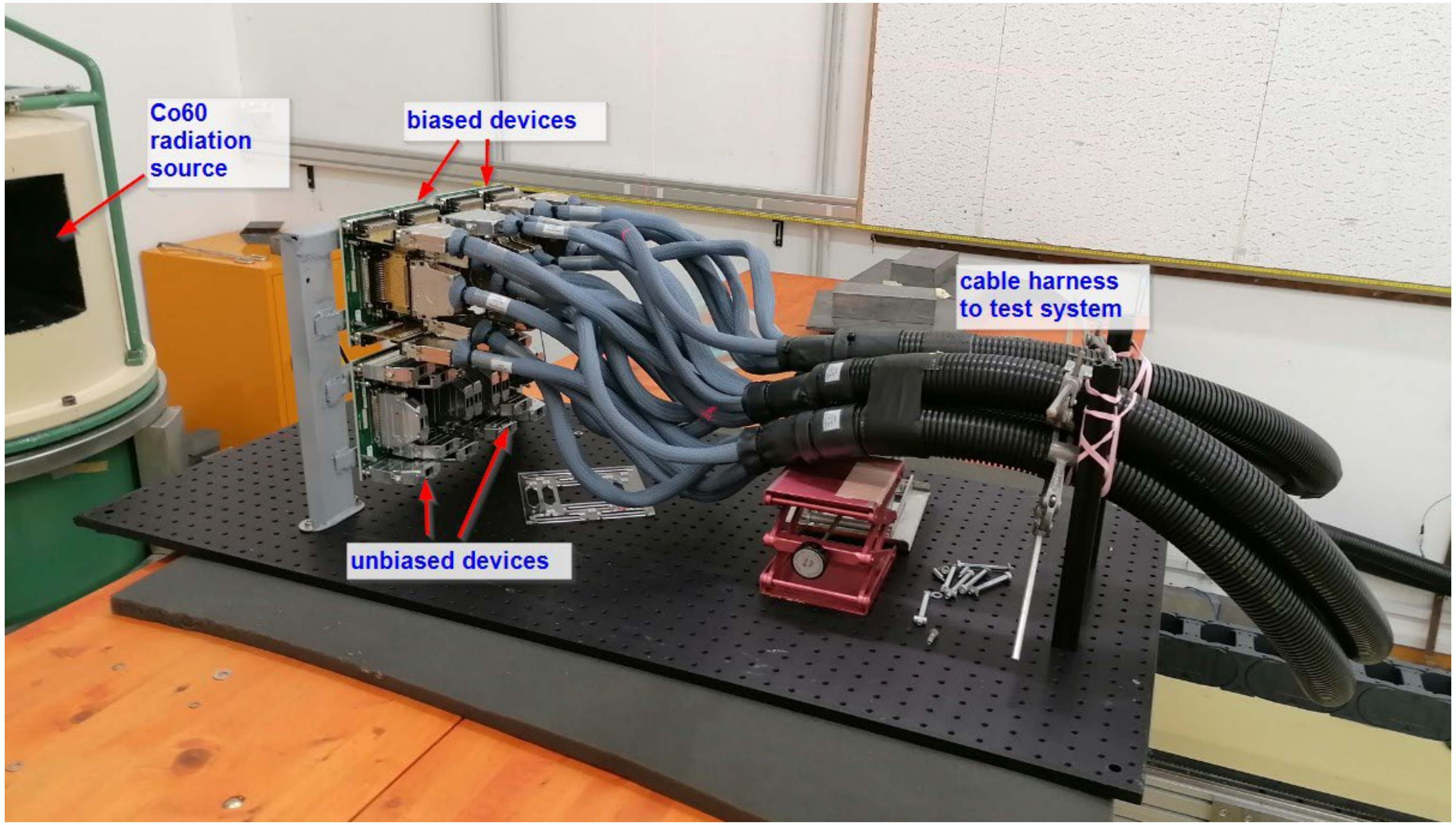
ALFA-C ASIC
10 * 16 mm² die size
bonded Chip on Board
350 bond pads

ALFA-C Controller ASIC – Characterisation

ASIC Chip on Board characterisation

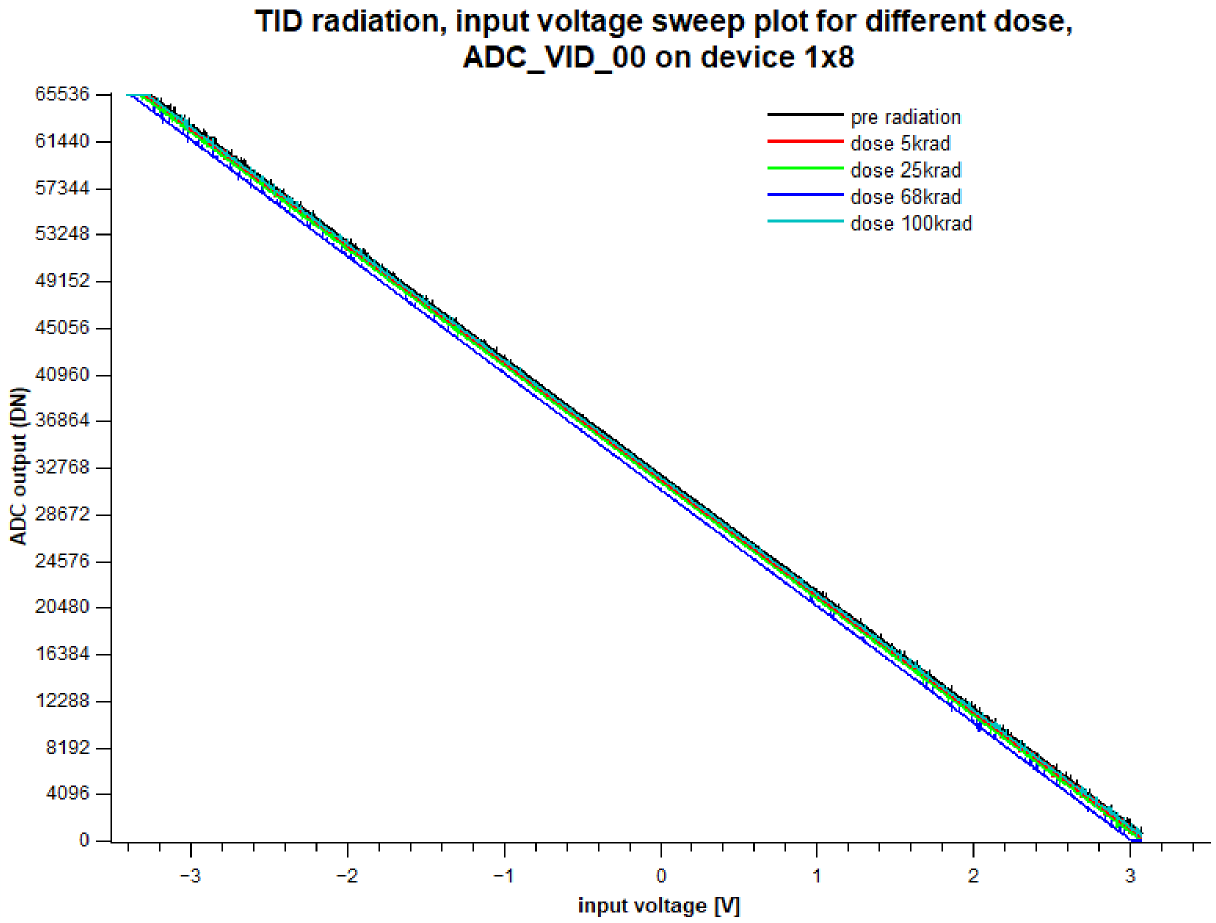
- Room temperature tests at Caeleste
- Cryo tests at Sron
- Heavy ion tests at LLN
- TID tests at ESTEC

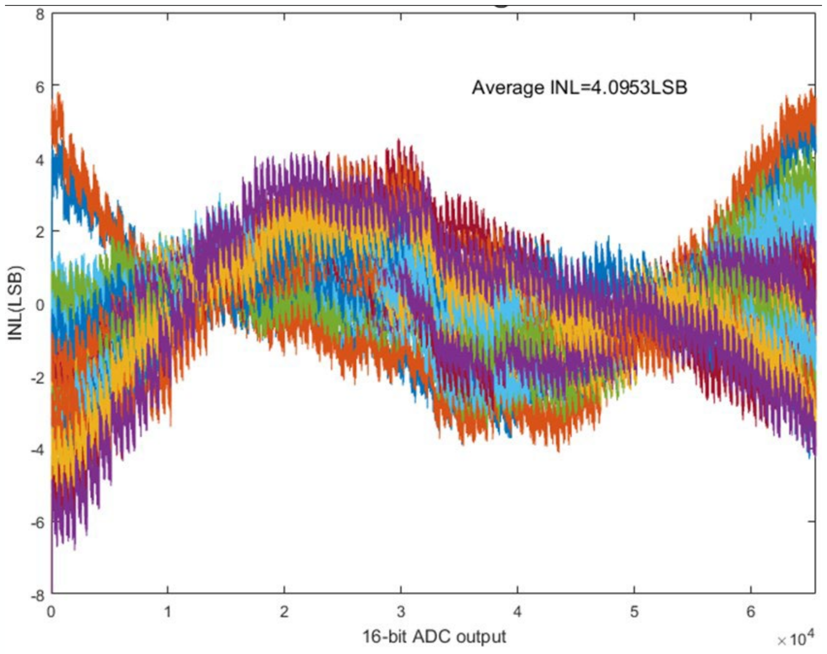
Co60 setup at ESTEC

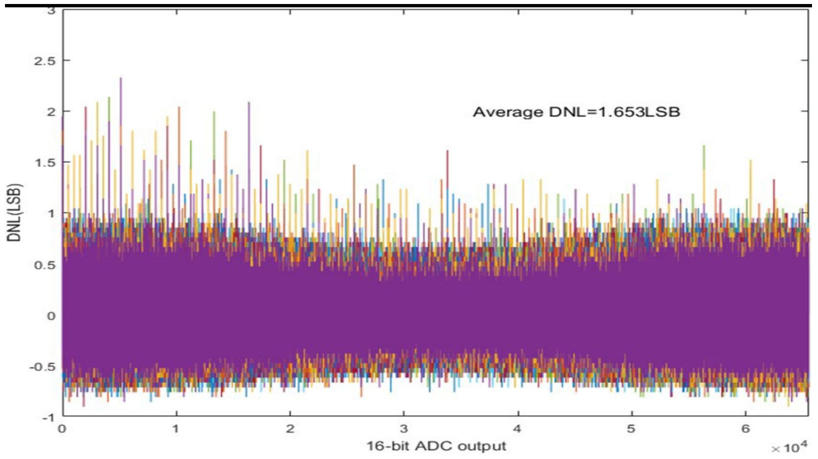


ALFA-C Control ASIC – Performance

Several ASICs have been characterised at room temperature, at cryo, under heavy ion radiation and under Gamma radiation







ALFA-C Control ASIC – Summary and Outlook

- ✓ Overall very good performance
- ✓ Operation from 24.5 to 300 K confirmed
- ✓ TID tested up to 290 krad, without significant degradation

- ❖ SEE on SRAM of digital part detected, deeper investigation needed
- ❖ A few issues identified
  - ✓ Some of them can be fixed with a metal redesign which is currently under negotiation

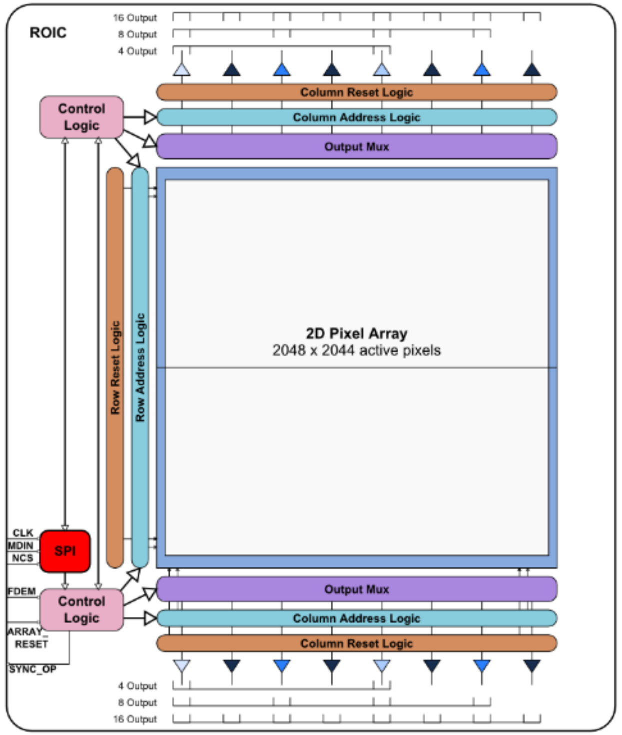
- More tests under preparation at ESTEC
- So far no package, only COB test and operation

Large-area MCT APD array development (LAPD – IBEX)

ESA is developing a new large-format array with Leonardo UK
Based on proven Saphira technology

Target Specification

Parameter	Value	Comment
Array size	2k x 2k	
Pixel pitch	15 um	
QE	>70%	@1550 nm
Read-out mode	Global shutter Rolling shutter	
CHC	100 ke-	
Dark current	3 e-/p/s	At APD gain=10
Read noise	10 e-rms	At APD gain=10
Frame rate	>1 Hz	
Operating temperature	80 K	Typical
Cut-off wavelength	2.5 um	
Cut-on wavelength	0.8 um	

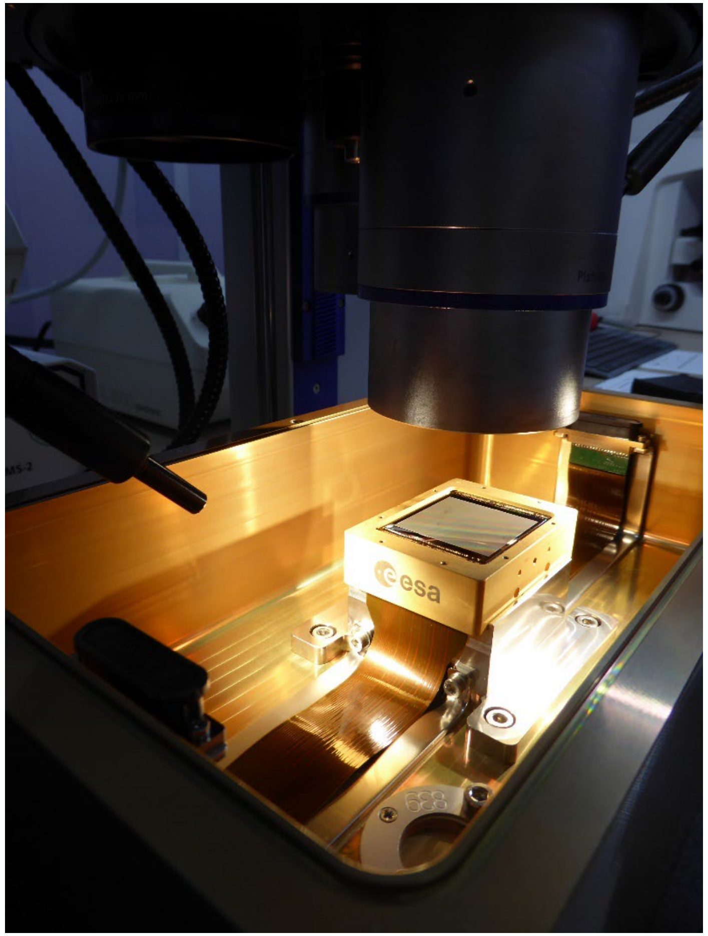


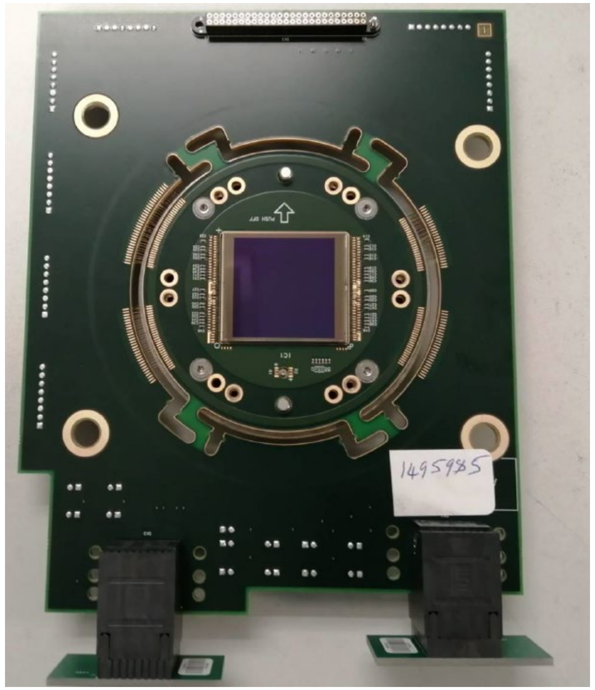
Large-area MCT APD array development (LAPD – IBEX)

Status

- ROIC design and manufacture complete
- MCT detection layer design and manufacture complete
- Cryogenic package design complete (ESA) – first package delivered
- ROIC functional test complete – all operational – supply voltage issue but work-around possible.
- First packaged ROIC delivered to ESTEC for test setup
- Three hybrid arrays mounted Chip-on-board for characterisation at Leonardo
- TRR completed – testing underway
- Full characterisation planned in new ESTEC test facility

Follow-on activity planned in 2023 for ROIC re-spin + MCT optimisation





Large Area APD – Other Developments

- Leonardo also funded by ESA and US entities to further develop the technology – in particular with pixel technology to suppress dark current at higher gains due to tunneling – enables simultaneous low read noise + dark current
  - 512x512 /24 µm Large Saphira for the European Extremely Large Telescope by ESO
  - 1kx1k/15 µm array for low photon flux astronomical imaging by NASA and University of Hawaii

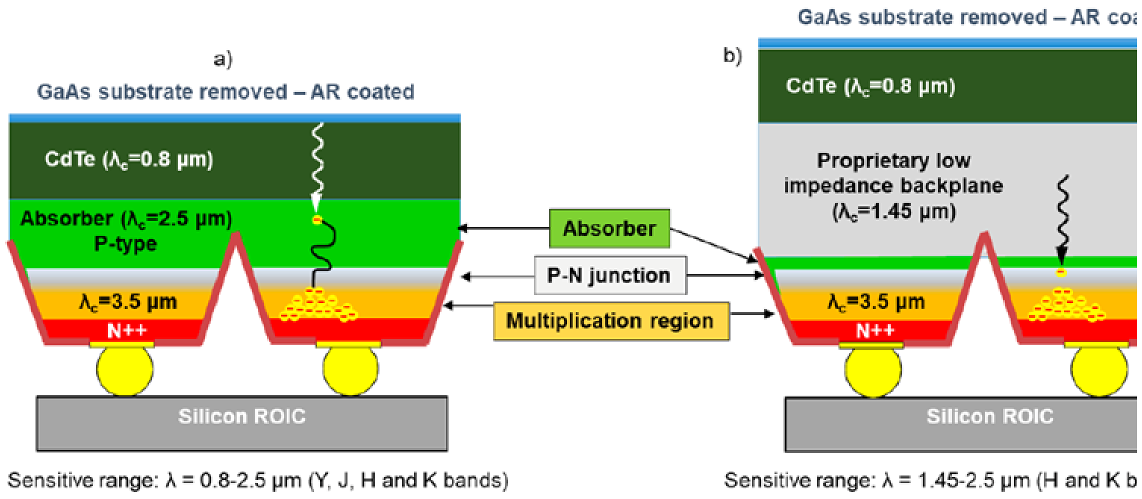
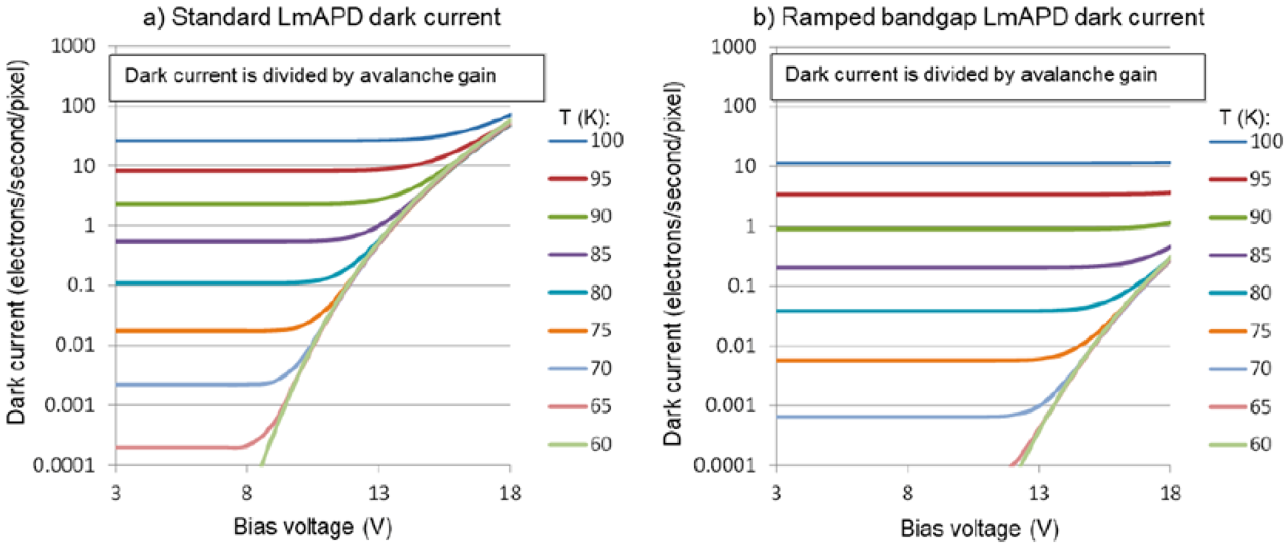


Figure 3: Schematics of device structures – a) Astronomy device structure and b) GHz structure.



Images courtesy Leonardo Proc SPIE 2022 12183

Future ESA Mission Large Area IR Detector Needs

- **Arrakhis F2 Mission** - https://www.cosmos.esa.int/web/call-for-missions-2021/selection-of-f2

- ARRAKIHS will image about one hundred nearby galaxies and their surroundings, using innovative twin binocular assemblies of small telescopes, to characterize the number and nature of low-mass dwarf galaxies and stellar streams in their vicinity. This survey, in visible and infrared wavelengths, will far exceed what is currently possible from ground-based telescopes and will provide the possibility to make tests of the so-called ΛCDM cosmology as well as producing a dataset of significant legacy value.

- Focal plane:
    - **2x 2kx2k 18 micron H2RG**
    - 2x 4kx4k 10 micron CCD 250 or 273

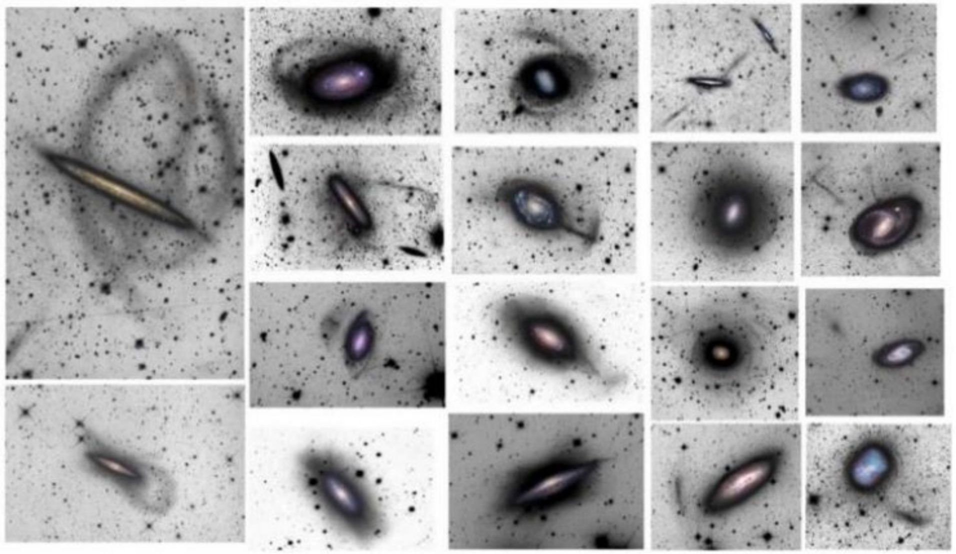


Figure 2: *Luminance filter images of nearby galaxies from the Stellar Tidal Stream Survey showing large, diffuse light structures in their outskirts (Martínez-Delgado et al., 2010, 2012, 2015)*

Future ESA Mission Large Area IR Detector Needs

- **THESEUS M7 Mission Candidate** - https://www.cosmos.esa.int/web/call-for-missions-2021/update-on-the-f2-and-m7-mission-opportunity

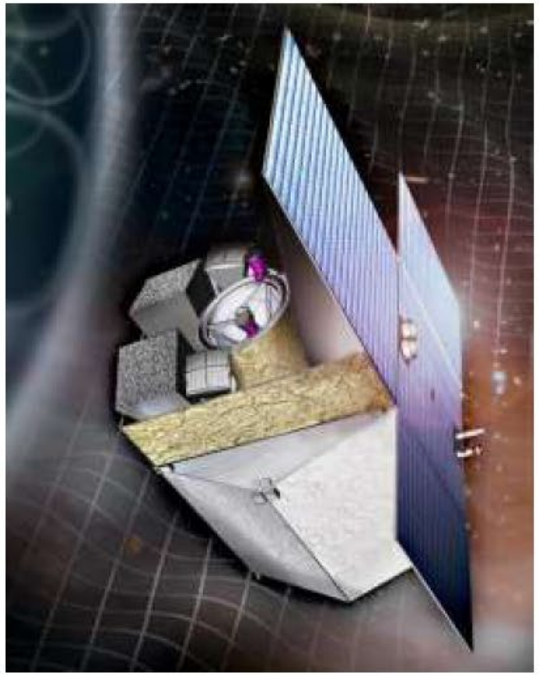
THESEUS - Transient High-Energy Sky and Early Universe Surveyor

Name of Proposer	L. Amati (IT)

Subject

- Objectives: transient detection and assessment at high redshift. The THESEUS mission will use long Gamma-Ray Bursts (GRB) to solve key questions about the early Universe and will contribute to multi-messenger and time-domain astrophysics.

Launcher	Vega-C
Launch year	2037
Target	LEO
Orbit	LEO, 600 km, i=6 deg. ; mentions that L2 will be studied



- Focal plane:
  - **IRT: 1x H2RG 2 micron cutoff**
  - SXI: 2x 8x CIS 2kx1k 40 micron [CIS221 prototype], XGIS: CsI scintillator + Si SDD readout

Future ESA Mission Large Area IR Detector Needs

- GaiaNIR as L5 mission candidate – see https://arxiv.org/abs/1907.12535 D. Hobbs et al **Voyage 2050 White Paper: All-Sky Visible and Near Infrared Space Astrometry**
- NIR TDI 0.8-2.5 or 3.5 micron
    - GeonSi: study with Te2v UK – lower cutoff, dark current?
    - Large area MCT APD: studies with Leonardo UK

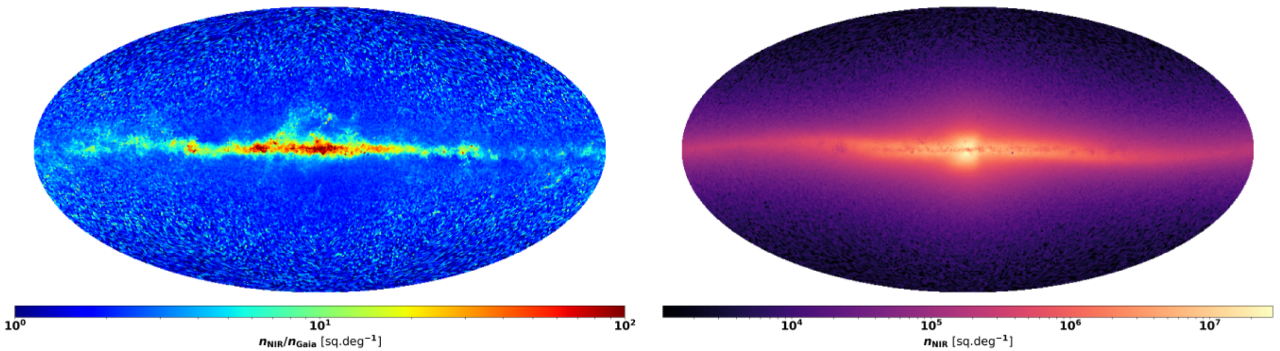


Fig. 1: *All-sky projection in Galactic coordinates of the star count ratio per square degree between GaiaNIR and Gaia (G-band limit of 20.7th mag giving 1.5 billion Gaia sources). In total 5 times more stars could be observed, especially in the disk where extinction is highest, by GaiaNIR for the H-band limit of 20th mag (left figure) and 6 times more stars could be observed by including the K-band limit of 20th mag. Crowding is not taken into account here and will limit the increase in numbers in the densest areas. In the right figure we show the corresponding H-band number densities. The underlying Milky Way model (which does not include clusters or external galaxies, e.g. SMC and LMC) is similar to GDR2mock (Rybizki et al. 2018) (using Galaxia (Sharma et al. 2011) with the extinction map of Bovy et al. (2016b)) but only 0.1% of the stars are sampled explaining the noise in low density regions. A note of caution, the estimation of the star count ratio between Gaia and GaiaNIR is uncertain due to the uncertainty in the extinction model used (older models gave a lower ratio of around 3), mainly towards the centre of the Galaxy. However, one could argue that this uncertainty is a key science case in itself that cannot be resolved by Gaia alone.*

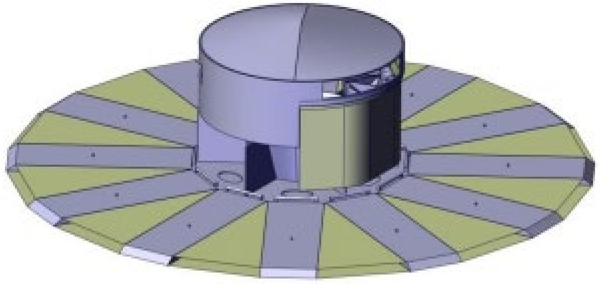


Figure 6-1: GAIA-NIR spacecraft orbital configuration

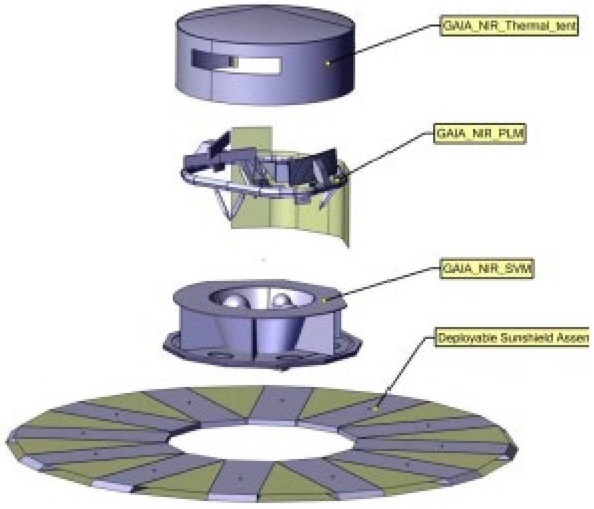


Figure 6-2: GAIA-NIR Spacecraft main elements