Safran Reosc

Adding optical functions on IR detectors: a key contribution

9th of June 2023

Thibault Laurent

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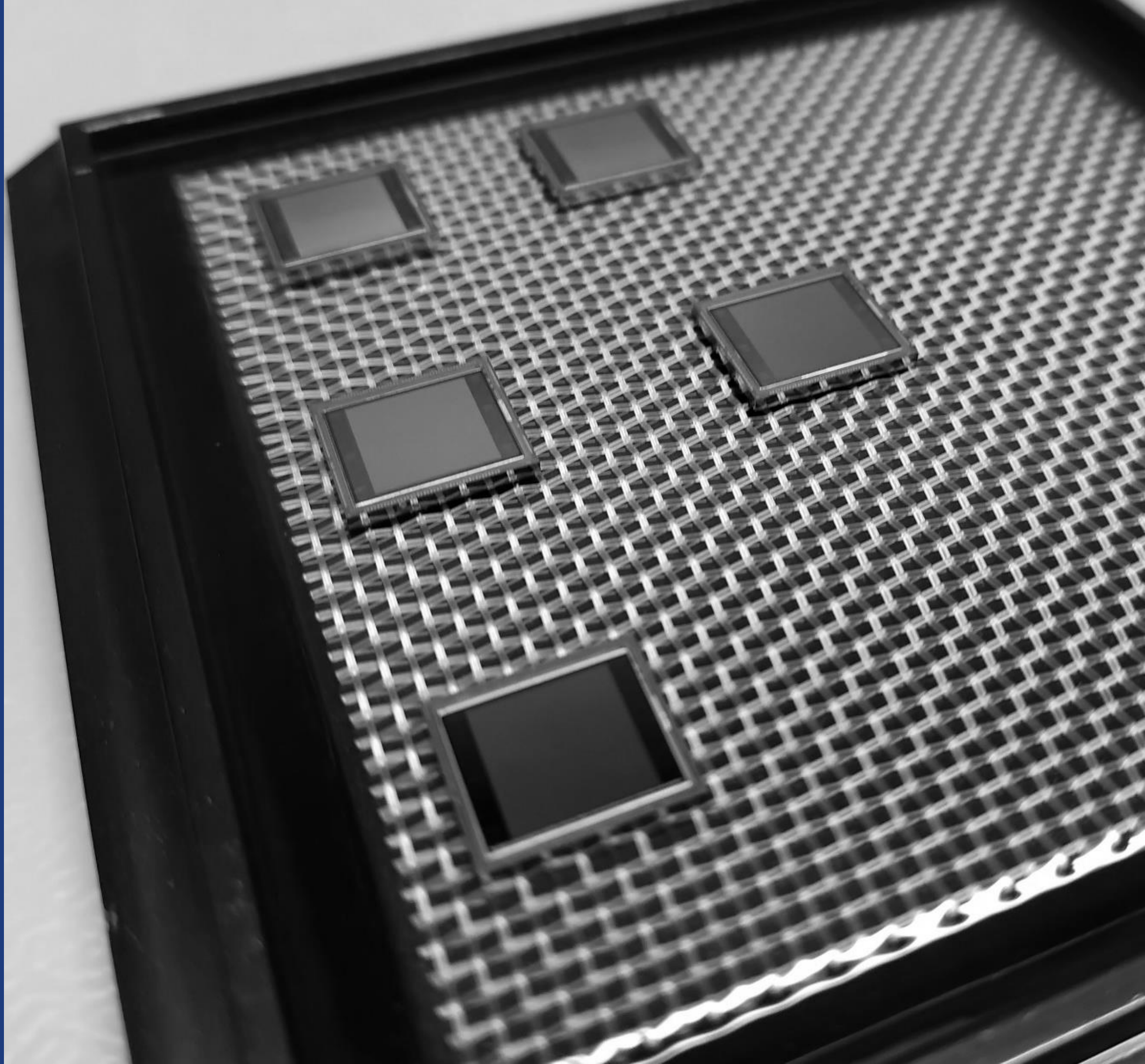

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Adding optical functions to detectors. Is it worth it?

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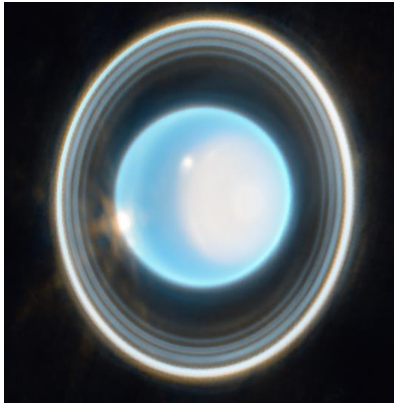
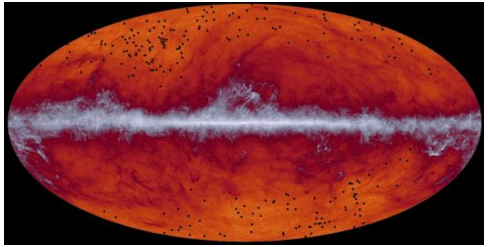
Adding optical functions to detectors. Is it worth it?

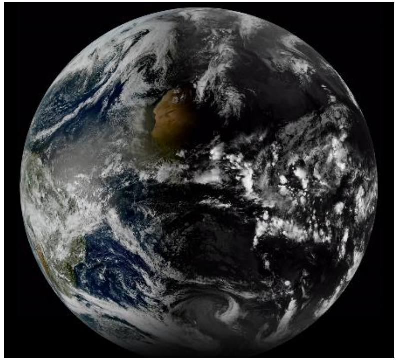
- **What are the needs in IR (and only in IR) for space observation:**
  - Science:
    - SWIR-LWIR for atmospheres / molecules / atoms analysis
    - SWIR for Galaxy tracking (Dopler)
    - SWIR-LWIR for deep space observation
    - And many others…
  - Weather forecast/global warming:
    - SWIR for CO2/CH4 tracking (e.g.: Microcarb / Merlin missions)
    - SWIR for land surface temperature monitoring (e.g.: LSTM mission)
    - SWIR/MWIR for water and temperature tracking (e.g. MTG-i missions)
  - Defense:
    - VIS-SWIR for SSA
    - VIS-SWIR-LWIR for observation
- **Main figures of merit:**
  - **Spectral bands (position and accuracy)**
  - **SNR**
  - **Resolution**



JWST NIRCam image of Uranus, credit: NASA, STScI



Herschel telescope entire sky map, credit: ESA and the Planck Collaboration

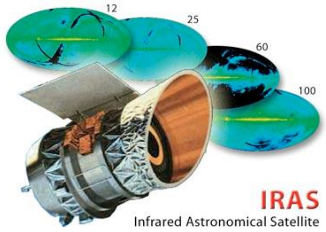


MTG-I1 first images, credit: EUMETAT

Adding optical functions to detectors. Is it worth it?

- **Example of scientific multi-spectral space telescopes operating in the IR**
  - IRAS – 1983
    - Survey array at 12, 25, 60 and 100 µm with 62 mono-element detectors
    - Low resolution spectrometer (7.5-23 µm)
  - ISO – 1995-1998
    - High resolution camera (2.5-17 µm)
    - Photo-polarimeter (2.5-240 µm)
    - Short wave spectrometer (2.4-45 µm)
    - Long wave spectrometer (45-197 µm)

- Spitzer Space Telescope – 2003-2020
  - IR array camera 256x256 px (3.6, 4.5, 5.8 and 8µm)
  - IR spectrograph (LR 5.3-14µm, HR 10-19.5µm, LR 14-40µm and HR 19-37µm)
  - Multiband Imaging Photometer (128x128 px at 24µm, 32x32 px at 70µm, 2x20 px at 160µm)
- Herschel Space Observatory – 2009-2013
  - Photodetecting Array Camera and Spectrometer (55-210µm)
  - Spectral and Photometric Imaging Receiver (194-672µm)
  - Heterodyne Instrument for the Far Infrared (157-625µm)
- Others…
  - Akari, WISE, …



Infrared Astronomical Satellite, credit: NASA/Goddard Space Flight Center

Spitzer Space Telescope, credit: Russ Underwood, Lockheed Martin Space Systems

Herschel Space Observatory, credit: ESA

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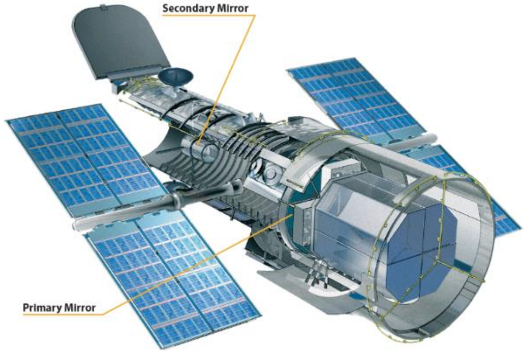
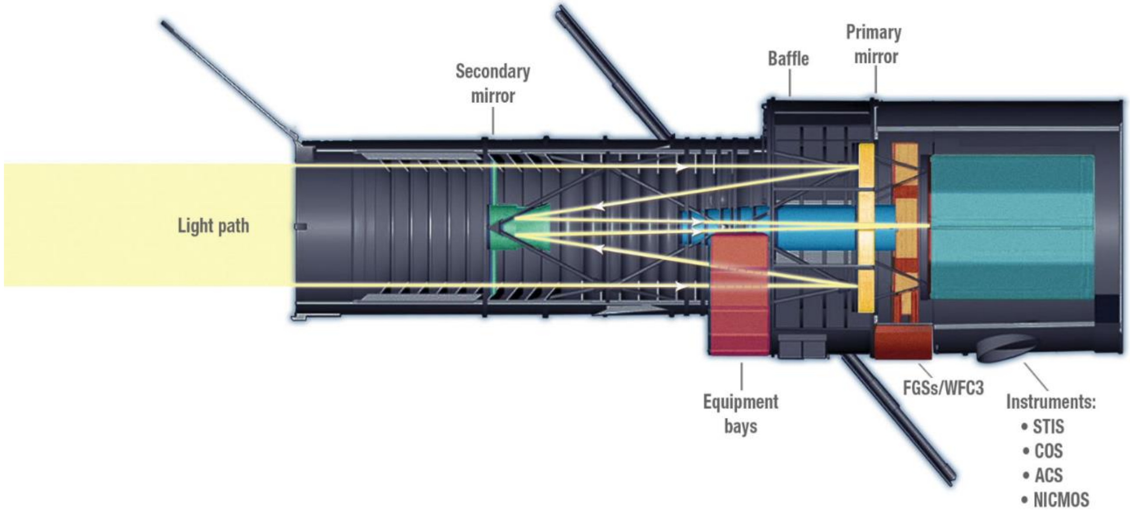
Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - Optical beam path in space telescopes:
  - Basic function: collect the maximum amount of light of the largest field and focus it to a focal plane (intermediate, or not) → **This is the input window, it creates a first spectral selection**





Hubble space telescope, credit: NASA, STScI

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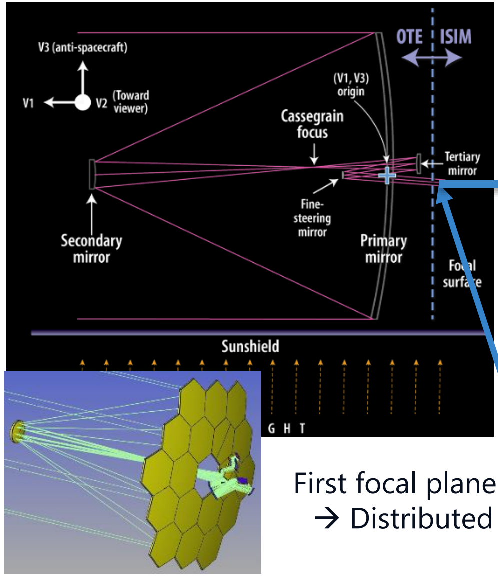
Adding optical functions to detectors. Is it worth it?

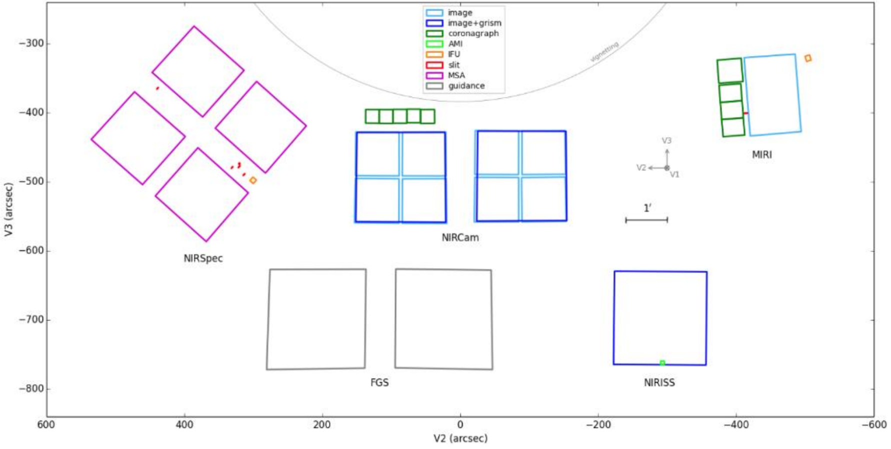
- **From space telescope architecture point of view:**
  - After telecope's first focal plane: optical mess is starting

JWST optical path, credit: JWST, F. Riguet



- NIRCam
- NIRSpec
- MIRI
- FGS/NIRISS

First focal plane of JWST (Ø 650mm)
→ Distributed over 4 instruments



JWST field of view, credit: JWST

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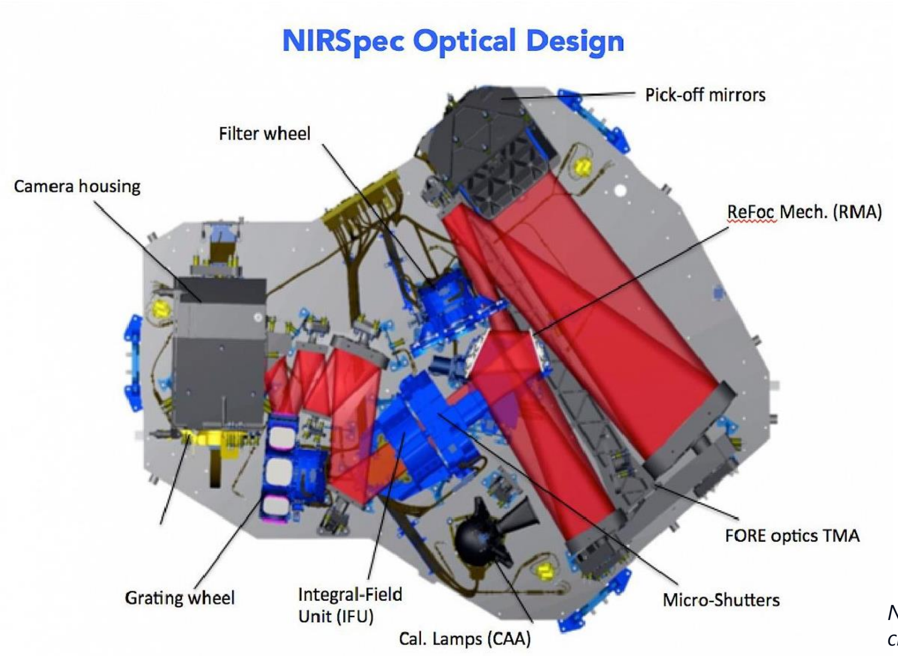
Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - After telecope’s first focal plane: optical mess is starting



NIRSpec architecture, credit: STScI

Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - Major stakes in space telescopes architecture
    - Optical apperture / focal plane dimension
    - Weight / size (in particular in the case of small satelites), **~3-20 k$/kg**

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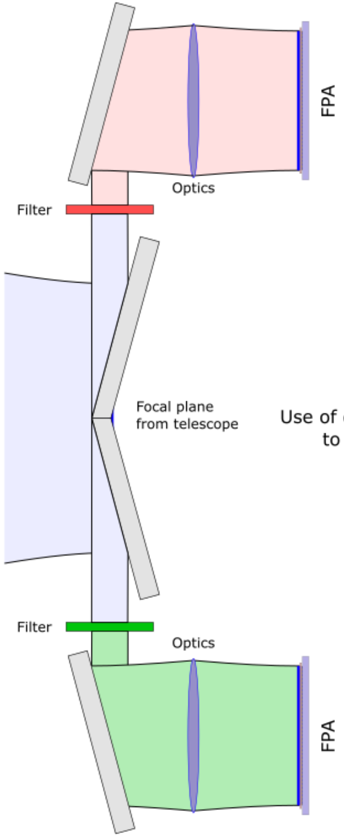
Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - How to get hyperspectral / multispectral images
    - **Spatial separation in the intermediate focal plane → more optics → filters → detection**
      - Advantages:
        - Simultaneous acquisitions of images above different spectral channels
        - Highest resolution on each channel
      - Drawbacks:
        - Heavy architecture (multiplied optics per channel)
        - Observed fields on different spectral bands are not the same
        - Limited number of channels
      - *<u>Example:</u> JWST field distrubtion over instruments*

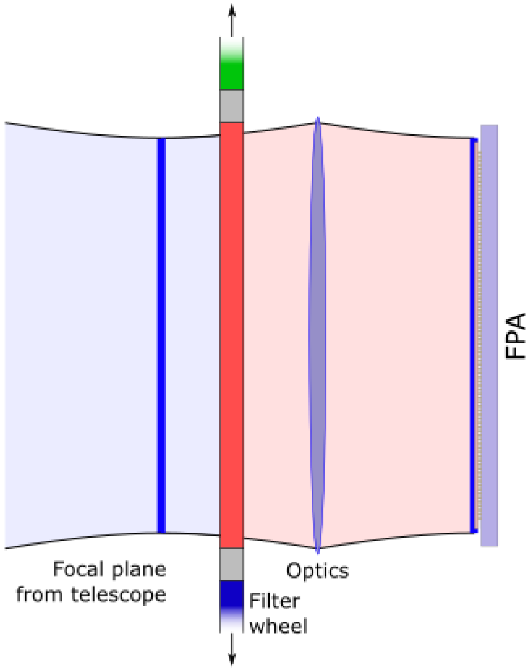


Spatial separation:
Use of different parts of optical field
to separate spectral bands

Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - How to get hyperspectral / multispectral images
    - **Spectral selection at the intermediate focal plane (filter wheel) → more optics → detection**
      - Advantages:
        - Light architecture (filter wheel directly on optical path)
        - Highest resolution on each channel
      - Drawbacks:
        - Sequential spectral acquisition of images
        - Needs a broad band detector covering all the spectral need
        - Needs mechanical movement
      - *<u>Example:</u> JWST's NIRSpec and NIRCam*

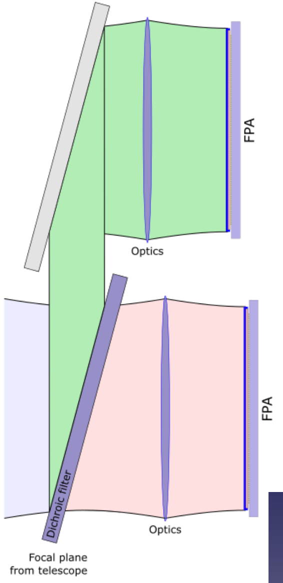
NIRSpec's filter wheel



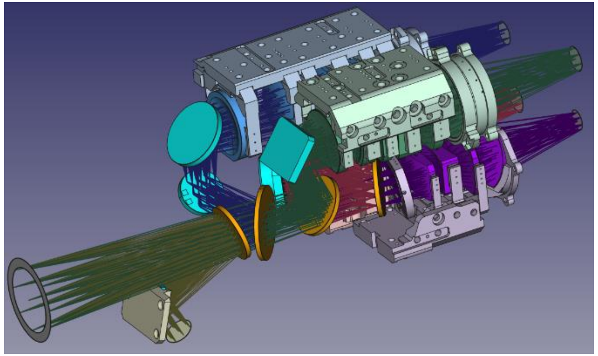
Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - How to get hyperspectral / multispectral images
    - **Spectral separation of the intermediate focal plane (dichroic) → more optics → filters → detection**
      - Advantages:
        - Simultaneous acquisitions of images above different spectral channels
        - Highest resolution on each channel
      - Drawbacks:
        - Heavy architecture (multiplied optics per channel)

      - *Example: Meteosat Third Generation (MTG) → 5 channels separated with dichroic filters*



Spectral separation:
Use of a dichroic filter to separate spectral bands

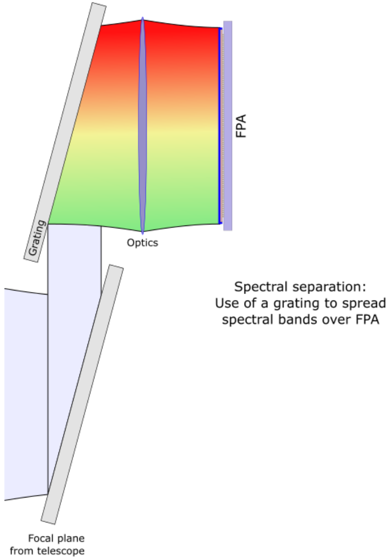


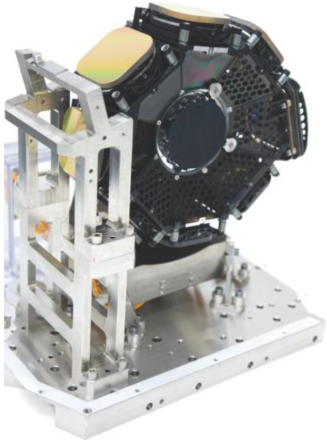
MTG SSA

Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - How to get hyperspectral / multispectral images
    - **Spectral spreading with optical grating → detection**
      - Advantages:
        - Simultaneous acquisitions of images above different spectral channels
        - Highest resolution on each channel
        - High number of accessible spectral bands
        - Compact architecture
      - Drawbacks:
        - Needs scanning
        - Needs a broad band detector covering all the spectral need
        - Not suitable for radiometry

      - *Example: NIRSpec spectral analysis*

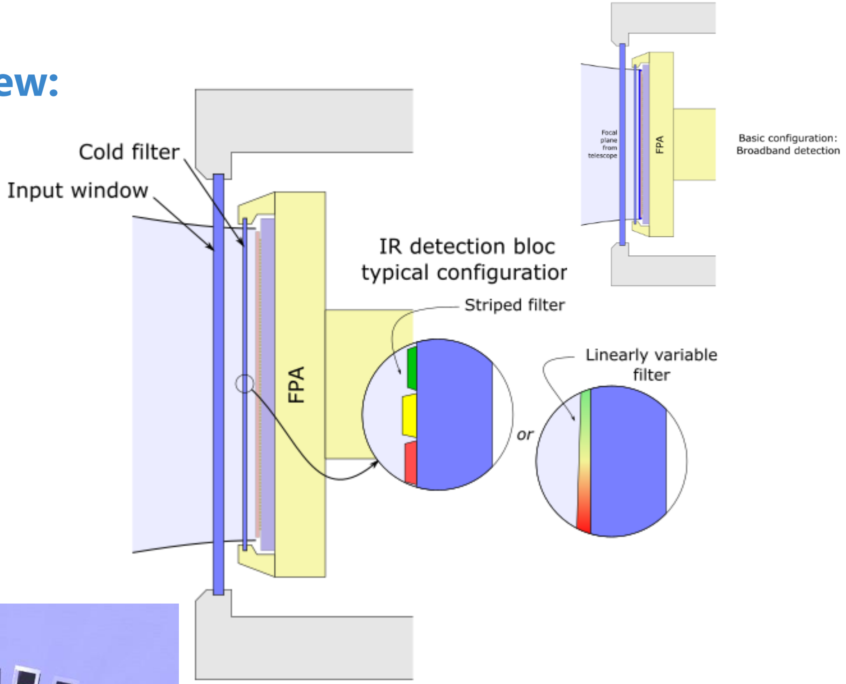


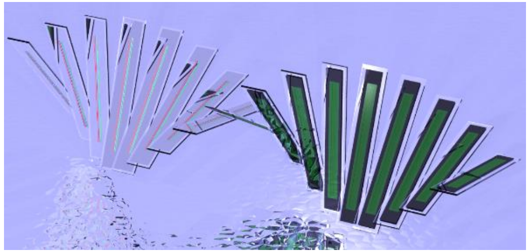


NIRSpec's gratings wheel

Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - How to get hyperspectral / multispectral images
    - **Spectral separation on the detector bloc (strip filters or linearly variable filter)**
      - Advantages:
        - Compact architecture (similar to grating configuration)
      - Drawbacks:
        - Needs scanning
        - Needs a broad band detector covering all the spectral need
        - Can generate ghost images
      - *Example: Pleiades ; MTG*

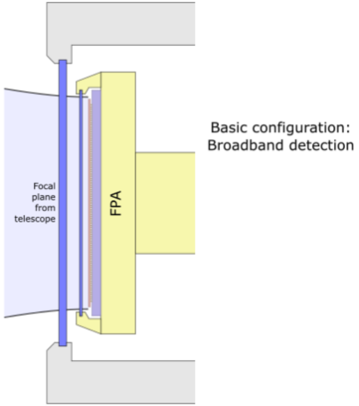


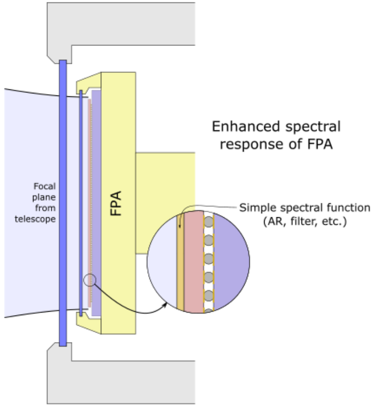


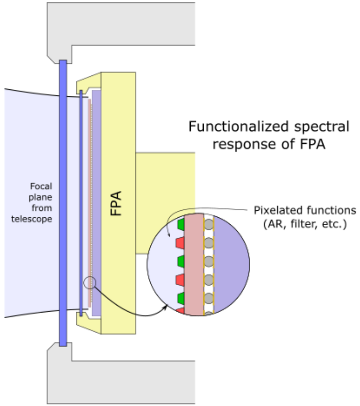
Pleiades strip filters

Adding optical functions to detectors. Is it worth it?

- **From space telescope architecture point of view:**
  - How to get hyperspectral / multispectral images
    - **Spectral separation on the detector surface (pixelated or linearly variable filters)**
      - Advantages:
        - Compact architecture (similar to grating configuration)
        - Simultaneous acquisition of different spectral bands
        - Identical observed field on different spectral bands
      - Drawbacks:
        - Lowers resolution on each channel
        - Needs a broad band detector covering all the spectral need
      - *<u>Example:</u> AR on detector on Sentinel 5 & Microcarb*







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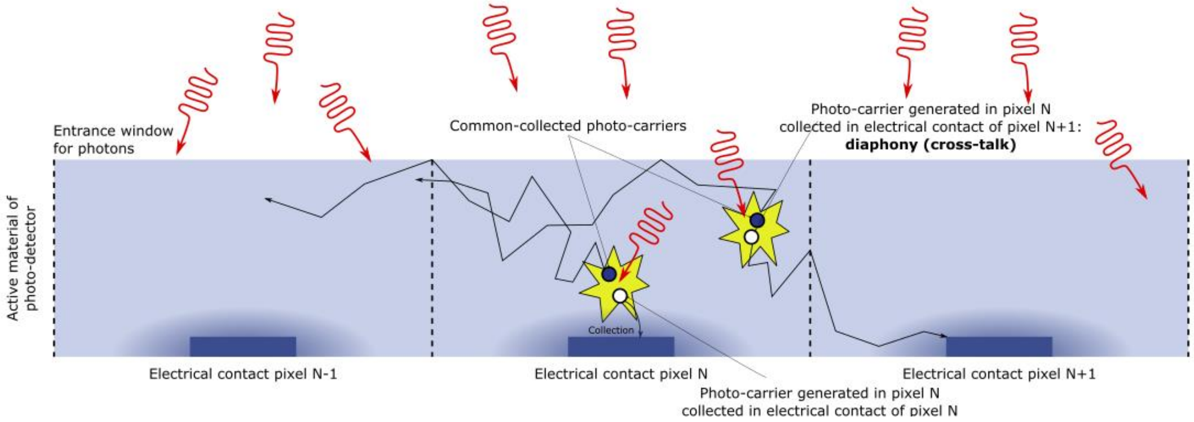
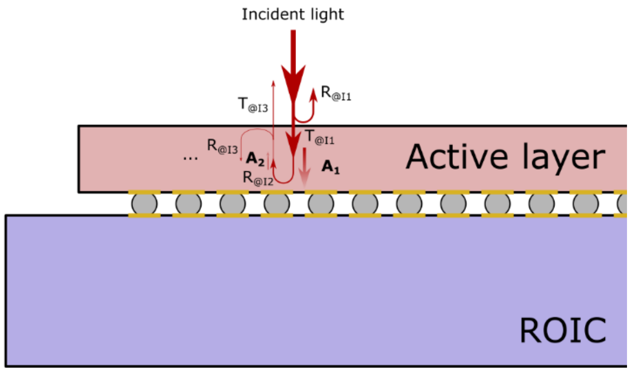
Adding optical functions to detectors. Is it worth it?

- **From detector point of view**
  - Bare IR detectors (any detection material/structure) lack of different limitations:
    - Native loss of light (reflected light from air to detector interface, transmitted after backside reflexion, etc.)
    - Cross-talk between pixels (tends to increase with pixel size reduction)
    - *Others that might not be overcomed with optical coatings…*





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Adding optical functions to detectors. Is it worth it?

Yes, it is.

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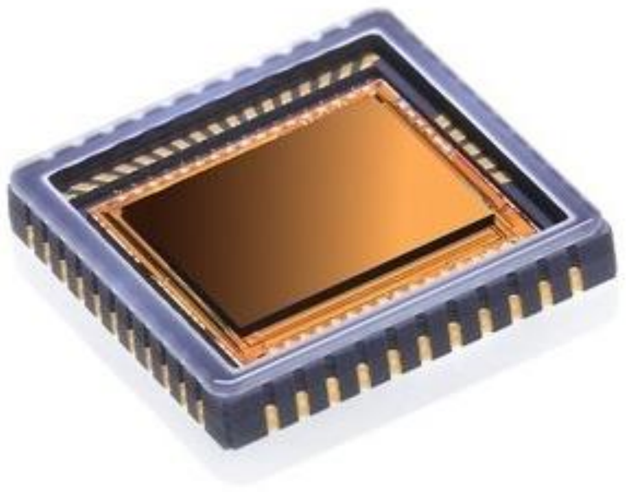
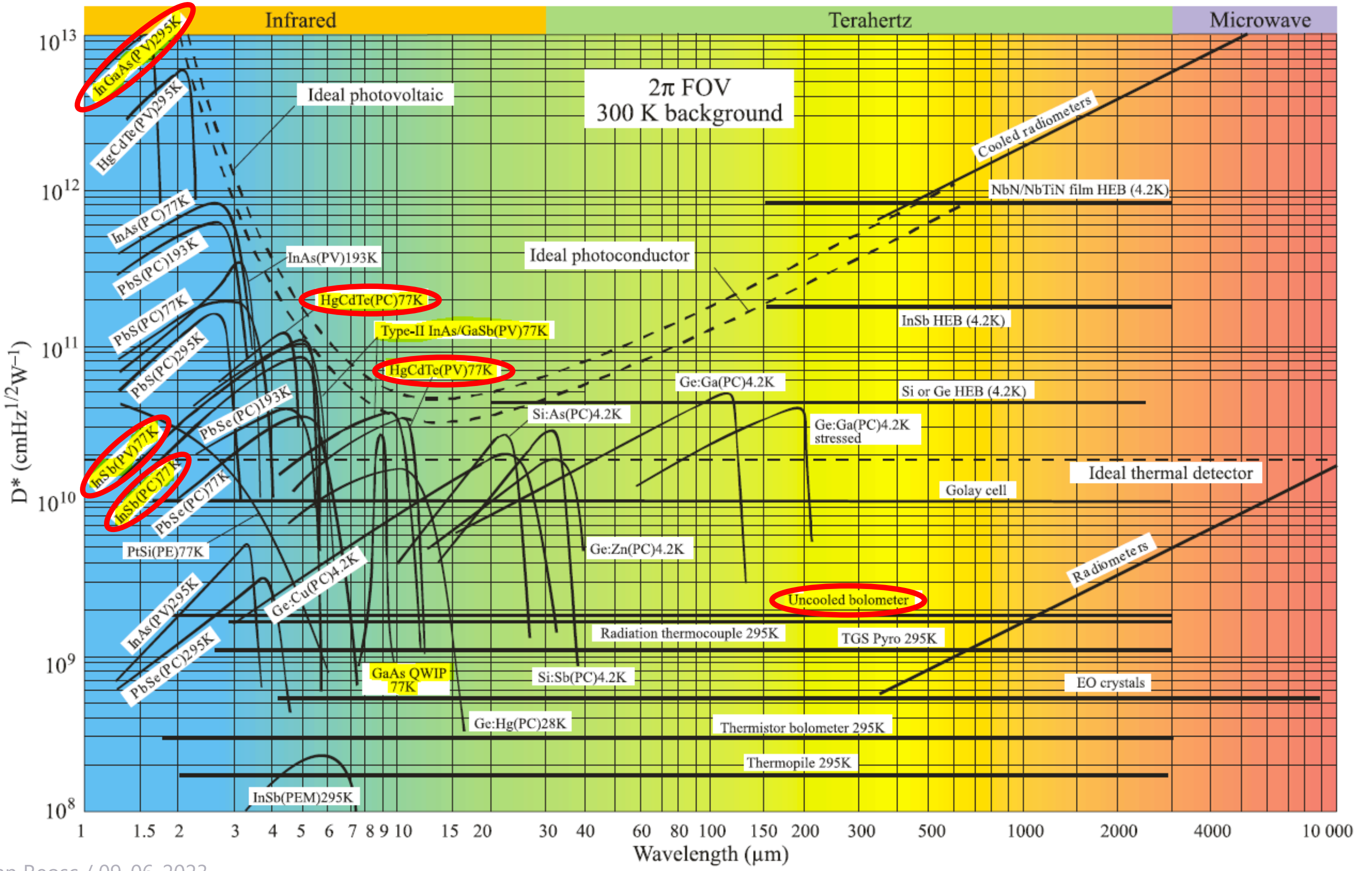
IR FPA detectors – COTS & roadmaps



Lynred's Snake SW tecless, SWIR VGA FPA

IR FPA detectors – COTS & roadmaps

A. Rogalski, History of infrared detectors Opto–Electronics Review 20(3), 279–308, 2012



Space mission applied

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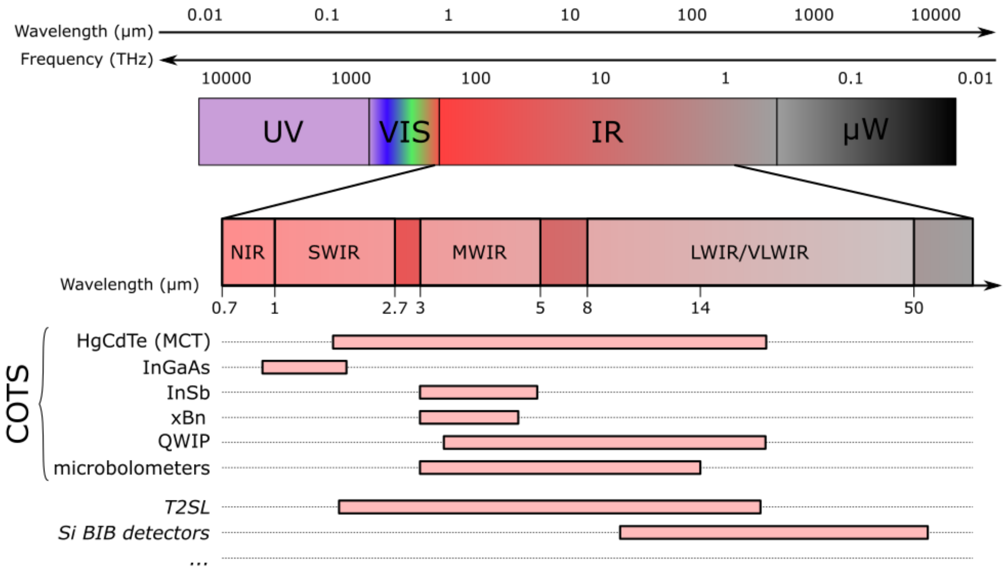
IR FPA detectors – COTS & roadmaps

- **IR detectors, main COTS technologies for space applications**
  - NIR/SWIR:
    - III-V based InGaAs → 1280x1024 @5µm
    - HgCdTe → $4k^2$ @10µm
  - MWIR:
    - HgCdTe → $4k^2$ @10µm
    - InSb → 2k x 1.5k @10µm
    - xBn → $1k^2$ @10µm
    - T2SL → 640x512 @15µm
    - QWIP
    - Microbolometers
  - LWIR:
    - HgCdTe → $1k^2$ @15µm
    - QWIP → $1k^2$ @15µm
    - microbolometers → 2k x 1k @12µm



New technologies, new actors?

Detector format gets bigger

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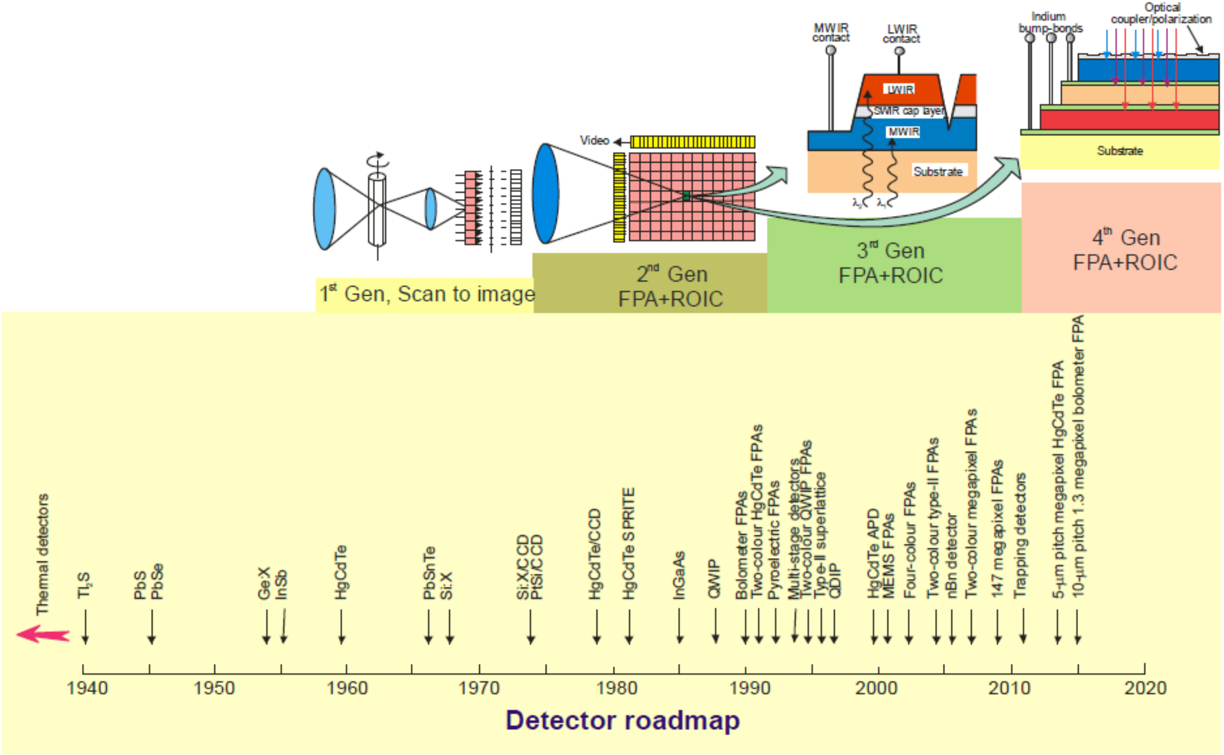
IR FPA detectors – COTS & roadmaps

- **IR detectors, main roadmap key features**
  - Increasing resolution: > 2k²
  - Decreasing pitch size: down to 5µm
  - Chip-level multi-spectral detection (see next slides)
  - Increasing working temperature
  - Gain on performances (sensibility, crosstalk, etc.)

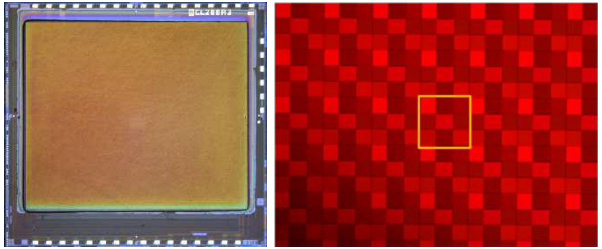


A. Rogalski, Next decade in infrared detectors, SPIE S+D, 2017

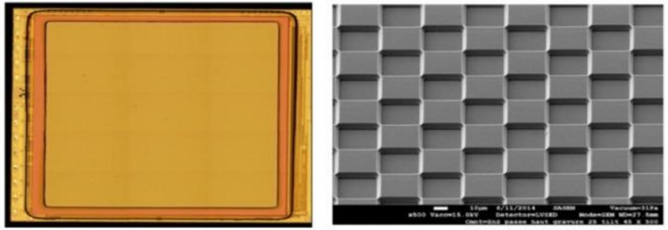
IR FPA detectors – COTS & roadmaps

- **Multispectral imaging at FPA level:**
  - Broad band detector + lots of pixels + filtering
    - Ex. Lynred/Silios/Thales collaboration, Snake VGA based SWIR, 9 bands
    - Ex. Lynred/Safran Reosc collaboration, HgCdTe 1280x512 MWIR, dual band
    - Ex. IMEC/SCD collaboration, Cardinal 640 based SWIR, >100 bands

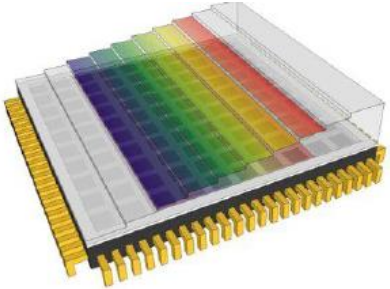
X. Lucquiault et al., Development of a multispectral SWIR imager protype using pixel level filtering OPTRO2022 079



N. Péré-Laperne et al., Optical functions integrated onto a mid-wave infrared detector



P. Gonzalez et al., An extremely compact and high-speed line-scan hyperspectral imager covering the SWIR range, SPIE Commercial + Scientific Sensing and Imaging, 2018



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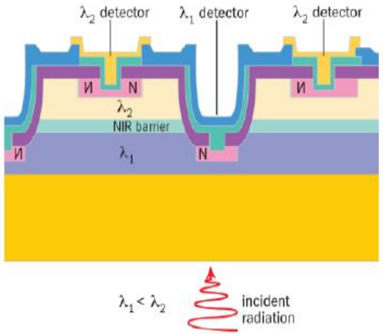
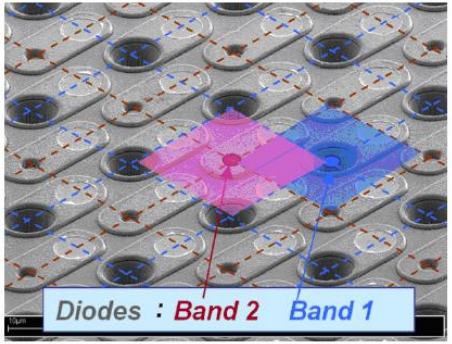
IR FPA detectors – COTS & roadmaps

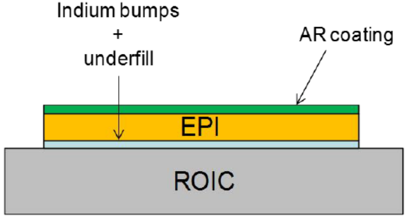
Y. Rebeil et al., Infrared dual-band detectors for next generation, SPIE Defense, Security, and Sensing, 2011

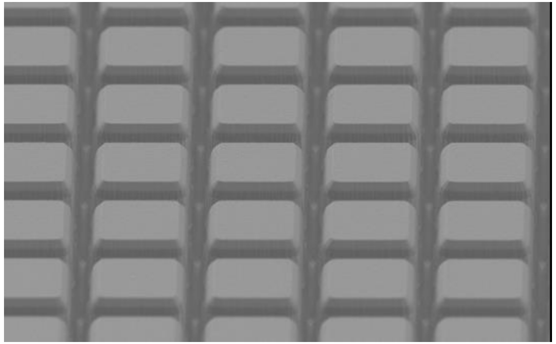
- **Multispectral imaging at FPA level :**
  - Superimposed narrow bands detectors at each pixel
    - Ex. Lynred, HgCdTe 640x512 MW/LWIR, dual band
    - Ex. Lynred, HgCdTe 640x512 MWIR, dual band
    - Ex. AIM, HgCdTe 320x256 MWIR, dual band
    - Ex. HRL, T2SL 1280x720 MW/LWIR, dual band
    - Ex. IRPDC, T2SL, 384x288 MW:LWIR, dual band

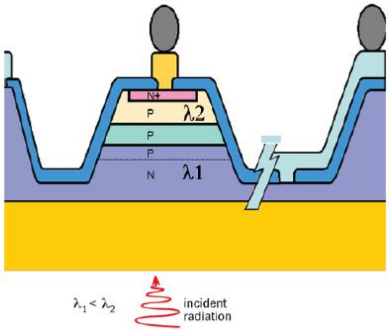


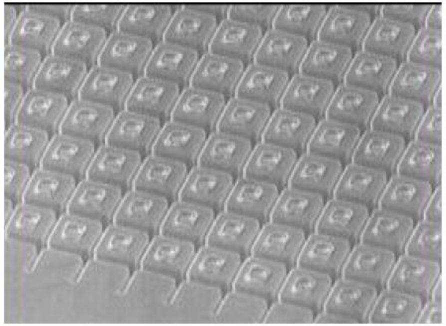


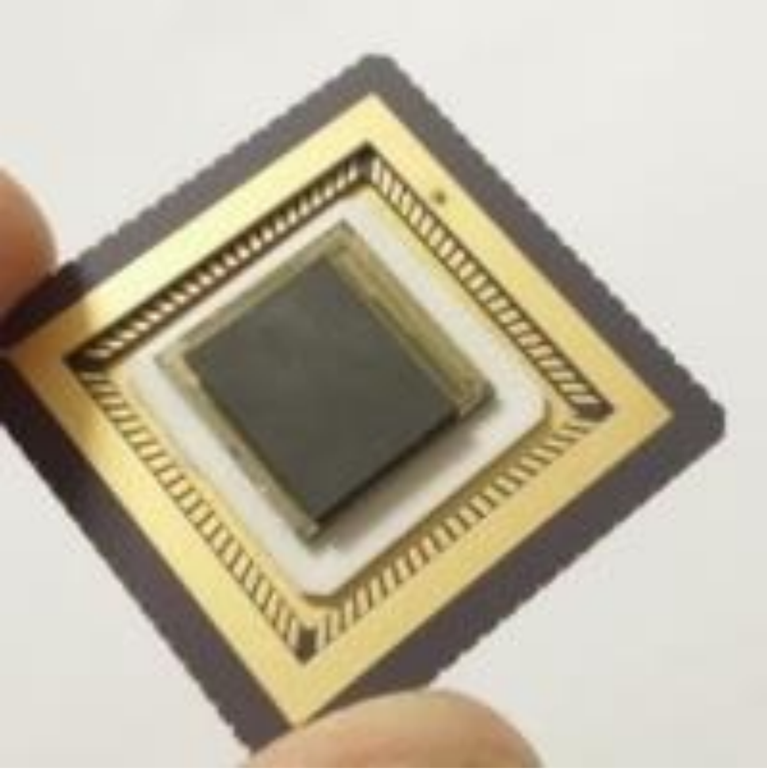
P.-Y. Delaunay et al., Advances in III-V Based Dual-Band MWIR/LWIR FPAs at HRL, SPIE Defense + Security, 2017











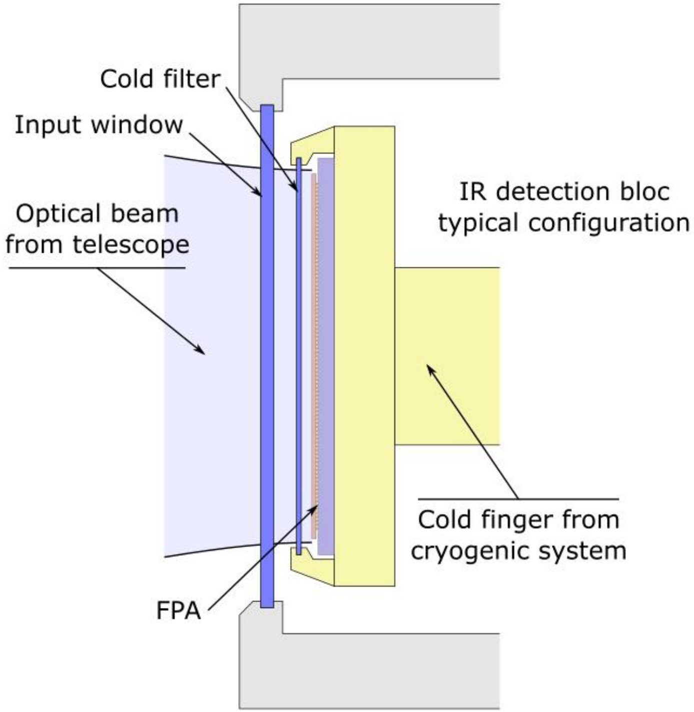
3

Available technologies and future developments

Available technologies and future developments

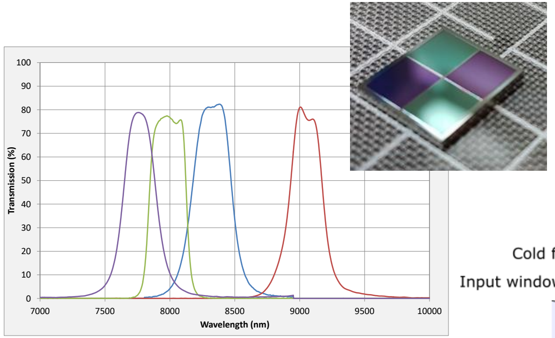
- **On detector bloc:**
  - Adding functions to cold filter
    - AR, filters, blockings
  - Adding functions to input window (if applicable)
    - AR, filters, blockings, absobers

- **On FPA:**
  - Improving FPA performances:
    - New generation of FPAs (T2SL, BIB, etc.)
    - Gain on quantum efficiency by adding AR functions
    - Gain on cross-talk by adding focusing functions
  - Adding spectral functions:
    - Filtering of pixels/submatrixes
  - Limitations:
    - Must comply with interfaced active material and structure specifications **and** space mission profile

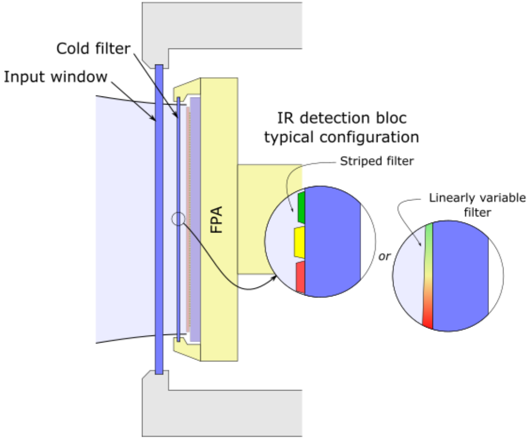


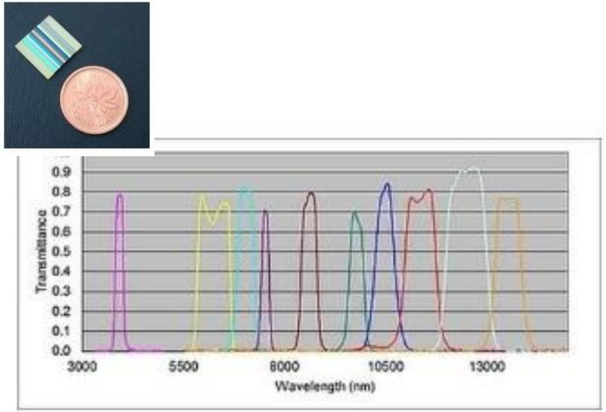
Available technologies and future developments

- **Focus on detector bloc technologies (in production)**
  - Different functions applicable on both sides of the cold filter / input window (filters, blockings, AR, etc.)
  - Strip / linearly variable filters

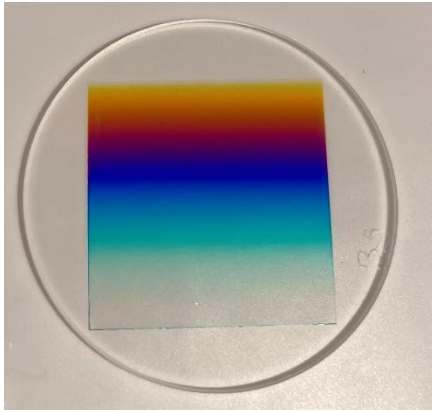


Juxtaposed IR filters developed at Safran Reosc



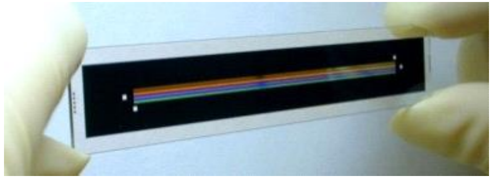


M/LWIR filter array and spectral curves, IRIDIAN, ABB Canada, CSA



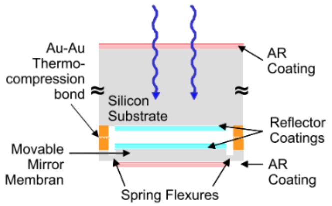
Linearly variable IR filters developed at Safran Reosc (under development)

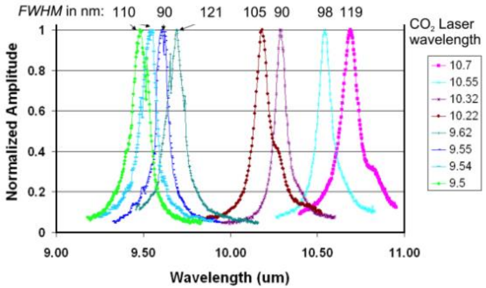
Stripped filters developed and manufactured at Safran Reosc for the Pleiades mission



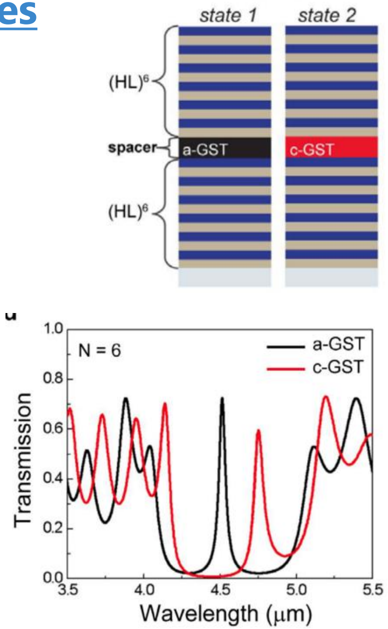
Available technologies and future developments

- **Focus on detector bloc technologies (in development)**
  - Tunable filters
  - Diffractive filters

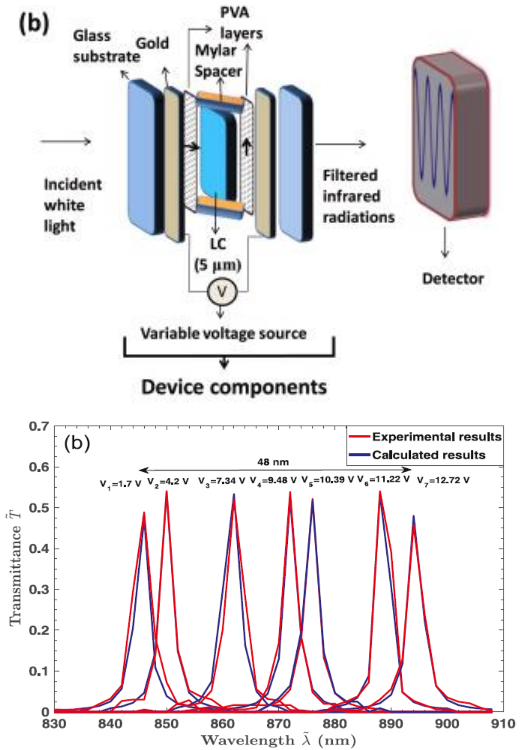




M. Ebermann et al., Proc. of SPIE vol 9760, pp. 97600H-1 (2016)



C. Williams et al, Optics Express Vol. 28, Issue 7, pp. 10583-10594 (2020)



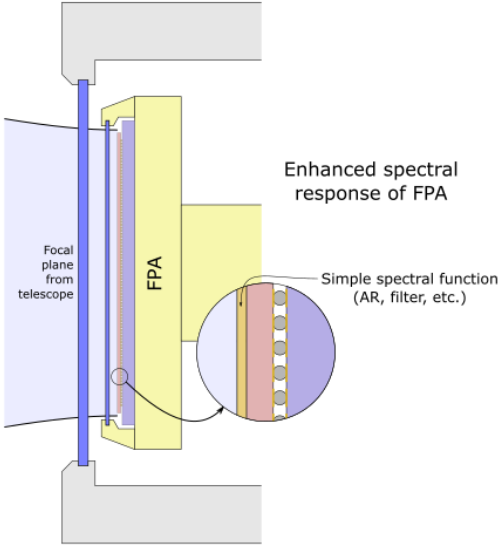
R. Nasir et al., IJLEO, 225 (2021) 165714

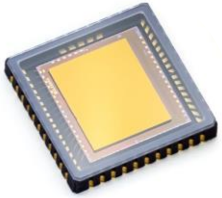
Available technologies and future developments

- **Focus on FPA technologies:**
- **Main challenge #1: preserving integrity of the sensor during processing**
  - Low temperature deposition
  - Prohibition of energetic process
  - Low defectivity required
  - Qualification at cryogenic temperature (< 77°K)
  - Adhesion on active materials: HgCdTe, InP, InGaAs, InSb…
- **Main challenge #2: Qualify technology for space missions**
  - Environmental resistance (radiations, atomic oxygen, sun illumination, etc.)

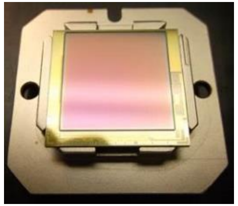
Available technologies and future developments

- **Focus on FPA technologies (in production) :**
  - All-pixel deposited optical function (AR, filter, etc.)
    - Uses standard deposition techniques
    - Easy way to improve FPA spectral performances

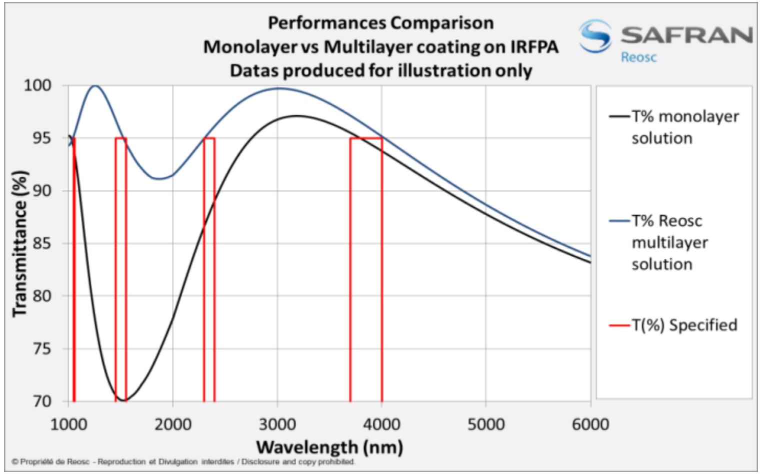




Lynred's Snake SW Tecless, with AR coating

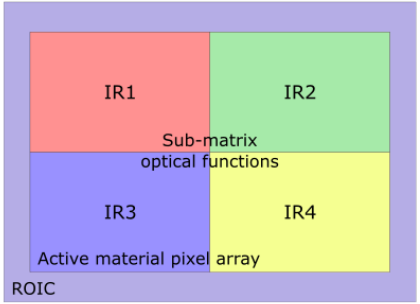


Lynred's NGP detector, with AR coating



Available technologies and future developments

- **Focus on <u>FPA technologies</u> (in development) :**
  - Sub-matrix level technologies
    - Separated functions on different parts of FPA
    - Spatial definition with lithography, lift-off or etching techniques
    - Allows simultaneous acquisition of different optical functions
    - Potentially simpler than pixelized function (no cross-talk between IR bands)
    - Observed fields are different
    - Lowers resolution of each optical function → *need of HD FPAs*



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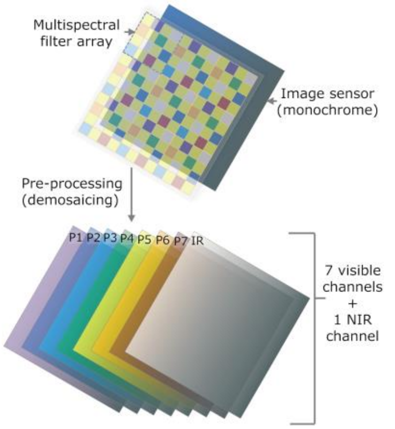
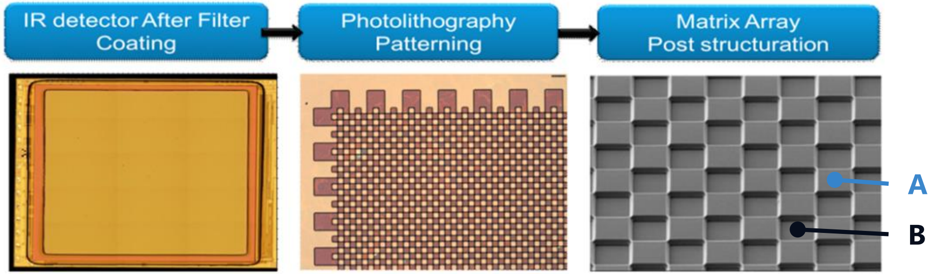
Available technologies and future developments

- **Focus on FPA technologies (in production) :**
  - Pixel-level optical functions (AR, filters, blockings, etc.)
    - Spatial definition with lithography, lift-off or etching techniques
    - Main technical challenge is related to thickness of optical functions (several microns, or even more than 10µm) with respect to pixel size
    - Tailors a broadband detection to specific needs
    - Allows simultaneous acquisition of the same field with different optical functions
    - Degrades individual resolution of each function → *need of HD FPAs*
    - Generates unwanted cross-talk between optical functions

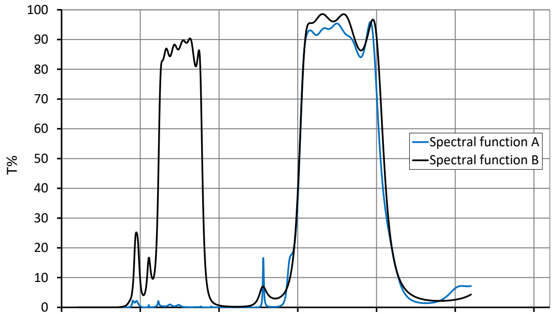
Multispectral filter array, credit: SILIOS Technologies

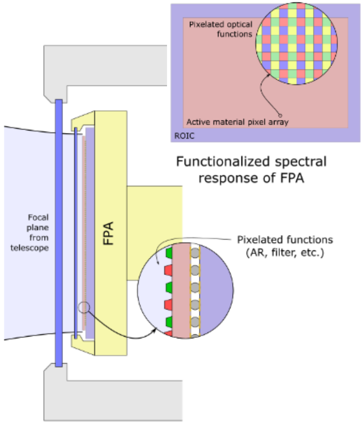




Safran Reosc knowledge applied on complex dual band filters

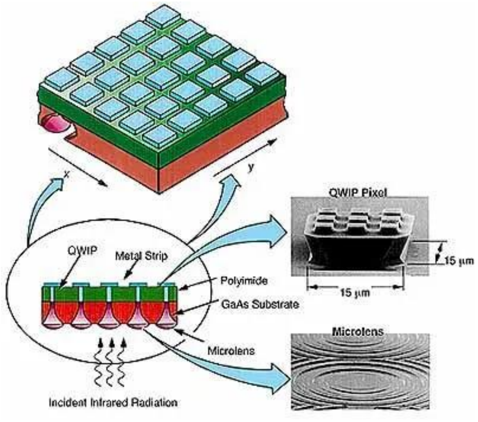
Transforms a broadband FPA in a bi-spectral FPA



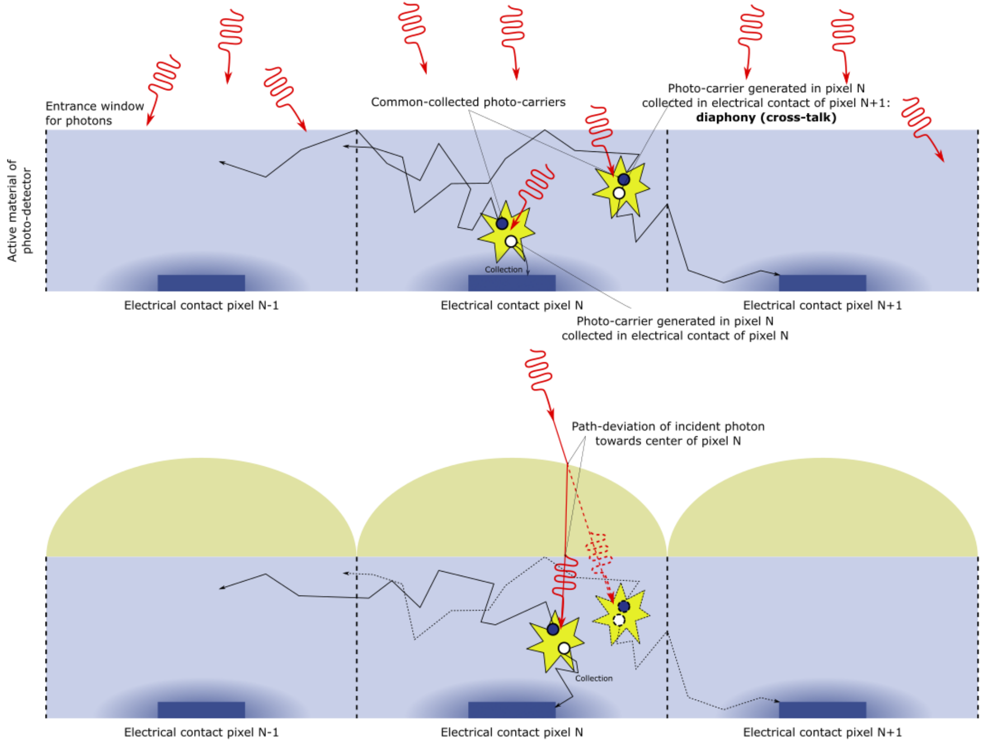


Available technologies and future developments

- **Focus on FPA technologies (in development) :**
  - Pixel-level 3D optical functions
    - Using state-of-the-art grayscale lithography techniques
    - Allows to improve cross-talk between pixels

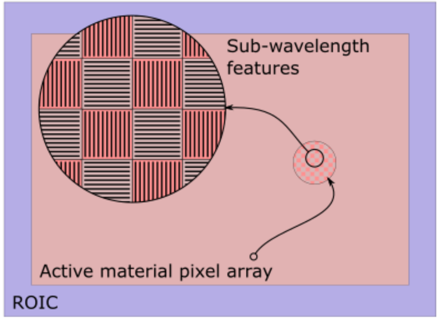


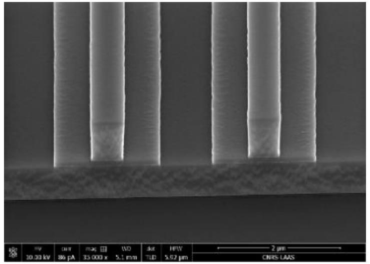
NASA's Jet Propulsion Laboratory, 1998



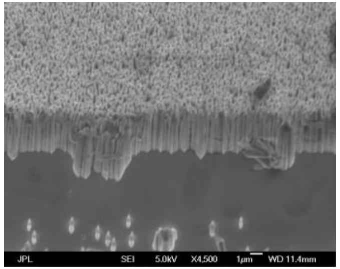
Available technologies and future developments

- **Focus on FPA technologies (in production/development) :**
  - Pixel-level subwavelength diffractive elements / metasurfaces

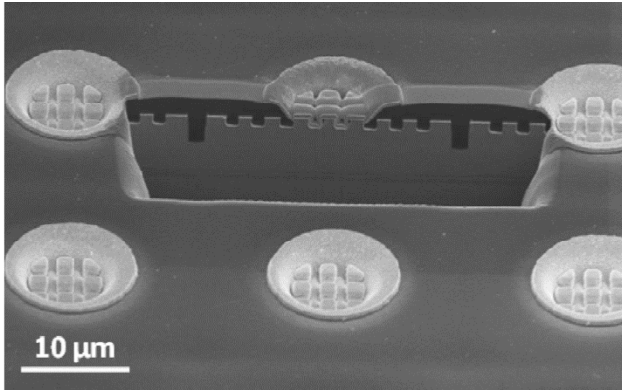




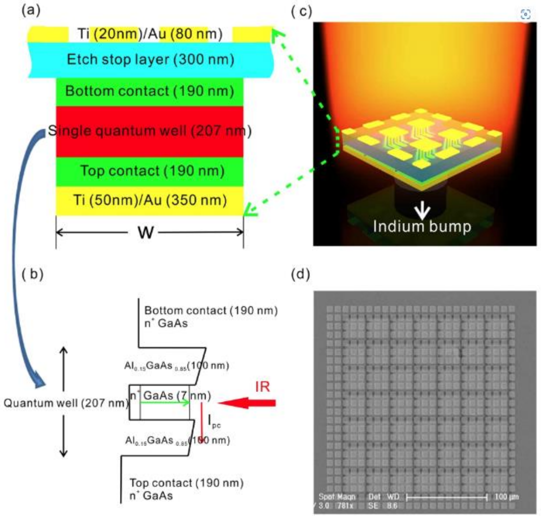
Guided mode resonance filters.
Credits: L. Macé et al., ICTON 2018



GeSb grass aiming at improving QE by increasing transmission of input surface. Credits: BJ Peper et al., SPIE DCS 2019



FIB cross cut of a Thales QWIP FPA revealing the subwavelength grating for incident light polarisation modification. Credits: P. Bois, Thales III-V Lab, 2011



Pixel-level plasmonic microcavity infrared photodetector, credit: YL J. et al. Scientific Reports volume 6, 25849 (2016)

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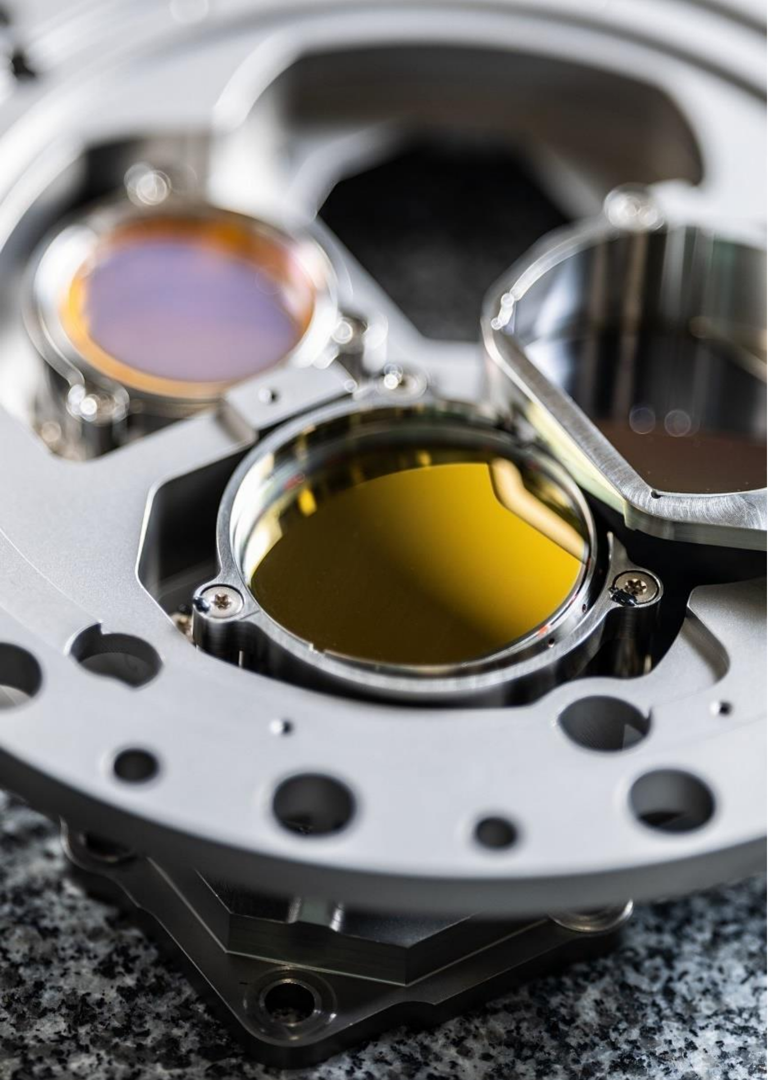

4

Strategies in the balance

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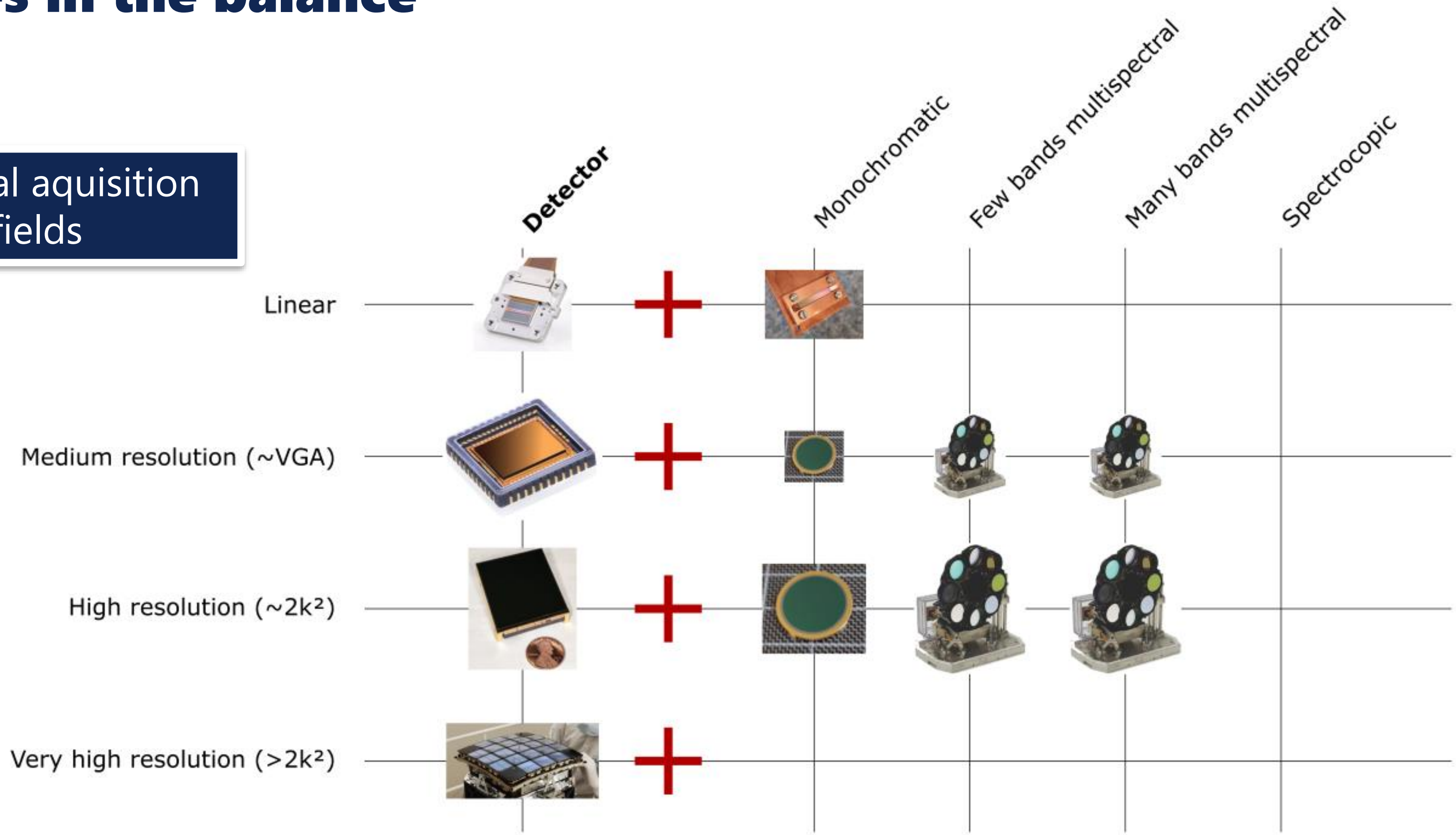
Strategies in the balance

- Sequencial aquisition
- Identical fields



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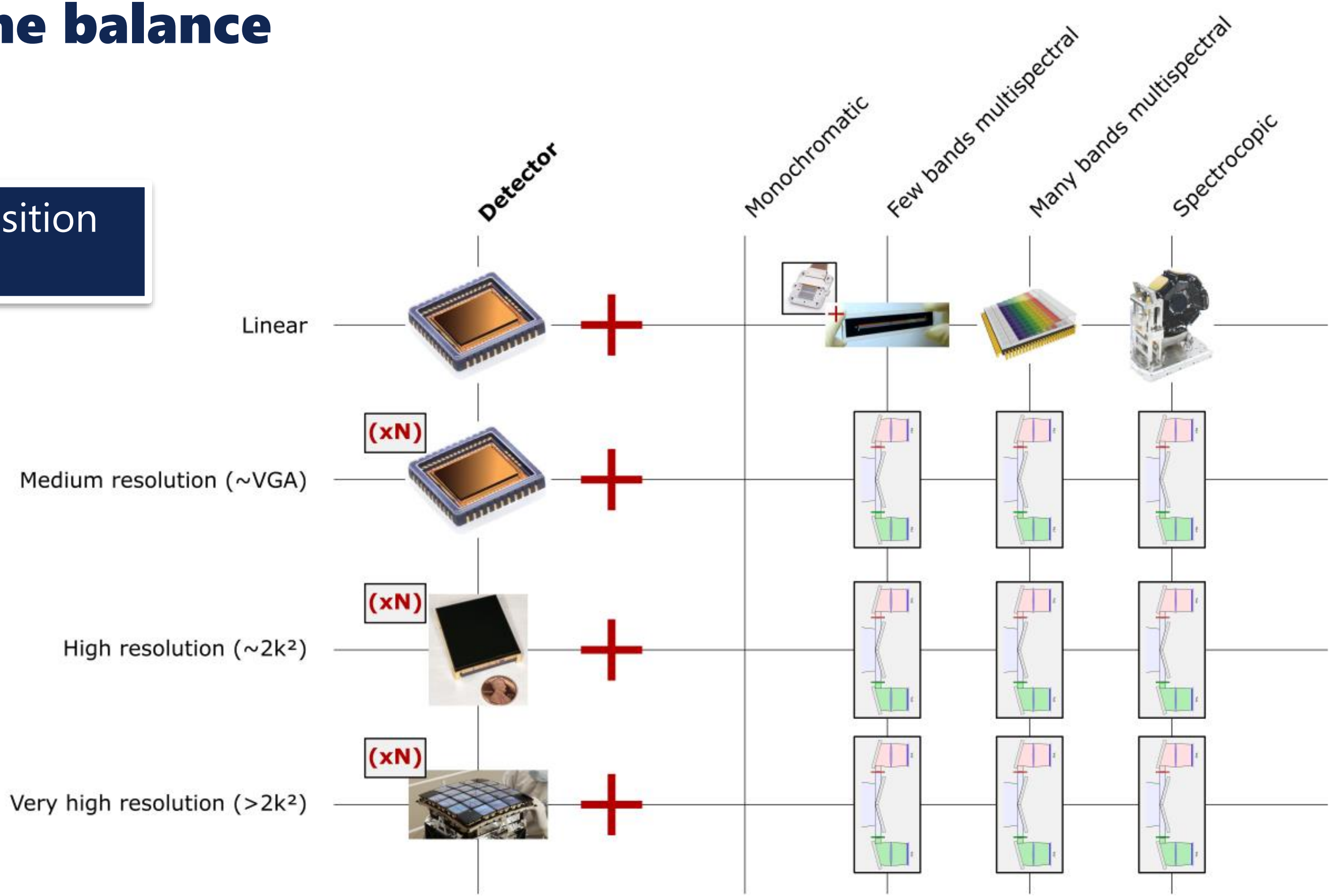
Strategies in the balance

- Simultaneous aquisition
- Separated fields



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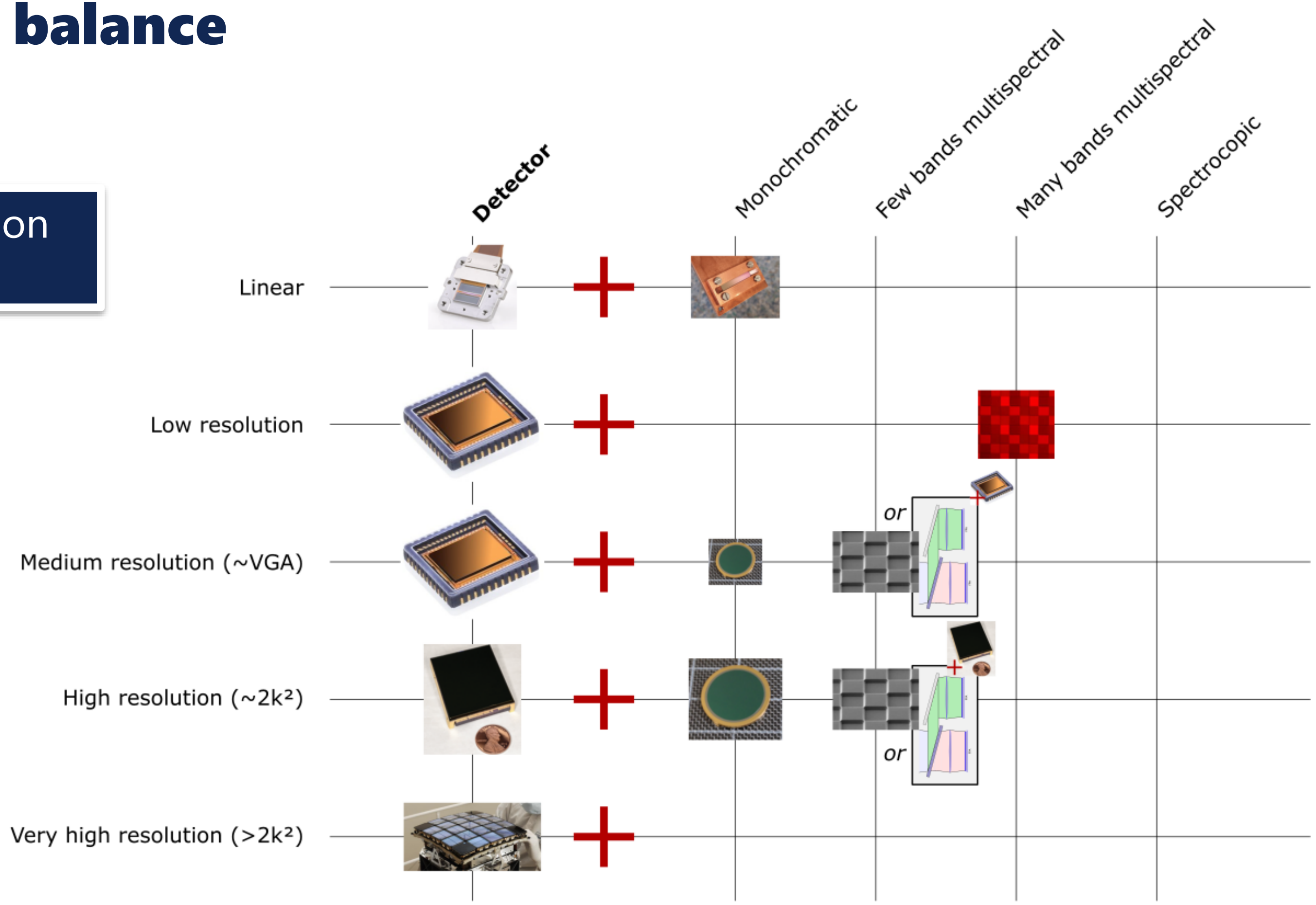
Strategies in the balance

- Simultaneous aquisition
- Identical fields



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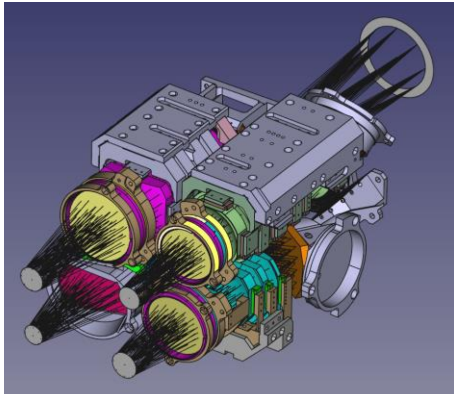
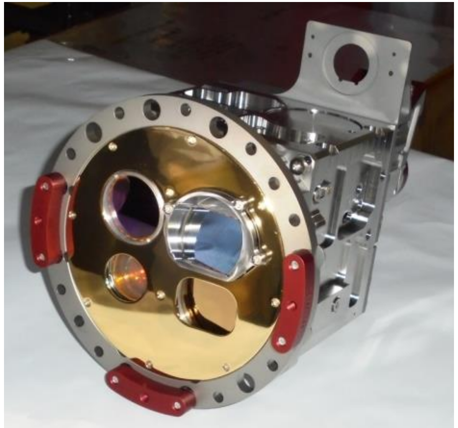
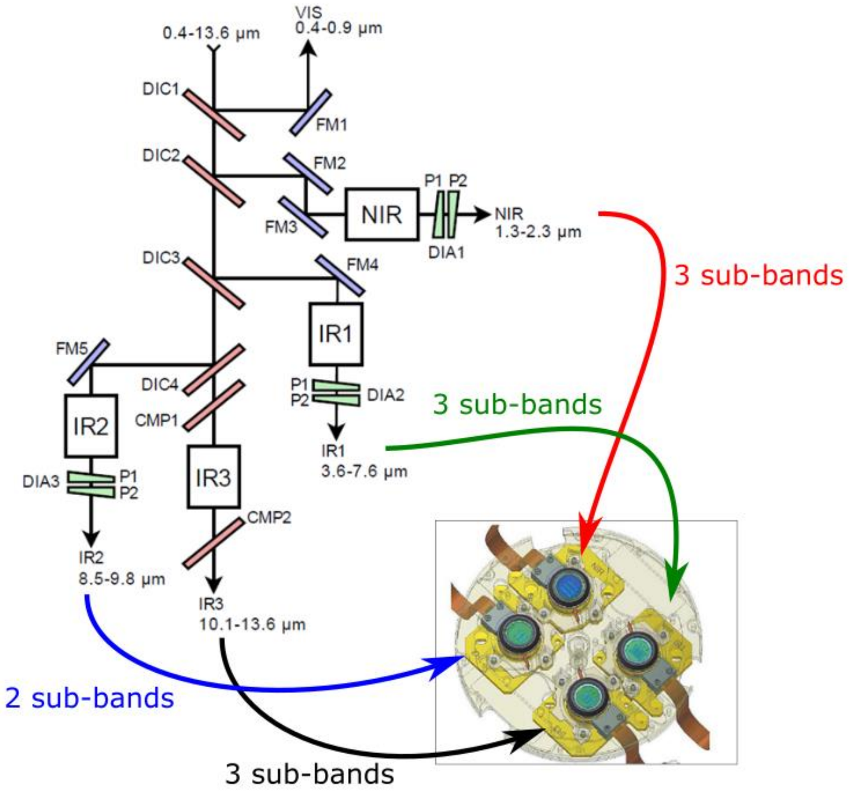
Strategies in the balance

<u>Example:</u> Spectral Separator Assembly (SSA) of Meteosat Third Generation (MTG)
(Safran Reosc designed and manufactured)



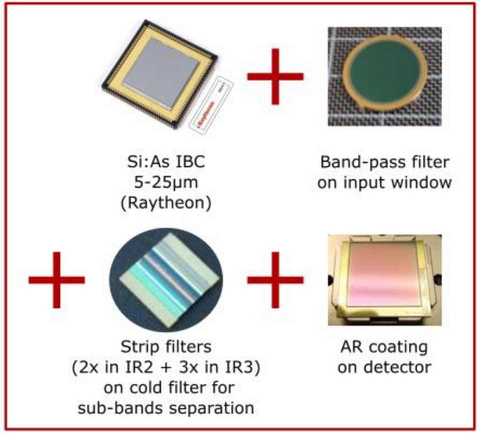


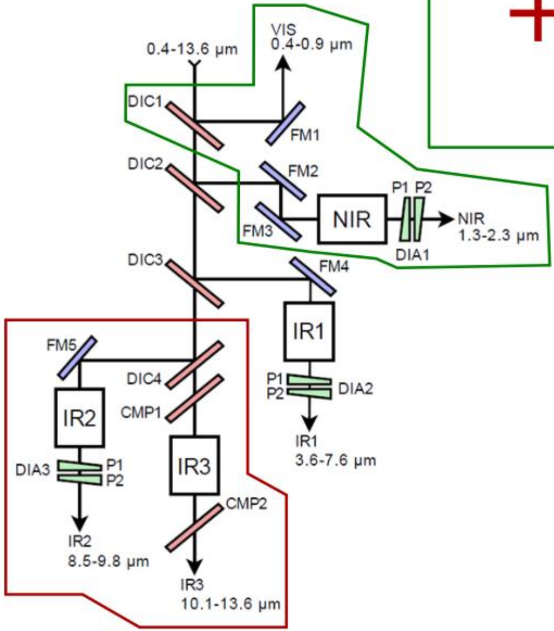


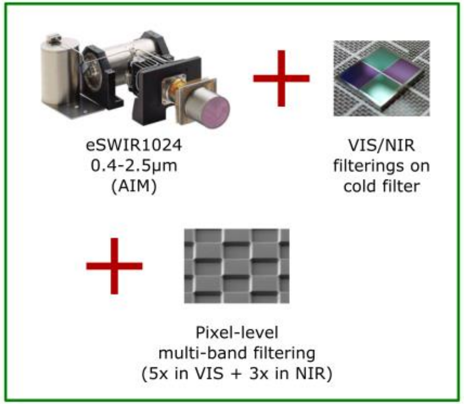
Strategies in the balance

Lighter design with different performances?

(other considerations also includes optical performances, cost, qualification, data collection, etc.)







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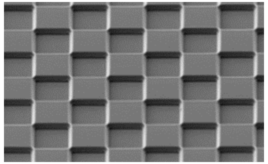
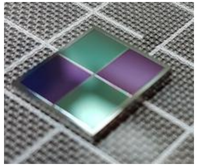
5

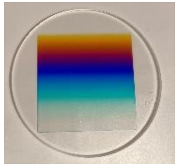
Conclusion

Conclusion



- **Future space missions can count on incredible developments over the last decade on all optical elements of the detection chain (either for space missions or ground applications).**
  - Detectors with unprecedented resolutions and performances have been developed
  - New generations of detectors are promising and close to production (T2SL, xBn, multi-spectral…)
- **Solutions to integrate optical functions directly in the detector bloc already exists and have been applied to space missions:**
  - Global optical functions on input windows / cold filters / FPA of the detector bloc
  - Stripped filters on detector bloc





- **Ground applications already use technologies that could be applied on space missions with environmental qualifications:**
  - Discretized functions directly on FPA (either at sub-matrices, lines or pixel levels)
- **Non-exhaustive global strategies to answer new space missions needs (covering state as well as « new space » programs) have been presented and suggest innovative strategies allowing compact multi-spectral solutions**

Integration of SEEING 130 Wide for micro/nano satellites

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