CMOS Image Sensor developments supported by the European Space Agency

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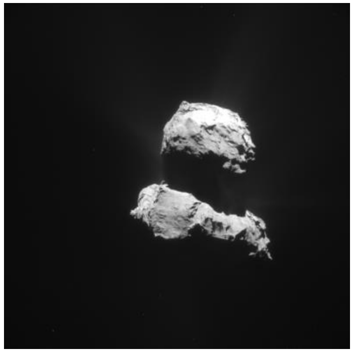
Introduction



High-performance detectors capture images containing enormous amounts of information across the electromagnetic spectrum

Image sensors: a fundamental part of space instrumentation

decades of development and investment ⇒

vast improvements in capability have been achieved but

still a performance-limiting component

Space science is hungry for ever better performance

Image sensors are a key part of ESA's technology development strategy

This talk: current status and aims of the Agency on CMOS detector technology

Application

Three main application areas for high-performance detectors in space

Earth Observation

Push-broom or staring spectrometers

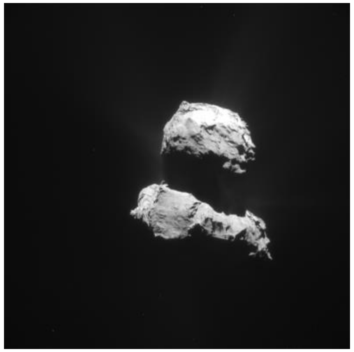
Large-format single detector array

Astronomy

Imaging telescope

Large-format multiple detector focal plane array

AOCS
(Attitude & Orbital Control Systems)



Imaging telescope

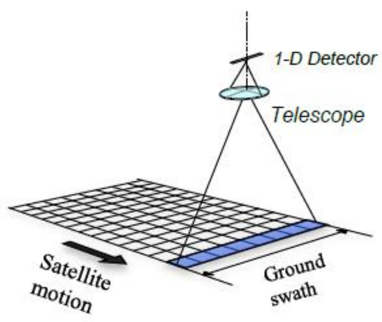
Medium-format single detector array

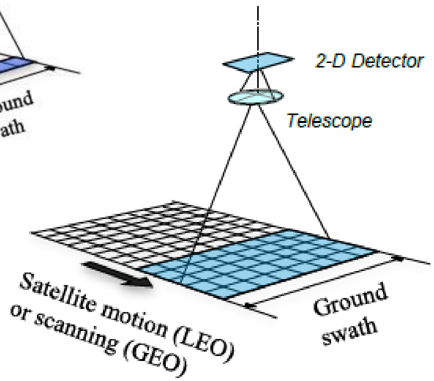
Capturing images

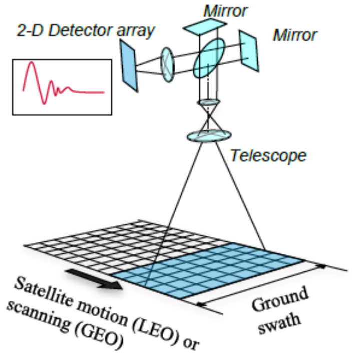
Image sensors can be:–

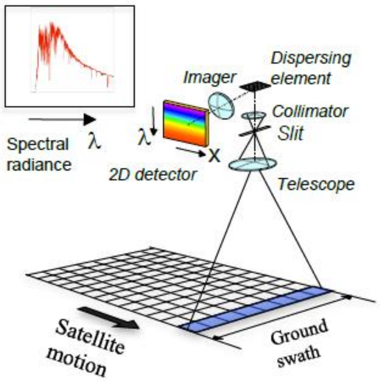
- A few pixels for simple scanning imagers
- Long 1D arrays for push-broom imagers
- Large 2D arrays for dispersive spectrometers or staring imagers/spectrometers

Remote sensing examples









Detector requirements

Detectors are a <u>performance limiting component</u> for space instrumentation

a) Instrument requirements – tend to be determined by the state-of-the-art + ‘better than before’

b) Functionality and performance of optical instruments – determined by *available* detectors

Usually <u>not</u> the same thing ->

continuous detector development and improvement

Current implementation

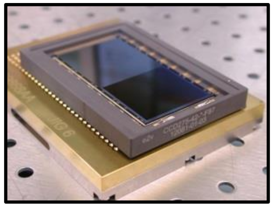
For maximum performance -

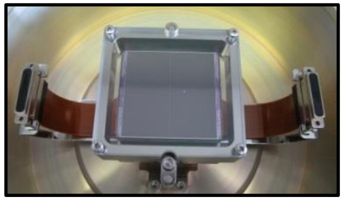
Earth Observation → Custom development per mission - Visible / Custom development per generation - IR

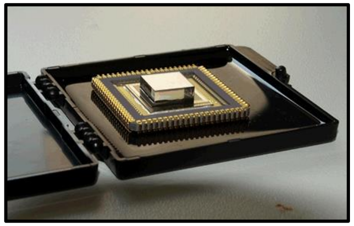
Astronomy → Custom development per mission - Visible / Custom development per generation - IR

AOCS (Attitude & Orbital Control Systems) → Custom development per generation

Based on existing technology bricks







Space detector requirements

Requirements for high-performance detectors in space are not always the same as those for commercial applications

Generalising -

On-ground ⇒ Lots & lots of small pixels, colour output, TV formats (HD, UHD…) or Film formats (APS-C, 35mm) video frame rates, digital output, …

In-space ⇒ Lots of large pixels, monochrome output, custom formats, variable frame rates (mHz ⇒ 10's Hz), analogue output, … and reliability!

Still some common goals ⇒ high QE, low dark current, good imaging performance (MTF, PRNU), high dynamic range, …

… and good overlap with ground-based science & astronomy.

Common drivers

Availability

Cost

Resolution
Larger overall array size
Higher pixel count
but still 'large' pixels

Increased Dynamic Range
Lower read-noise

Operating temperature
Dark current

Common drivers for both (2D) Visible and IR detectors

Spectral response
Material and ARC

Reliability
Radiation tolerance

SNR
Best quantum efficiency
Lowest Dark Current

Imaging performance
Crosstalk - MTF

Materials

Effectively two 'workhorse' materials for high-performance imaging sensors in space –

- **UV-Visible waveband– Silicon**

Ubiquitous material for commercial ICs and detectors (mobile phones, digital cameras etc). Response from UV to 1.1 um. Available in large wafer sizes, very high quality and with custom parameters (e.g. epi thickness, resistivity).

Array detector types – monolithic CCD or CIS, hybrid CIS

- **NIR/SWIR Infrared waveband – Mercury Cadmium Telluride (MCT or HgCdTe)**

Tertiary material semiconductor alloy with adjustable cut-off wavelength – from <2um to 20um+.

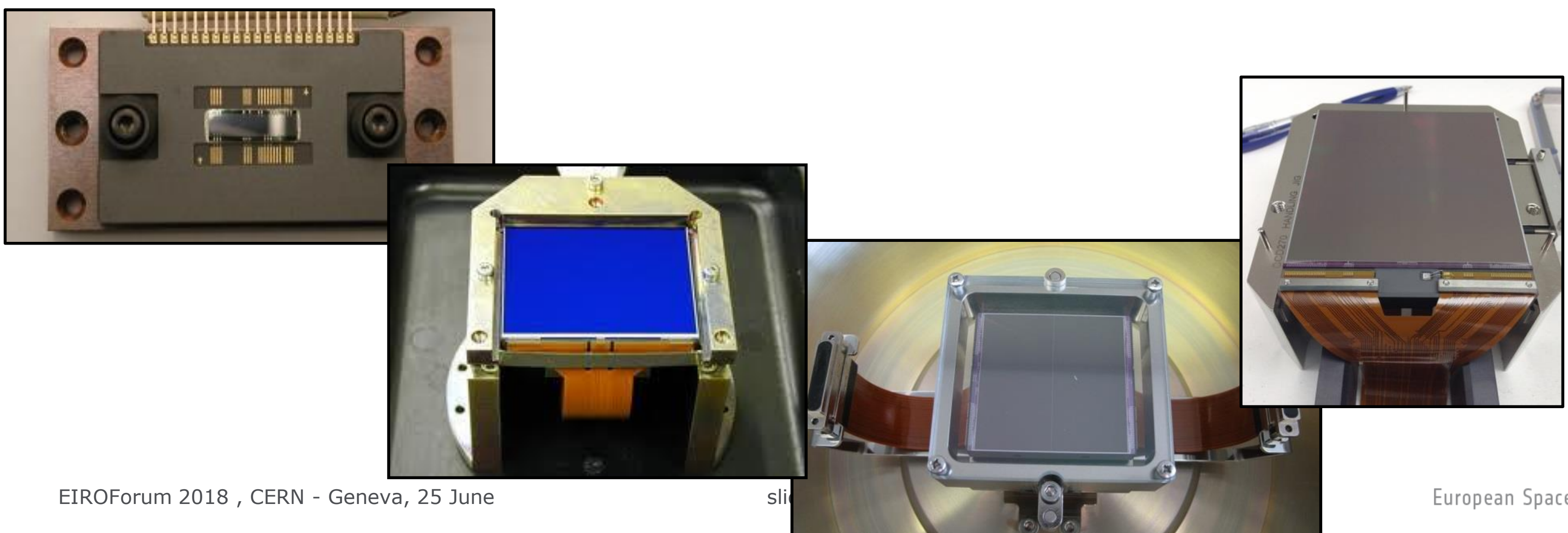
Array detector types – hybrid CIS

But - willing to work with other materials to get best performance

Where are we now?

Visible waveband

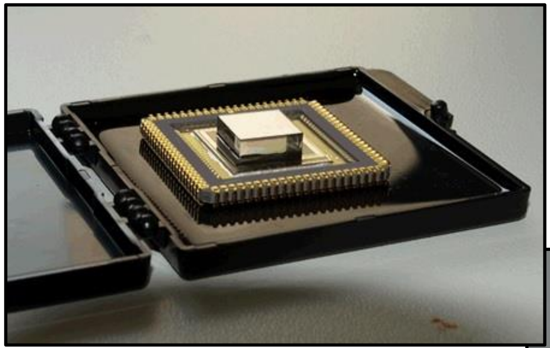
- For both Earth Observation and Astronomy applications, **dominated by CCD**
- Mature technology – stable supply – custom array design as standard – excellent electro-optical performance – wafer scale devices (6”)

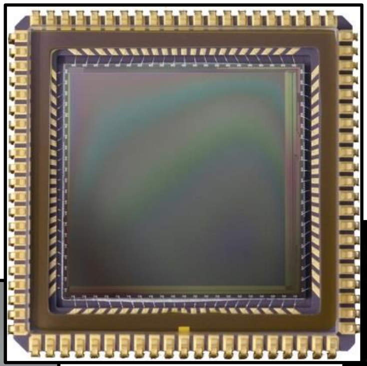


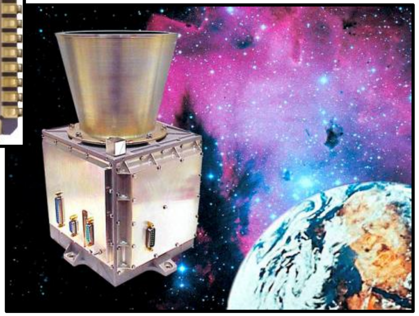
Where are we now?

Visible waveband

- But, **a different story** for AOCS
- CIS now dominating (~95%)
- Developing technology – ideal target for CIS capabilities -> increased on-chip functionality







Examples

Mission	**Application**	**Use / Need**
MTG	Earth Observation	CIS
Earth Explorer 7	Earth Observation	Biomass: Not applicable
Earth Explorer 8	Earth Observation	CarbonSat and FLEX: custom Frame transfer CCD
Metop 2nd Gen	Earth Observation	3MI: Custom frame transfer CCD
Sentinel 2	Earth Observation	MSI (Multispectral Imager):CIS
Sentinel 3	Earth Observation	OLCI (Ocean and Land Color Instrument): CCD
Sentinel 4	Earth Observation	UVN (Hyperspectral spectrometer): 2 frame-transfer CCDs
Sentinel 5	Earth Observation	Custom Frame transfer CCD
Sentinel-5 Precursor	Earth Observation	TROPOMI (UV-VIS-NIR-SWIR push-broom grating spectrometer): back-illuminated frame transfer CCDs
PLATO	Science	Large area CCD (for the visible cameras)
EUCLID	Science	Large area CCD (for the visible cameras)
JUICE	Science	Backside CIS
Cheops	Science	Off-the-shelf backside CCD
Solar Orbiter	Science	Frontside and backside Intensified CIS

Detector development strategy – Science

Science

- **CIS** – basic technology development
- Complementary detector to CCD – potential advantages include radiation hardness, readout speed, readout flexibility, power consumption and ease of operation.

- Development aims are matched to high-performance imaging spectrometer applications
    - 2D array
    - High QE
    - High dynamic range (>80dB)

- Additional aim to verify full high-performance CIS design and manufacturing capability within Europe.
  several capable design houses in Europe, but CMOS foundries mainly outside Europe

- Parallel development of hybrid visible CIS

CMOS in Europe: Development Options

1. European design house coupled with non-European foundry

   likely to provide the best performance in the shorter term, but is only partial non-dependence and consequently subject to more external influences.

2. European design house coupled to European foundry

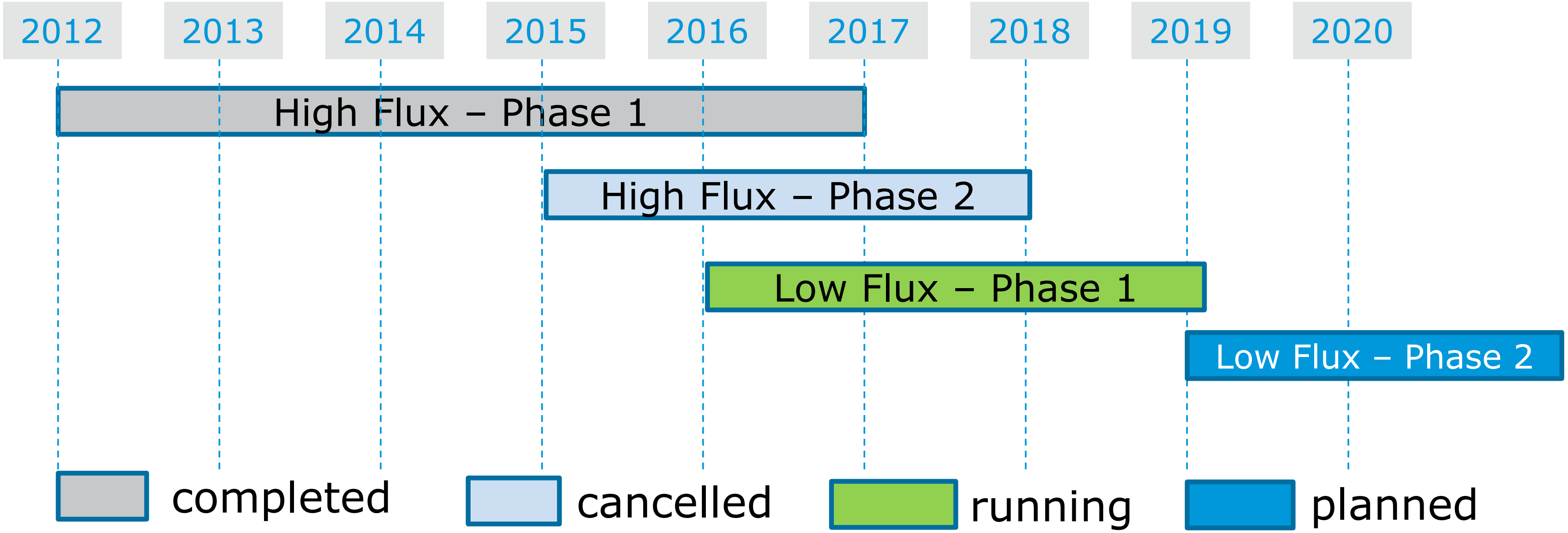
   implies full European non-dependence and potentially better control over the processes. Unfortunately, the current situation for CIS manufacturing capabilities is not in line with the demand and expectation of industry. Industry is strongly suffering from this situation, despite the following actions that tried to alleviate the situation:

- actions launched by ESA during the 2 last years (EuroCIS High flux and Low flux) → See next slide
- FP7 funding (IMEC action)
- actions and funding from national agencies for space dedicated CIS (CNES and DLR)
- actions supported by other national funding (French PIA, UK actions)

CMOS Development Roadmap

- **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)



European High-Flux CIS
CMOSIS(B) – TRP 1125keuro (2012 – 2017)

CMOSIS member of the ams group · epc espros photonics corporation · imec · THALES

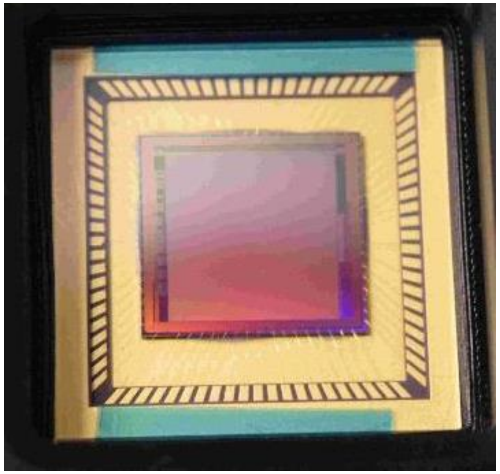
High-Flux CIS

Development of European CIS for Earth observation applications – high charge handling capacity. Original idea: 2 parallel Foundry processes:

(a) EPC 150nm node (OHC15L): development stopped before tape-out

(b) IMEC 130nm node (C013CIS): results below

Full-process chain within Europe



Higher CHC/higher noise

512 x 512, 20um pitch back-thinned array

CHC 500 ke-, 50 e-rms read-noise

The cause of non-functional FSI imagers is identified and a process-fix is proposed. Since this can not guarantee final success and it requires substantial additional funding, ESA and the Consortium agreed to stop the activity.

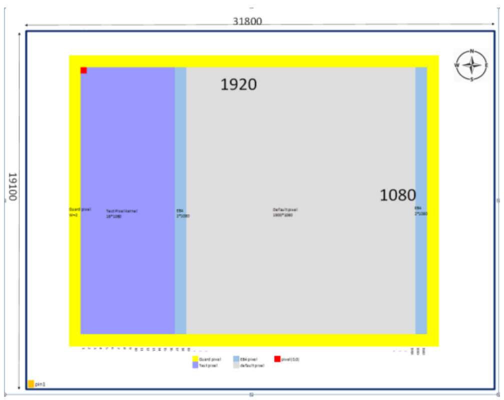
European Low-Flux CIS
Caeleste (B) – TRP 1650keuro (2016 – 2018)

Objectives

Development of European CIS for science/astronomy applications – low noise.

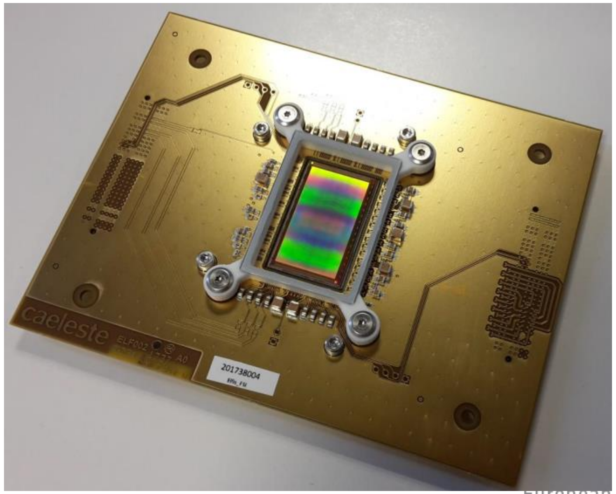
15um pitch, 1920x1080 pixels

- Matrix (4x3) of stitch blocks of 480x360 pixels
- Rad hard 15µm 4T, HDR, GS pixel
- 16 differential outputs
- Read Noise <5e
- Dark Current BOL< 50pA/cm2, EOL< 200pA/cm2
- FWC:200Ke (low gain), FWC: 7.5Ke- (high gain)



Results

Image acquired using the first FSI. However, test structures showed unexpected high pining voltages. Updates on the process are on-going. When functionality is confirmed we will proceed to BSI (BSI expected to be ready: Sept 2018)



FSI CIS packaged on COB

ELOIS II: Development of the EQM of a Compact Spectrometer based on a Free Form Grating

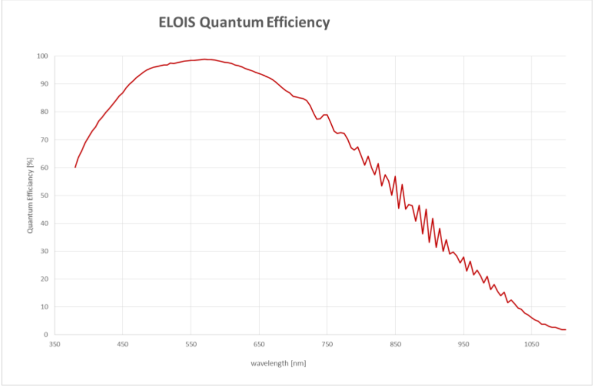
Caeleste (B) – TRP 1650keuro (2016 – 2018)

Objectives

Visible Hyperspectral CMOS detector. Few upgrades wrt ELOIS I are requested:

Increase of the pixel clock up to 20MHz in order to accommodate the 200 frame/s in binned mode with Correlated Double Sampling (CDS) and optimization of MTF and QE for 400-1000 nm

- Technology : BSI, thick EPI=10.5um high resistivity
- Design: 15.5um pitch, 2048 (spatial) x256 (spectral) pixels, global shutter, Tower 0.18um
- Binning on chip 1x4, MTF >50% @ Nyquist
- Dark Current < 50 e-/s/pixel @ 25°C,
- FWC: HG=40Ke-, LG=200Ke-
- Read noise: HG=9e-, LG=34e-



Results

Image acquired using the BSI sensor. Full EO characterization is on-going.

Detector developments

Hybrid Si CIS

A number of advantages in the design and development of a hybrid CMOS image sensor – silicon photodiode layer bump-bonded to a silicon readout integrated circuit (ROIC) – have been identified

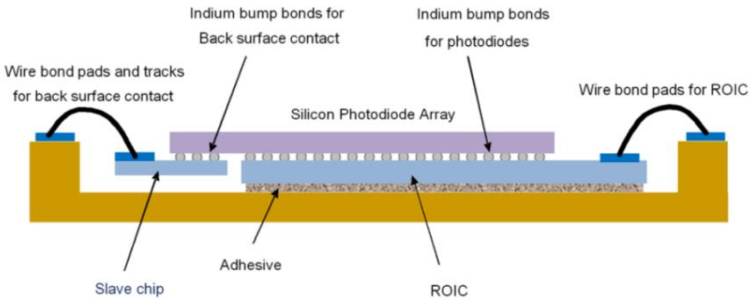
- Separate optimisation of the photodiode and ROIC architecture
- Photodiode design not limited by CMOS foundry
- High fill-factor by default
- Less parasitic light sensitivity
- Increased options for detector manufacture within Europe

High-performance silicon visible hybrid CMOS image sensor
e2v(UK) – TRP 800keuro (2016 – 2018)

Objectives

To demonstrate the potential of hybrid technology for high-performance silicon visible CMOS image sensors.

- Si 2D photodiode array (PDA)
  - Target thickness 300um, full depletion at <50V
- ROIC: Selex ME930
  - 15um pitch, 1280x1024 pixels
  - Part of the large format NIR array program
  - Designed for low flux, low read noise and for scaling up to a 2k x 2k array format.
  - 4, 8, 16, or 32 analogue video outputs
  - Source-follower with elements of radiation-hard design

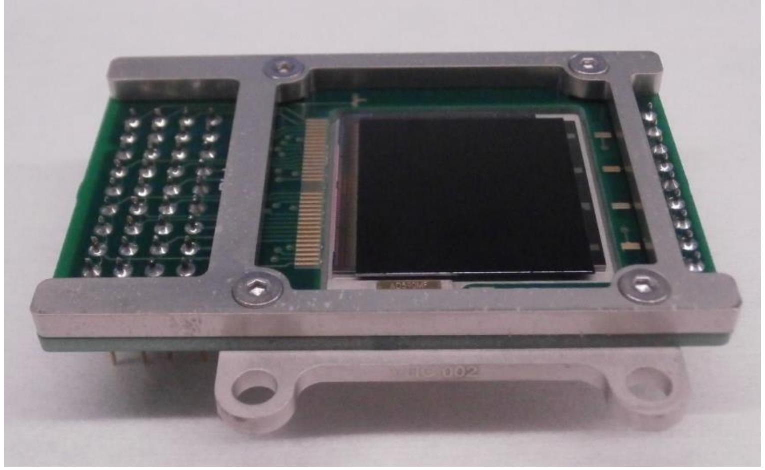


Hybrid CIS assembly

Results

First manufacturing run was completed successfully with fully functional sensors. Images are acquired.

Second manufacturing run implementing small corrections on the design and process is currently taking place.



Packaged hybrid CIS

Second Generation APS for AOCS : HAS3

On Semi (B) – GSTP 1700keuro (2011– 2018)

Objectives

Two phase activity to prototype then qualify the future replacement for the HAS2 (Detector for Star Trackers) APS detector. Key specs are :

- 1280*1280 array,
- 11 micron pitch,
- 12 bit ADC,
- custom hermetic package

Results

Detector functionality and performance is good.

End user agreement currently needed with Israel to export the component.

But power consumption is much higher than anticipated.

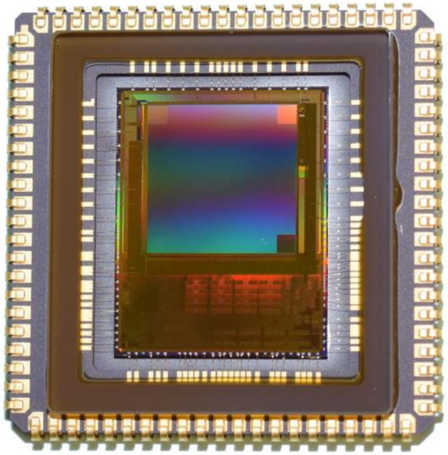
Second Generation APS for AOCS : Faint Star
AMS (B) – GSTP 1750keuro (2012– 2018)

www.ams.com

Objectives

Two phase activity to prototype then qualify a detector aimed at STR remote OH, navigation, inspection and descent and landing cameras. Key drivers are the incorporation of the image pre-processing on chip for these applications.

- 1024*1024 array,
- 10 micron pitch,
- 12 bit ADC,
- JLCC package



Results

Pixel performance exceeding expectation.

Second silicon (FM silicon) received in March 2018. Blind-Packaged devices already under test in industry (users), AMS and ESA.

First image 18th April 2018. Availability of FM-like devices later in 2018. Evaluation programme to be engaged this summer.

Back end microlenses deposition process evaluation for CMOS image sensors
(IMEC)– TRP 400keuro (2014– 2018)

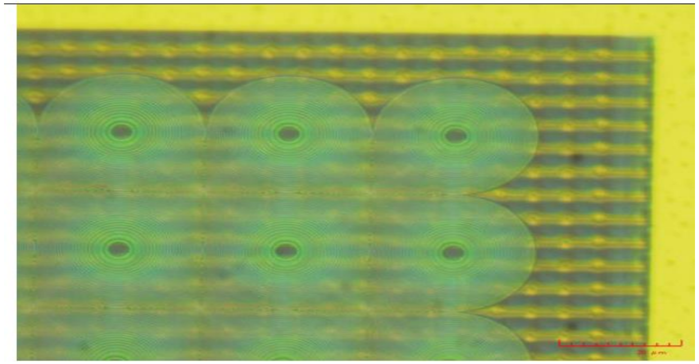
Objectives

Evaluate performance of non-organic microlenses and their sensitivity to the environmental stress conditions, including irradiation by gamma rays or proton particles.

Results

Activity completed: Fresnel microlenses appear to provide an additional protection for the CMV12000 chips under irradiation with gamma rays or protons. The Fresnel microlenses are found to be not sensitive to any of these conditions.

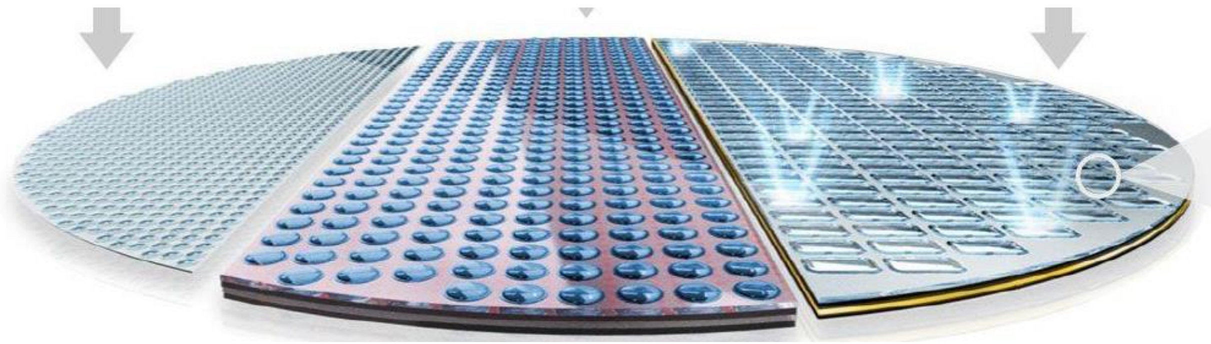
- No negative impact on the basic chip characteristics by the irradiation is found to be associated with Fresnel microlenses.
- The presence of microlenses reduces impact of gamma irradiation on the dark current and dark current non-uniformity.
- They reduce impact of irradiation by protons on the dark current and photoresponse non-uniformity.



Microlenses deposition for backside-illuminated imagers (CSEM)– TRP 250 keuro (2017– 2019)

Objectives

Design, manufacture and test the application of microlenses on a back thinned and back illuminated CMOS image sensor under space environment conditions



Results

- Image sensor identified and procured from Caeleste.
- Microlens material identified after outgasing test and handling trials.
- Microlens design and simulation is completed with promising performance prediction.
- Deposition of microlenses on the packaged dies has started and will be completed end of July/early August.

The Future

- **CCD and CIS are seen as complementary: <u>CIS is not a CCD replacement</u>**

  - Partly because of technology limitations (e.g. modern CMOS processes)
  - Mostly because the Commercial path has diverged so far from the Science path

- **CIS has many advantages over CCD** – Radiation tolerance, easier to interface, flexible operation….

  - Demonstrate basic space instrument performance capabilities
  - Exploit the CIS advantages in instrument design – i.e. look at instrument operation from CIS point of view – not just as an alternative for CCD

- **Hybrid visible CIS** – possible route custom high-performance detectors
  - Exploit the NIR/SWIR model

- **AOCS/Star-trackers** ideally positioned to utilise CIS capabilities and high-levels of functionality integration

- Foundry situation???

Priorities and actions needed

1. Help develop a full European supply chain for CIS
   - *Sustainable foundries in Europe is still considered as the first priority.*
   - *Some of the main characteristics of such foundry(ies) should be:* ***competitiveness****,* ***sustainability*** *and* ***unrestricted market access*** *(e.g. NO import/export limitations).*
   - *In the meanwhile we should still investigate on commercial foundries outside Europe.*
2. CIS Development: target widespread use of CIS in space science applications
3. CCD Development: maintain industrial capability to ensure high-performance CCD detectors are available for future missions
4. Other Technologies: support the ongoing development of detector technology to improve performance and reliability: 3D hybrid construction, deposition of anti-reflection coatings, filters, microlens, black coatings

CIS European Supply Chain and the Roadmap of ESA

1. AIM A: Full European Supply Chain for CIS

➢A1 European Low-Flux CIS Development and Optimisation (Phase 1)

Development and validation of CIS designs and read-outs, covering UV, visible and NIR wavebands and consolidation for Science applications. Phase 1 aims to investigate foundry capability through submission of a single design to one foundry.

➢A2 European Low-Flux CIS Development and Optimisation (Phase 2)

Development and validation of CIS designs and read-outs, covering UV, visible and NIR wavebands and consolidation for Science applications. Phase 2 will concentrate on the optimisation and qualification of a foundry line.

➢A3 European High-Flux CIS Development and Optimisation (Phase 1)

Development and validation of CIS designs and read-outs, covering UV, visible and NIR wavebands and consolidation for Earth Observation applications. Phase 1 aims to investigate foundry capability through submission of a single design to more than one foundry.

➢A4 European High-Flux CIS Development and Optimisation (Phase 2)

Development and validation of CIS designs and read-outs, covering UV, visible and NIR wavebands and consolidation for Earth Observation applications. Phase 2 will concentrate on the optimisation and qualification of a foundry line.

➢A5a Radiation and reliability preliminary assessment of European CMOS Imaging processing capabilities(Phase 1)

Radiation validation or evaluation of European CMOS Image Foundry. The aim is to investigate one or more Foundries (with parallel contracts in the latter case). Phase 1 will focus on Radiation assessment

➢ A5b Radiation and reliability preliminary assessment of European CMOS Imaging processing capabilities(Phase 2)

Radiation validation or evaluation of European CMOS Image Foundry. The aim is to investigate one or more Foundries (with parallel contracts in the latter case). After successful Phase1, Phase 2 will aim on environmental testing.

➢A6 Validation of European CMOS Imaging Multi Project Wafer MPW services

Validation of European Foundry capabilities on manufacturing CMOS Image Sensors for space applications. The aim is to validate one or more Foundries (with parallel contracts in the latter case).

All of these activities above will be developed using a European CMOS foundry with an open access flow.

Activities A1 – A6 are in line with the TDP and form the basis of this strategy.

CMOS Image Sensor Based on High-Resistivity Epitaxial Silicon
(TBD)– GSTP 1000keuro (2018 – 2020)

Open ITT: AO9442

proposal submission deadline end Aug 18

The main focus of this activity is the design, manufacturing and characterisation of a CMOS image sensor which should be: monolithic, backside illuminated, fabricated on high-resistivity thick starting material and being possible to operate in a fully depleted mode.

The benefits of the developed technology will be:

a. Better electro-optical performance will be achieved, due to the use of thicker starting material e.g. increased Quantum Efficiency (QE) at higher photon energies (above ~3keV) or at long wavelengths (NIR).
b. (2) The possibility to achieve improved Modulation Transfer Function (MTF) performance by using appropriate processes and controlling the photodiode depletion with respect to the total thickness of the material.

Take home message

1. ESA is aiming on high performance detectors
2. CIS are an essential part of the detector development strategy
3. CIS is seen as complementary to CCD, not a replacement
4. The Agency recognizes the importance of not only improving and optimizing the performance of detectors but also in supporting their continued availability
5. Related R&D activities are on-going, more are included in the Roadmap

With the inputs of:

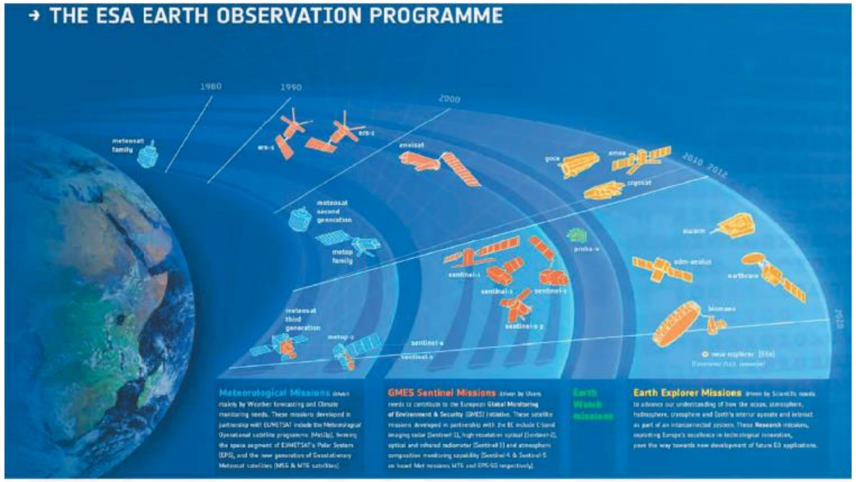
N. Nelms
A. Ciapponi
H. Weber
S. Wittig
B. Leone
P. Crouzet
S. Kowaltzek

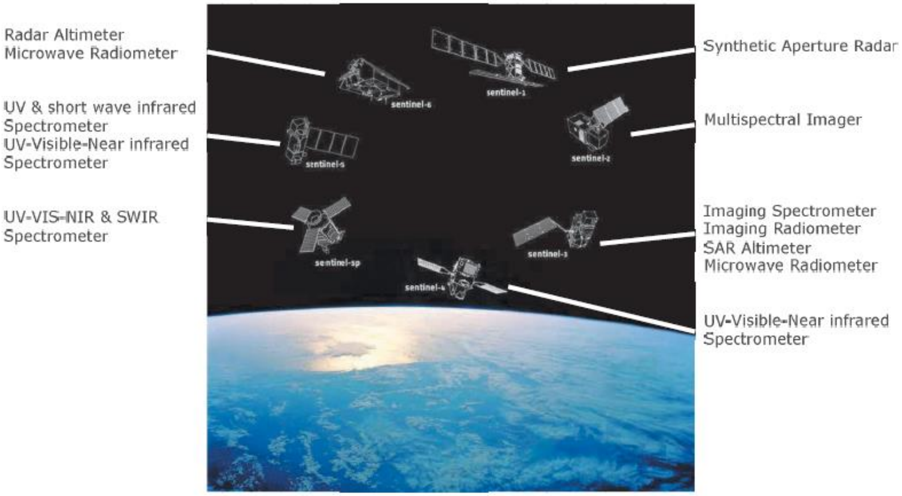
Thank you!

More slides....

Earth Observation Missions

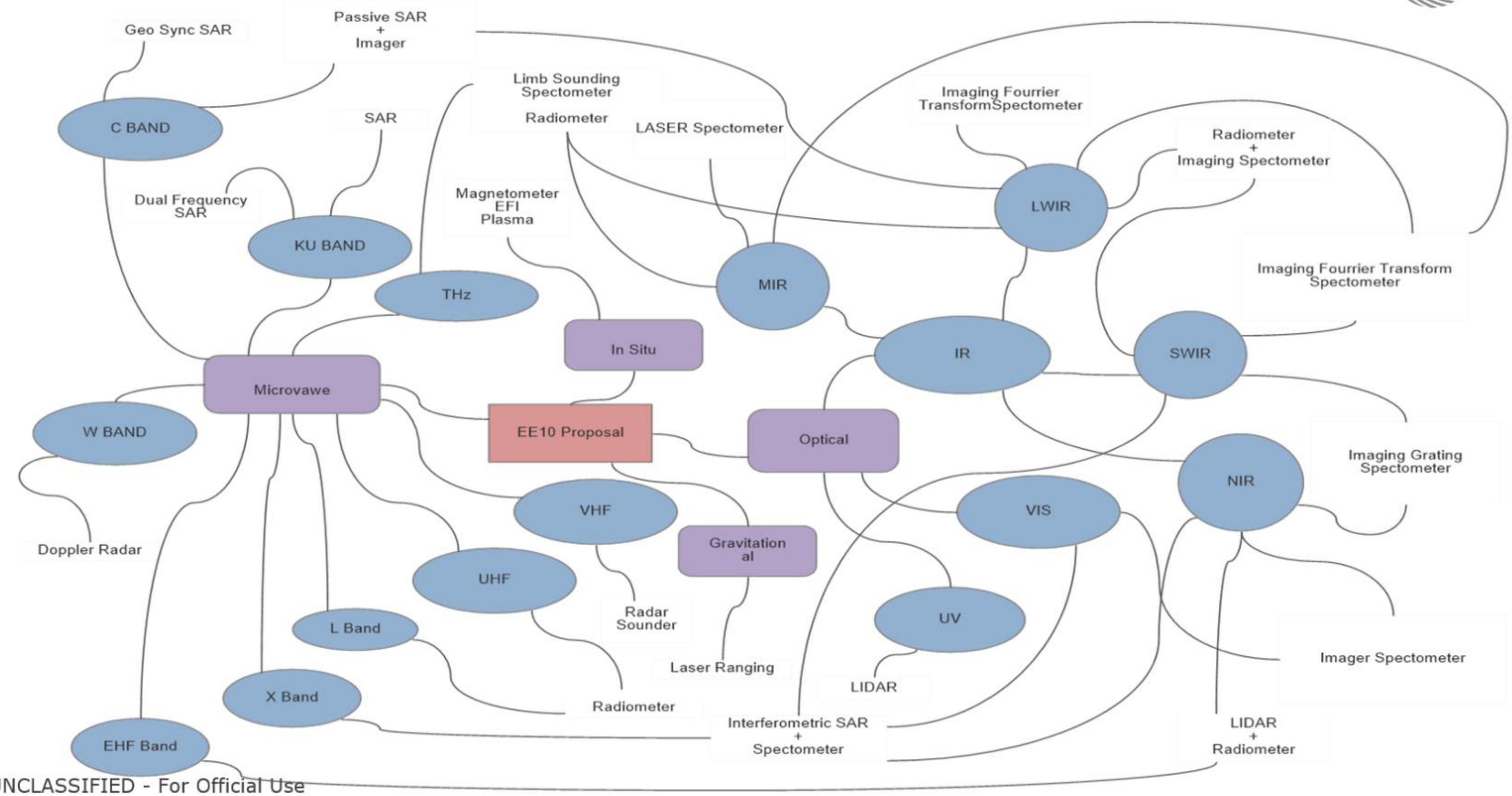
IL3 Payloads and Space Applications
Earth Observation





Future Earth Observation Missions needs

EE-10 candidate missions



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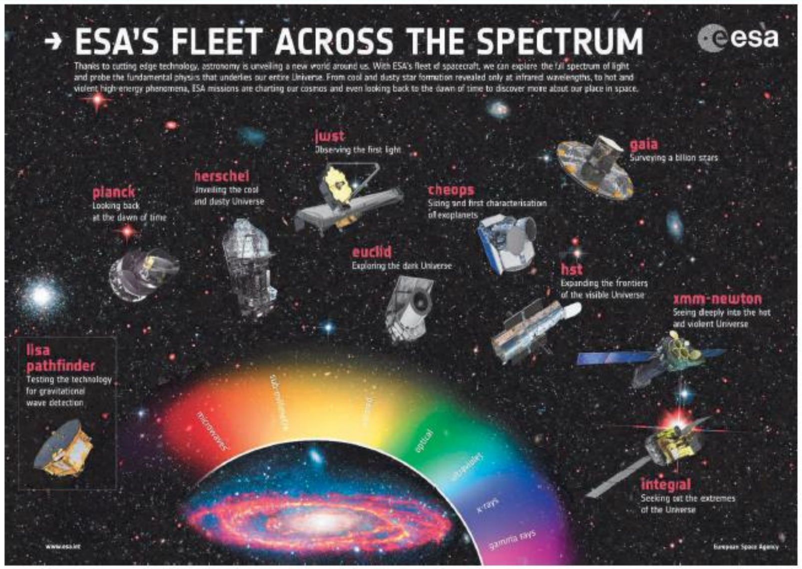
Slide 4

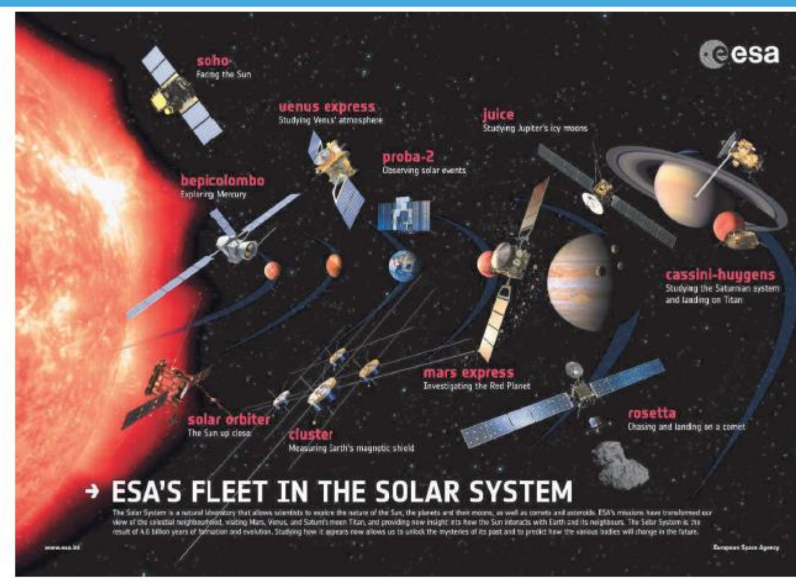
European Space Agency

Science Missions

IL3 Payloads and Space Applications
Cosmic Vision (1)



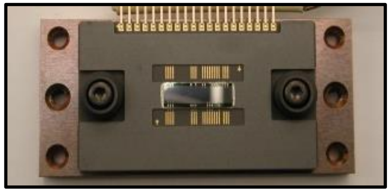
IL3 Payloads and Space Applications
Cosmic Vision (2)



Detector developments - Visible

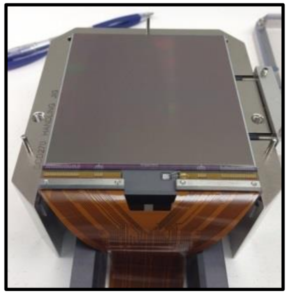
Science

- **CCD** – more evolution than revolution
- Versatile customisation of qualified technology – detector topology, operation, packaging.



EarthCARE – ATLID (CCD, e2v – UK)
- LIDAR detection at 355 nm
- 6 x 8 pixels, 30 um pitch
- Very low noise (<3 e-rms)
- Image binning, storage and addition -> atmospheric column profile on-chip

PLATO (CCD, e2v – UK)
- Exo-planet detection
- 4510 x 4510 pixels, 18 um pitch
- Back-illuminated
- Full-frame and frame-transfer variants
- CHC 1.0 Me-, 20 e-rms read-noise



PLATO CCD image area is 150,000 x greater than ATLID CCD image area

- Technology development of coatings (ARC + shield)