Heritage and history of European infrared detection for space applications

Infrared Detection
for Space Applications Workshop

Olivier Saint-Pé 7th of June 2023

AIRBUS

- Introduction
- 1970-1980: pioneering IR detectors for space applications
- 1980-1990: moving to multiplexed detectors
- 1990-2000: the boring decade (in Europe)
- 2000-2010: ramping up
- Conclusion?

Introduction

- Presentation prepared as the testimony of an engineer who has been active in the field of European IR detection for space for more than 35 years

- Potential interests could be to
  - ✓ contribute to capture the space IR detection global picture (technical, industrial…)
  - ✓ inform about some technologies/inventions emergences
  - ✓ help understand the current context
  - ✓ support “lessons learned” exercise

Introduction: opening remarks (1/2)

EOS

- The completeness of the presented European landscape is far from complete
  - ✓ suffers from “French-centric view” bias
  - ✓ infrared detection community is not the most open to external communication
  - ✓ any information shared in this presentation is extracted from open literature / internet
    → more emphasis on civilian space missions
- ➢ *any comment or additional information will be welcome*

- Although being a presentation centered on Europe, comparisons are made with the United States as leader of IR detection field (including space)

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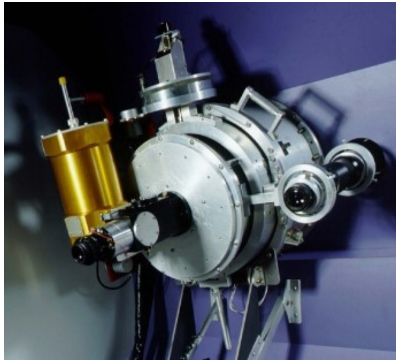
- Space missions for Earth observation and exploration of the Universe are often considered separately
  - ✓ Needs might significantly differ
  - ✓ not the same constraints in terms of development cycles, supply chains, IR detector procurement rules and risks management

- For reasons of available time, thermal sensing technologies (e.g. micro bolometers arrays) and sub-mm detectors (> ~200 µm) are not covered in this presentation, as well as aircrafts, stratospheric balloons and rockets missions

1970-1980: pioneering IR detectors for space applications

1970-1980: still First Gen limited

- ❑ Most of the topics interested in the use of space infrared payloads were already identified (meteorology, defence, astrophysics…)
- ❑ As well as tactical applications, main limitation at (1st Gen) detector level were
  - ✓ the limited size/format of IR photosensitive areas
  - ✓ the lack of multiplexing capability to efficiently manage a significant amount of photodetectors
- ❑ A side limitation was the capability to efficiently cool down the IR detectors

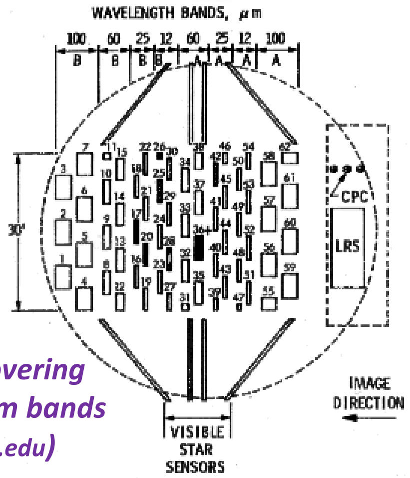


Franck Low pioneering IR astronomy: Learjet aircraft 12-inches IR telescope
(https://www.si.edu/object/telescope-infrared-airborne-learjet%3Anasm_A19830086000 https://en.wikipedia.org/wiki/Frank_J._Low)

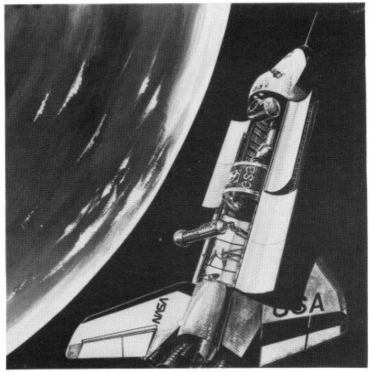
Texas Instrument 180–photoconductive MCT element Common Module FPA mounted on a dewar stem
(M.A. Kinch, "Fifty years of HgCdTe at Texas Instruments and beyond," Proc. SPIE 7298 (2009))

1970-1980: astrophysics missions

- Three US infrared missions studied at this time
  - ✓ IRAS (Infra Red Astronomical Satellite), dedicated to a full sky survey at 12, 25, 60 and 120 µm
    - 0.57 m diameter cooled telescope (4 K via superfluid He tank)
    - Launched in 01/2003 (10 months lifetime)
    - 3 K Survey focal plane built with 62 rectangular extrinsic photoconductors (Si:As, Si:Sb and Ge:Ga)
  - ✓ SIRTF (Shuttle Infrared Test Facility), which will ultimately lead to Spitzer IR observatory launched in 2003
  - ✓ COBE (Cosmic Background Explorer), launched in 1989, predecessor of Planck ESA mission
- In Europe, study of the GIRL facility (German Infra Red Laboratory)
  - ✓ Program stopped in 1985 but having significantly contributed to ISO and IBSS mssions



IRAS Focal Plane covering 12, 25, 60 and 100 µm bands (https://irsa.caltech.edu)

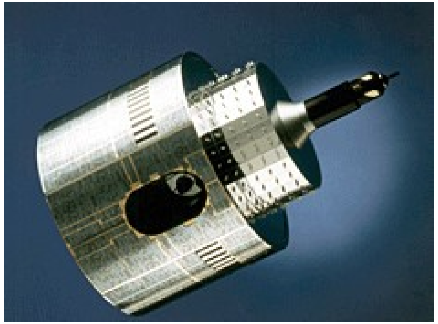


Artists view: GIRL onboard Spacelab (MBB)
(D. Lemke et al. "German Infra Red Laboratory (Girl)-Liquid Helium-Cooled Infrared Observatory for Spacelab", Proc. SPIE 0183 (1979))

1970-1980: Earth observation

- Archetypical Earth Observation space mission was Meteosat OPerational (MOP)
  - ✓ Aerospatiale Cannes as Prime Contractor, Matra Toulouse responsible for the radiometer development
  - ✓ GEO orbit, spin-scan radiometer (100 rpm), 400 mm diameter Ritchey-Chretien telescope, passive cooling (90 K), 1 image / 30 mn
  - ✓ 3 spectral channels: VIS (0,45-1 µm), water vapor (5.7-7.1 µm) and VLWIR (10.5-12.5 µm), 2.5/5 km GSD
  - ✓ IR detectors were PV and PC MCT monodetectors built by Mullard Space Science Laboratory (Southampton) (*)
  - ✓ first (and the only one for many years) European operational space program ensuring service continuity: 7 satellites launched from 1977 to 1997

(*) Mullard Lab also delivered detectors to Hugues Corporation from 1974 for the US Visible Infrared Spin Scan Radiometer (VISSR)



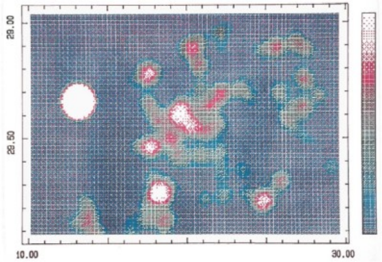
Meteosat Operational satellite, MVIRI radiometer integrated in Matra facility and monodetectors (silicon PV and MCT PV and PC)

1980-1990: moving to multiplexed detectors

- SWIR/MWIR multiplexed IR arrays started to be available end of 70s (mainly based on InSb), with trade-off between monolithic & hybrid technologies
  - ✓ Monolithic InSb CID (Charge Injection Device) introduced by General Electric mid of 70s (based on InSb MIS capacitance)
  - ✓ InSb photodiodes array hybridized on top of CCD MUX
- The real change came through SBRC (Santa Barbara Research Center) in 1986
  - ✓ 58x62 InSb photodiodes arrays
  - ✓ CMOS SFD (Source Follower per Detector) ROIC with signal processing options (e.g. Fowler sampling)
- For TIR range, Si:Ga / Si:As hybridized arrays were developed, also based on CMOS SFD ROIC

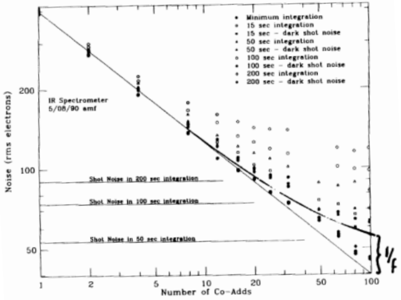
Galactic center @ 2,2 µm acquired with SAT InSb CID at ESO La Silla

(https://mcombes.sciencesconf.org/data/program/05_Hommage_Michel_Combes_cameras_IR.pdf)



Read out noise reduction with SBRC 58x62 pixels

(A. Fowler et al "Noise reduction strategy for hybrid IR focal-plane arrays", Proc. SPIE 1541 (1991))

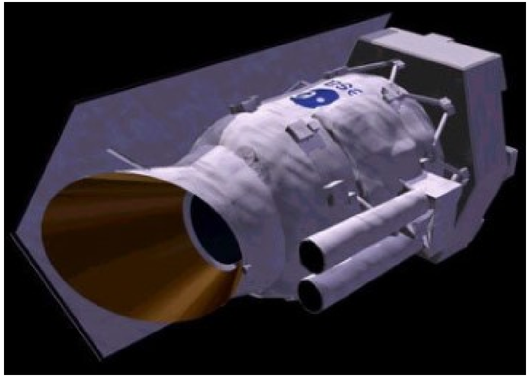


58x62 Si:Ga array caracteristics

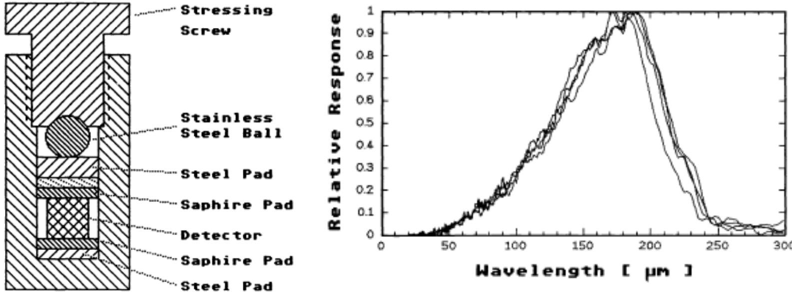
(D.Y. Gezari et al "a 58x62 pixel Si:Ga array camera for 5-14 µm astronomical imaging", Proc. SPIE 0973 (1988))

Manufactruer	Santa Barbara Research Center
Multiplexer	CRC-228 DRO (direct readout)
Detector material	Si:Ga
Spectral response	5 - 17 µm
Format	58 x 62 pixels
Number of pixels	3596
Pixel center spacing	75 microns
Active pixel area	5.1×10^{-5} cm^2
Detector active area	92%
Well size	7×10^5 electrons
Detector capacitance	0.07 pF
ηG_{pc} product	0.3
Read noise	< 200 electrons/read
Dark current	< 10^{-16} amps (<630 e/sec)
Array gain variations	< 10% (r.m.s.)
Active pixels	> 99%
Crosstalk	< 5%

- ESA decision to launch ISO (Infrared Space Observatory) program had an very positive effect on the development of space IR detection chains
  - ✓ Aerospatiale Cannes as Prime Contractor
  - ✓ 0.6 m diameter cooled telescope (< 10 K)
  - ✓ Launched in 1995 (18 months lifetime extended to 28)
  - ✓ Four instruments at about 4 K (2 K for focal planes)
    - ISOCAM (Fr): camera (2.5-17 µm)
    - ISOPHOT (Ge): imaging photopolarimeter (2.5-240 µm)
    - SWS (NL): short wavelength spectrometer (2.5-45 µm)
    - LWS (GB): long wavelength spectrometer (45-197 µm)
  - ✓ Apart from ISOCAM, detectors are non multiplexed doped Si and Ge extrinsic photoconductors
    - mainly developed by Batelle Institute (Frankfurt)
    - For ISOPHOT, 144 detectors read out via a Cryogenic Readout Electronics developed by IMEC (B. Dierickx)



(https://www.esa.int/Science_Exploration/Space_Science/ISO_overview)



Stressed Ge:Ga detector and related spectral response > 200 µm

(J. Wolf, "Low-background far-infrared detectors and arrays, Optical Engineering, 1994, Vol. 33, n°5))

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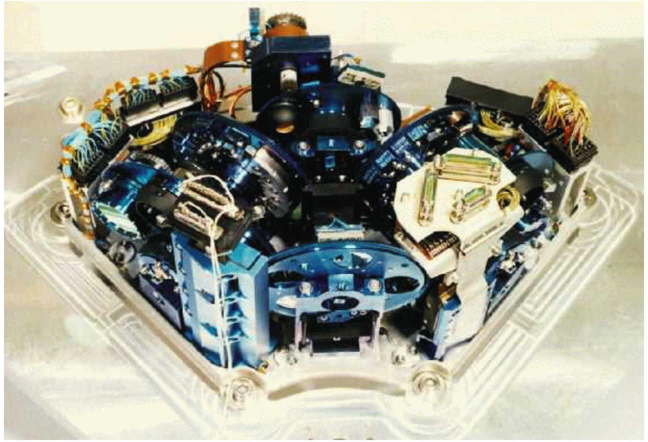
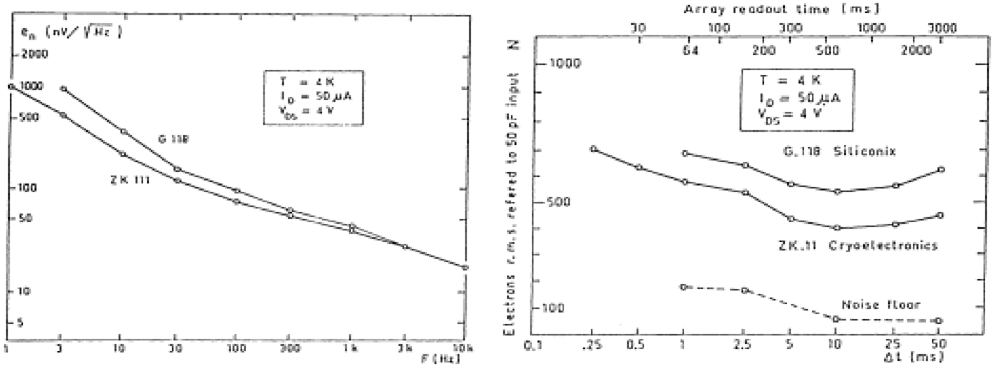
1980-1990: astrophysics missions (3/3)

DEFENCE AND SPACE

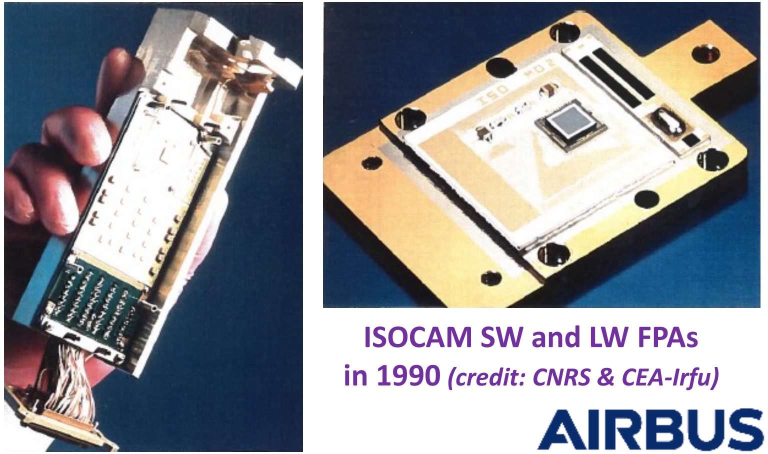
- ISOCAM (CNES funding) was equipped with two FPAs (state of the art in 1985)
  - ✓ A SW FPA based on a 32x32 pixels COTS monolithic CID InSb array from SAT (Safran today) with an integrated cold electronics designed by DESPA/Paris Observatory (reset switch, preamplifier and scanner: < 10 mW)
  - ✓ A LW FPA based on a custom 32x32 pixels (100 µm pitch) Si:Ga array with a CMOS SFD ROIC from CEA/LETI



ISOCAM opto-mechanical test bench (< 3K) developed by Aerospatiale Cannes *(Credit: CNRS)*



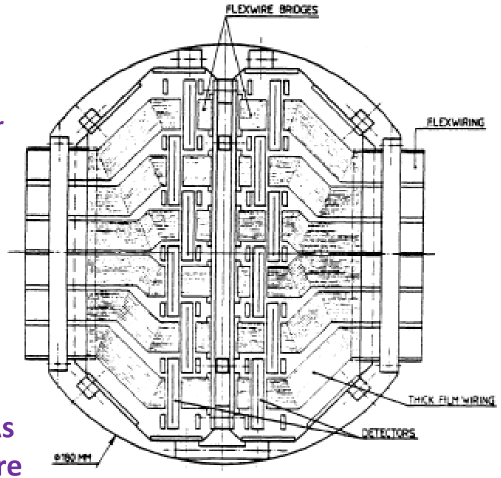
G118 (Siliconix) and ZK111 (Cryoelectronics) MOSFET noise spectral density and voltage follower noise level *(credit: CNRS & CEA-Irfu)*



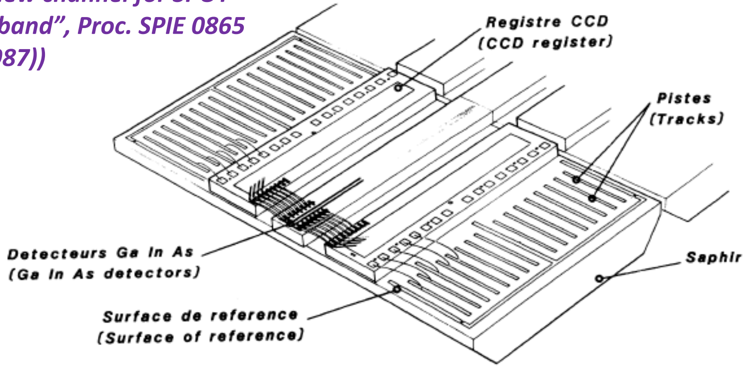
ISOCAM SW and LW FPAs in 1990 *(credit: CNRS & CEA-Irfu)*

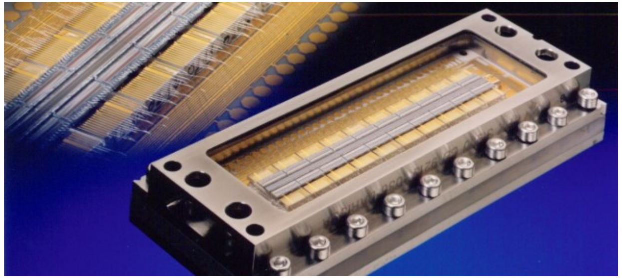
- In the field of Earth imaging, this decade was strongly marked by the development and success of the SPOT mission, and related stakeholders have worked on its extension in the IR (starting with SWIR)
- While the initial plan was to cover full SWIR range, the accommodation breakthrough generated by the use of InGaAs detectors at near ambient T° led to the withdrawal of the 2.2 µm band for SPOT 4 and 5 MIR and vegetation channels

Focal plane design for an IR optical imaging instrument
(A. Peraldi "Large IR detectors arrays for space applications – a user standpoint", Proc. SPIE 0395 (1983))



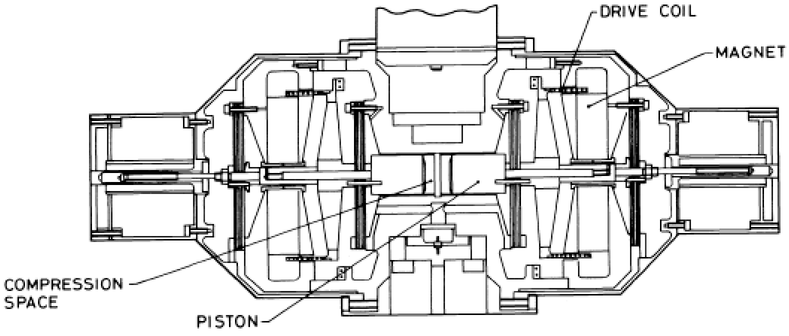
300 pixels module with 26 µm InGaAs photodiode in staggered topology wire bonded with 2 CCD multiplexer
(P. Bodin et al. "A new channel for SPOT satellite in the SWIR band", Proc. SPIE 0865 (1987))





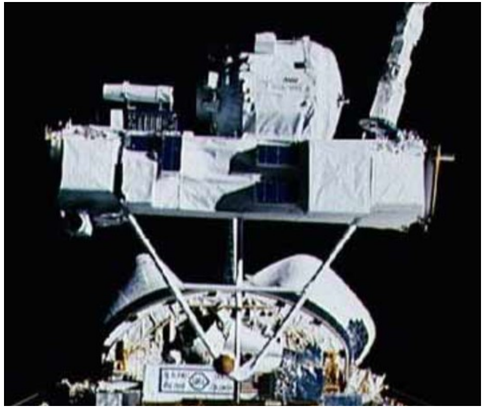
3000 pixels MIR detector developed by Thomson TCS (CNES funding)
(http://spot4.cnes.fr/spot4_fr/hrvir.htm)

- ATSR has been successfully developed by UK team led by RAL for ERS ESA mission (launched in 1991) for Sea Surface T° retrieval
  - ✓ InSb PV (1.6 & 3.7 µm) and MCT PC (11 & 12 µm monodetectors (Mullard Lab)
  - ✓ Stirling cooler to extract 0.5W@80 K (lifetime>3 years)
- The US-German IBSS (Infrared Background Signature Survey) program on board space shuttle (retrievable carrier) has been completed, with IR detectors provided by Aerojet for the spectrometer (Si:As, Si:Bi, Si:In) and by AEG for radiometer (Si:In)
- ESA Earth observation payloads studies at the end of the decade were mainly driven by ENVISAT (formerly POEM), Meteosat 2nd Gen (MSG) and METOP, including several IR instruments (MIPAS, SCIAMACHY, AATSR, SEVIRI, IASI) mainly developed in the 90s



ATSR stirling cycle head-to-head compressor
(J. Delderfield et al. "The Along Track Scanning Radiometer (ATSR) for ERS1", Proc. SPIE 0589 (1986))

IBSS-Shuttle Palette Satellite
(https://space.skyrocket.de/doc_sdat/ibss-spas.htm)



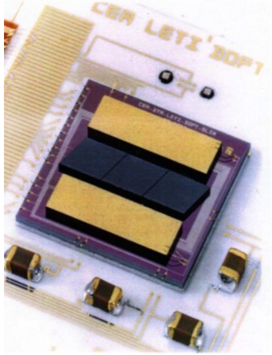
1980-1990: Earth observation (3/3)

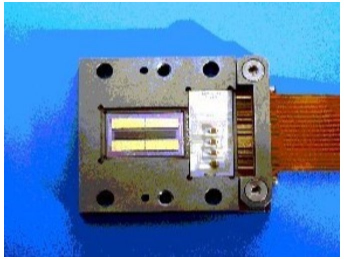
EOS

DEFENCE AND SPACE

- ❑ Two IR instruments have been studied as Envisat candidates and were finally not selected
  - ✓ HRIS hyperspectral instrument (CHIME precursor)
  - ✓ HRTIR thermal imager (Trishna/LSTM precursor)
- ❑ ESA has funded related detectors pre-developments (mainly in the 90s) for both of them (2 phases):
  - ✓ HRIS 2D array, 128x140 pixels (30 µm pitch) MCT 2.5 µm SWIR array with DI CMOS ROIC, built by GMIRL
  - ✓ HRTIR linear array, 512 pixels (30 µm pitch) MCT 12.3 µm VLWIR array, with DI CCD ROIC, built by CEA/LETI
- ❑ Both arrays have been characterized by Matra Marconi Space Toulouse. The results have fed ESA PRISM (1990-2000) and SPECTRA (2000-2010) missions studies

HRIS 128x140 pixels SWIR MCT array built by GMIRL (formerly Mullard Lab and Philips PICS now Leonardo UK) and tested in Matra Marconi Space detection





HRTIR 222 and 512 pixels VLWIR MCT linear array developed by CEA/LETI

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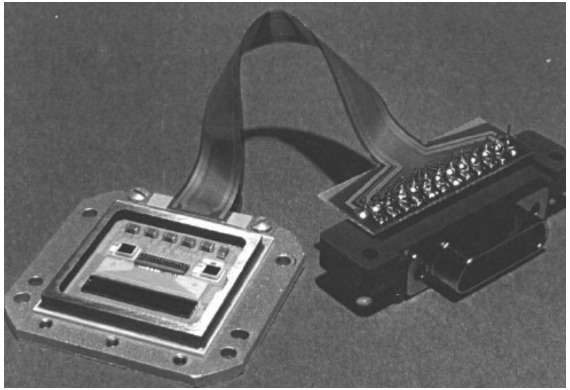
1980-1990: solar system exploration

EOS

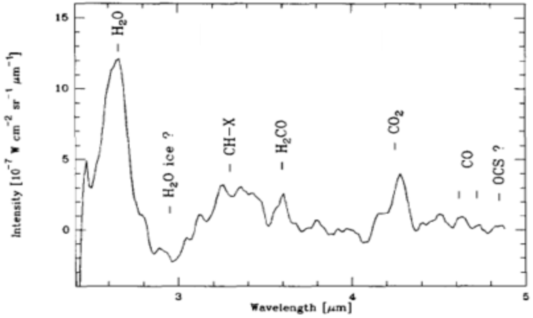
DEFENCE AND SPACE

- Paris Observatory team in charge of ISOCAM SW detector has been responsible for the development of 3 custom multiplexed detectors, using the same ecosystem, including SAT (now Safran) and Thomson TCS, with CNES support
  - ✓ 64 PbS staggered pixels (100 µm pitch) linear array with on chip impedance adaptor & lock-in amplifier (256 Hz), cooled down at 200 K for the ISM Imaging Spectrometer on board Phobos missions
  - ✓ 2x128 InSb pixels (90x120 µm pitch) bilinear array (CCD MUX from SPOT MIR detector) operated at 77 K for the OMEGA imaging spectrometer on board Mars 1996
  - ✓ 2x150 InGaAs pixels (38x200 µm pitch) bilinear array (CCD MUX as well) operated at 200 K for the DISR (Descent Imager-Spectral Radiometer) instrument on board Huygens probe (Titan study)
- Previously, the same team developed IR detection chain for IKS spectrometer on board Vega spacecrafts for Halley comet RV, based on InSb & MCT monodetectors (cooled down by JT cooler)



OMEGA InSb 2x128 pixels bilinear arrays with CCD multiplexer

(D. Tiphène et al. "French SWIR technology used for astronomy", Proc. SPIE 4130 (2000))



Halley comet spectrum observed by IKS

(Credit: CNRS)

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1990-2000: the boring decade (in Europe)

1990-2000 (2010 or even 2020): astrophysics missions (1/2)

EOS

- ❑ The absence of a European IR space program after ISO and the lack of related market for military applications put an end to the development of large format detectors suitable for low flux (including TIR arrays)
- ❑ Progress in terms of format & readout noise were considerable in US
  - ✓ Rockwell Scientific Center (which will become Teledyne TIS) MCT FPAs
    - NICMOS 256x256 pixels array for HST (1990)
    - Hawaii 1k x 1k array (1994)
  - ✓ SBRC (which will become Raytheon IR Center of Excellence) InSb and Si:As BIB FPAs
    - 256x256 pixels InSb array (1992)
    - Aladdin 1k x 1k array (1994)
    - 256x256 pixels Si:As BIB array
- ❑ While SBRC/Raytheon provided most of the detectors for Spitzer mission (formerly SIRTF, launched in 2003) , Rockwell/Teledyne finally won the competition for JWST MWIR arrays (Raytheon still producing the Si:As BIB array for MIRI)

Spitzer IR observatory launched in 2003, notably using 256x256 InSb and Si:As BIB arrays (IRAC) as well as 128x128 Si:As and Si:Sb arrays (IRS) *(https://en.wikipedia.org/wiki/Spitzer_Space_Telescope)*

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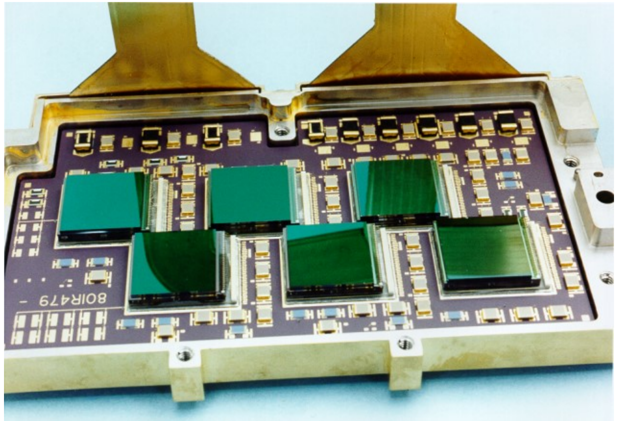
- The extensive and fast development of large format / low noise arrays (from SWIR to TIR) has been driven by the need to optimize the US "*vital strategic defense systems*": *cf "Status of focal plane arrays (FPAs) for space-based application" from D.T. Wilhelm et al. (Proc. SPIE 2217 (1994))* (working with Air Force Research Lab, formerly Phillips Lab.) discussing in detail the following topics
  - ✓ The specificities of space IR detectors wrt military and interceptors needs
  - ✓ the system benefits of having access to large format sensors
  - ✓ the supply chain optimization in order producing several tens such IR detectors flight models
  - ✓ the need to access to a relevant CMOS foundry and the related radiation hardness issues
  - ✓ the potential interest of new technologies such as T2SL

Parameter	Surveillance			Astronomy		Units
	Minimum	Nominal	Maximum	Nominal	Maximum	
Format		1024 × 1024		1024 × 1024		Pixels
Temperature		[illegible]				K
Cutoff Wavelength	3.15	3.15	3.20	2.5		µm
Cell Pitch		18.5		18.5		µm
Mean R_oA Product	$>10^6$	$7x10^6$		$>10^{12}$		Ω-cm²
Detector Breakdown Voltage	1.0		>1.5	>0.5	>1.0	V
Noise Spectral Density @ 1 Hz	$<10^{-18}$	$<10^{-17}$	$2x10^{-15}$	$<10^{-22}$		$A/Hz^{1/2}$
Quantum Efficiency	60	74	85	>70	85	%
Nominal Operating Bias	0.02	0.1	0.8	0.5	>1	V

Parameter	Astronomical		Surveillance		Units
	Nominal	Maximum	Nominal	Maximum	
Format	1024 × 1024		1024 × 1024		Pixels
Cell Pitch	18.5		18.5		µm
ROIC Package (Optional)	84 pin		84 Pin		LLCC
Custom ASIC Technology	0.8 µm		0.8 µm		CMOS
Input Circuit	Source Follower		Capacitive TIA		

(L. Kozlowski et al. "Low-noise, low-power HgCdTe/Al_2O_3 1024x1024 FPAs", Proc. SPIE 0589 (1996))



US Early Warning SBIRS focal plane downloaded in free access on internet in 2003 (no more available now…)

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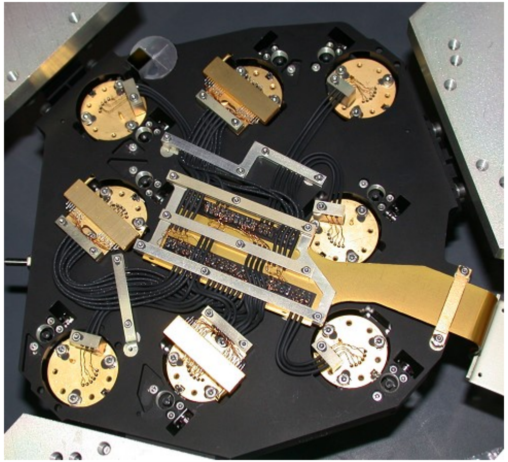
- For most of IR payloads to be successfully developed during this decade (AATSR-MIPAS/Envisat launched in 2002, SEVIRI/MSG launched in 2002, IASI/METOP launched in 2006), the trade-off between use of 1st Gen and 2nd Gen detectors turned in favor of 1st Gen
  - ✓ GMIRL (now Leonardo UK) as supplier for AATSR, MIPAS and SEVIRI
  - ✓ SAGEM (now Safran) as supplier for IASI
- The only instrument for which 2nd Gen detectors have been selected is SCIAMACHY / Envisat (the only one without thermal channel)
  - ✓ Regular and extended 1024 pixels (13x500 µm pitch) InGaAs linear arrays from Epitaxx, operated at 150 K
- In the scope of the French military program Helios, Sofradir has been involved as the supplier of the IR detector and its MCT technology has been space qualified

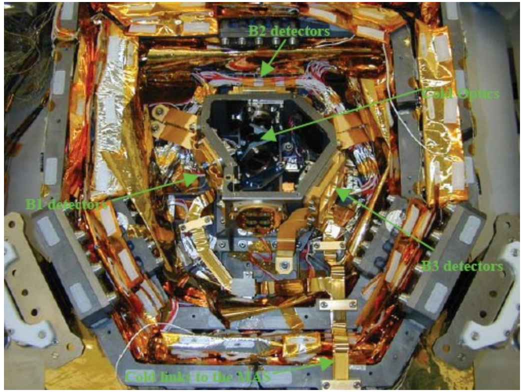
(P. Chorier, P. Tribolet "High-performance HgCdTe SWIR detectors for hyperspectral instruments", Proc. SPIE 4540 (2001))

Seviri radiometer focal plane with 8 IR spectral channels, using Leonardo UK (formerly GMIRL) 1st Gen PV and PC SWIR to VLWIR MCT detection modules (launched in 2002)

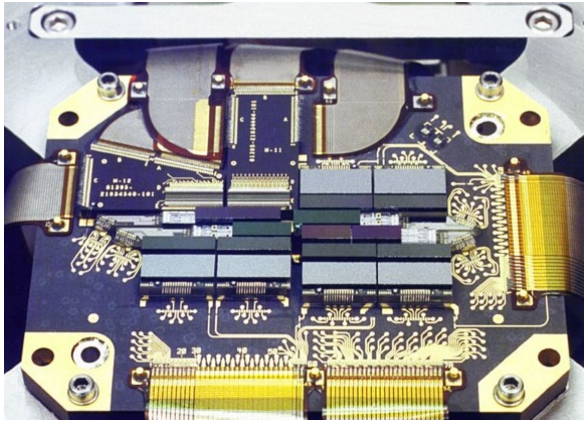


IASI IRFTS Cold Box with 3 IR spectral channels, using Sagem (formerly SAT) 1st Gen PV and PC MWIR to VLWIR MCT/InSb detection modules (launched in 2006)

(P. Nicol et al. "The IASI detection chain", ICSO Conference, 2004)

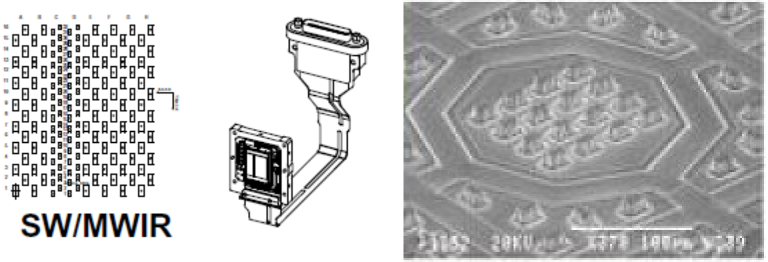


- Regarding US IR Earth observation programs, two of them defined the detection state of the art at that time
  - ✓ AIRS (Atmospheric Infra Red Sounder –dispersive spectrometer-, launched in 2002) focal plane operated at 58 K, with 10 PV and 2 PC modules, covering a 53 x 66 mm² optical footprint, from 3.7 to 15.4 µm (2378 spectral channels), direct & indirect hybridization on custom CMOS ROICs and with 526 lines to operate the focal plane
  - ✓ VIIRS (Visible Infrared Imaging Radiometer Suite- close to DLR / Eumetsat METimage instrument- launched in 2011), with SWIR to VLWIR PV p/n MCT photodiodes coupled to microlenses and operated at 80 K



AIRS focal plane built by LM IR Imaging Systems

(J.H.Rutter et al. "Performances of the PV/PC HgCdTe focal plane/ dewar assembly- for the AIRS", Proc. SPIE Vol. 3437, 1998)



VIIRS IR FPAs and pixel detail

(C.F. Schueler et al. "NPOESS VIIRS: next generation polar-orbiting atmospheric imager", Proc. SPIE 4891 (2003))

- To our knowledge, only one custom detector dedicated to solar system exploration has been built in Europe during this period, developed for CIRS (Composite Infra Red Spectrometer) on board Cassini (launched in 1997) by CEA/SAp & CEA/LETI
  - ✓ PV MCT linear array (10 pixels with 200 µm pitch) covering 7 to 9.3 µm range, operated at 80 K, connected to 10 TIA amplifiers
- Due to the lack of suitable European products, Paris observatory group has to procured a MWIR CTIA IRCMOS from Raytheon for VIRTIS-H part of Rosetta infrared imaging spectrometer

	Requirements	FM#1	FM#2
Spectral Range (η>50%)	7-9.1 µm min.	6-9.4 µm	6-9.4 µm
Peak responsivity pos.	8.2±.5 µm	8.85±0.07µm	8.81±0.06µm
Cutoff pos.	> 9.2 µm	9.41±0.01µm	9.39±0.02µm
uniformity of responsivity	20 %	5 %	5 %
Quantum Efficiency (η)	>50 %	65 %	65 %
Peak Responsivity	> 3.3 A/W	4.3 A/W	4.3 A/W

Electrooptic properties of CIRS Focal Plane#4 FM arrays *(L. Rodriguez et al. "Photovoltaic HgCdTe linear arrays for the Composite InfraRed Spectrometer of the Cassini mission", Proc. SPIE 2268, 1994)*

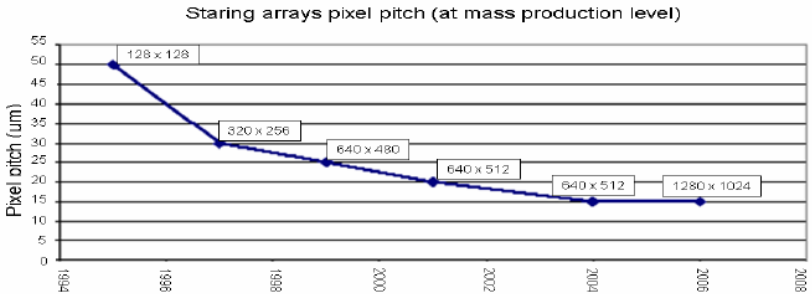
VIRTIS-H detector, based on 436x270 MWIR MCT photodiodes (38 µm pitch) hybridized on top a CTIA ROIC *(P. Drossart et al. "VIRTIS-H: a high spectral resolution channel for the Rosetta infrared imaging spectrometer", Proc. SPIE 4131, 2000)*

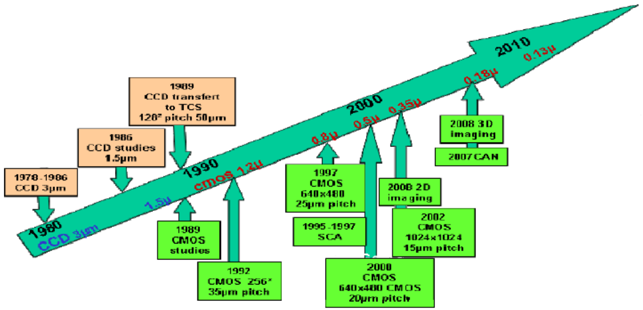
1990-2000: technologies advances

- Despite the absence of ambitious space technology programs during this decade, the tactical/military market pushed European IR detectors manufacturers to make significant progress in order to stay competitive, notably for export market
  - ✓ Highly focused on MWIR and LWIR bands
  - ✓ The usual “smaller pixels / larger format” race
  - ✓ How to decrease the manufacturing cost?
- One of the steps that had a strong impact on space programs has been the discontinuation of CCD technology in favor of CMOS for the design of ROICs

(C. Arthurs, I. Baker et al. “CMOS / CdHgTe hybrid technology for long-linear arrays with time delay and integration and element deselection”, Proc. SPIE 2744, 1996)

(M. Audier, P. Tribolet “Design of focal plane functions”, Proc. SPIE 2552, 1995)





Sofradir reduction of pixel pitch for tactical detectors and transfer from CCD to CMOS *(P. Bensusan et al. et al. “50 years of successful MCT research and production in FPA”, Proc. SPIE 7298, 2009)*

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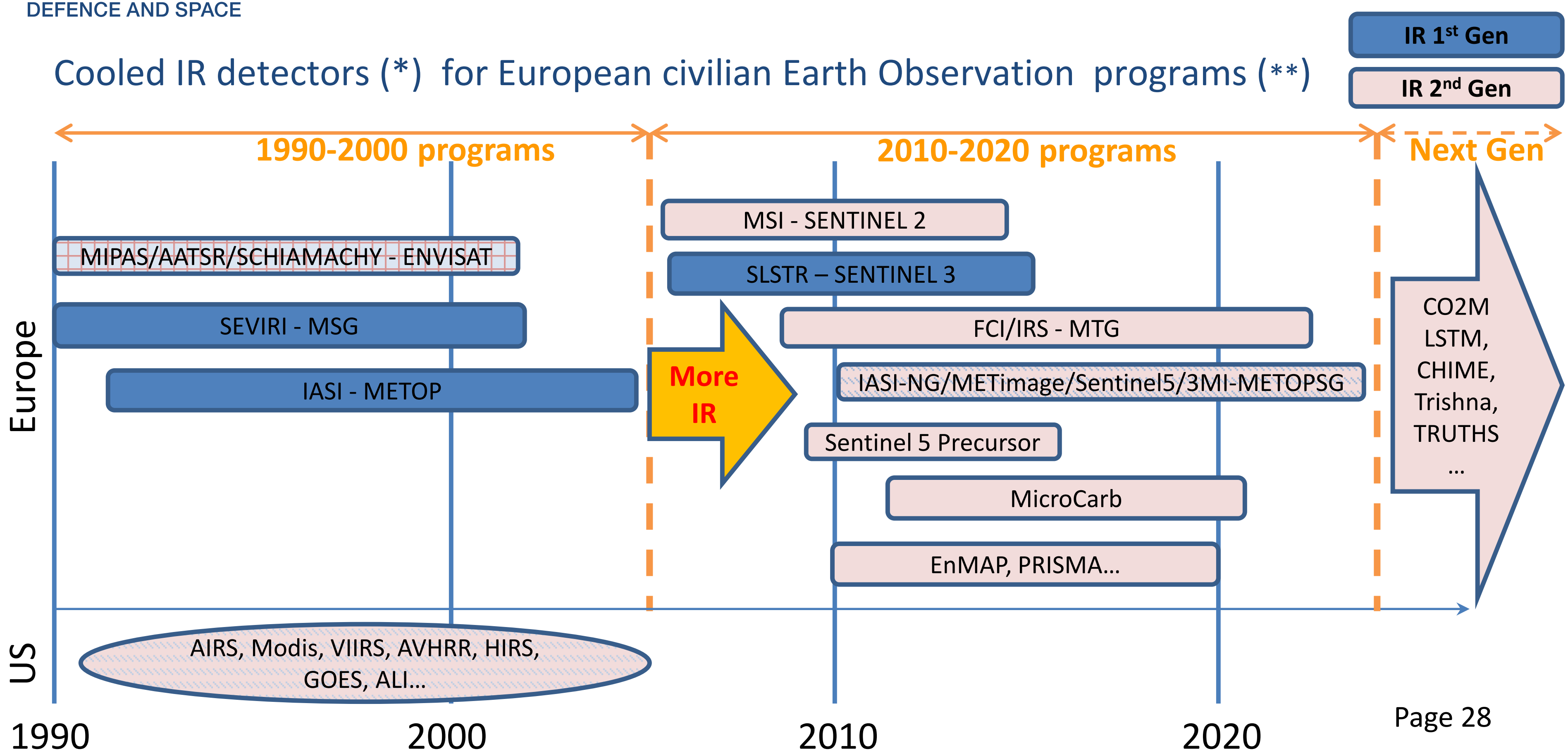
2000-2010: ramping up

2000-2010: ramping-up (1/3)

- Space ramp-up is asking for investments in specific subjects not covered by military / tactical roadmaps, mainly:
  - ✓ SWIR and VLWIR photodetectors
  - ✓ Large format / low flux FPAs (e.g. ROIC design and hybridization process)
  - ✓ FPAs interfaces mastering (e.g. package, interconnection, optical coatings…)
  - ✓ Space environment evaluation (including effects of radiation)
  - ✓ Characterization means well matching electro-optics requirements (e.g. MTF, spectral response, radiometric sources…)

- The start of a new cycle of Earth observation programs (including Copernicus) from 2005 greatly contributed to the ramp-up, in addition to national programs / initiatives or to manufacturers internal investments, leading to the transition from 1st Gen to 2nd Gen IR detectors for most of space instruments

Cooled IR detectors (*) for European civilian Earth Observation programs (**)



(*) regular InGaAs ranked as “uncooled” (**) different story for uncooled IR and for Science programs

- A (non-exhaustive) list of IR detectors activities who contributed to this transition during this decade is provided below:
  - ✓ ESA funding of SWIR MCT 2D arrays (CTIA ROIC) breadboarding for hyperspectral instruments, which leads to the development of Lynred successful Saturn product
  - ✓ CNES MCT VLWIR R&T activities entrusted to CEA/LETI, increasing confidence in the capability to build about 1 cm^2 VLWIR MCT arrays with fair operability
  - ✓ AIM pre-development to serve DLR EnMAP SWIR program, up to the delivery of space qualified IDDCA
  - ✓ ESA Sentinel 2 pre-development, initializing the first European space program requiring several 10s of SWIR FPA FM
  - ✓ ESA MTG FCI and IRS VLWIR pre-development (2 instruments x 2 primes x 3 manufacturers =12 configurations)

Conclusion?

Conclusion?

EOS

- ❑ No conclusion, the European IR detection story continues with this exciting workshop …

- ❑ Few facts and observations known to all

  - ✓ Development of space IR detectors has been and is still mainly programs driven. Time and money is better used by anticipating the future needs in order avoiding maturity issues

  - ✓ Space IR detectors feature very specific needs, not covered by any other market. Giving time without any investment does not bring a solution

  - ✓ While robust suppliers are definitively required to produce custom IR detectors flight models for operational missions, more flexible supply chains (e.g. availability of generic ROICs) would allow faster proof of concepts and even serve space demonstrations

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