Freeform optics design and manufacturing
Microcarb

Roland GEYL
VP Business Development
Safran Reosc

Club Calcul Optique
13 Déc 2017

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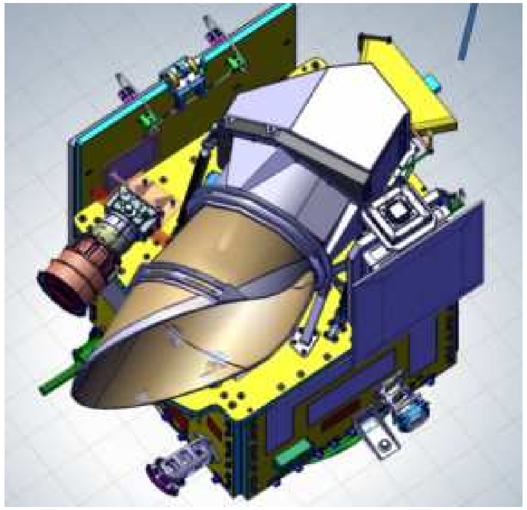
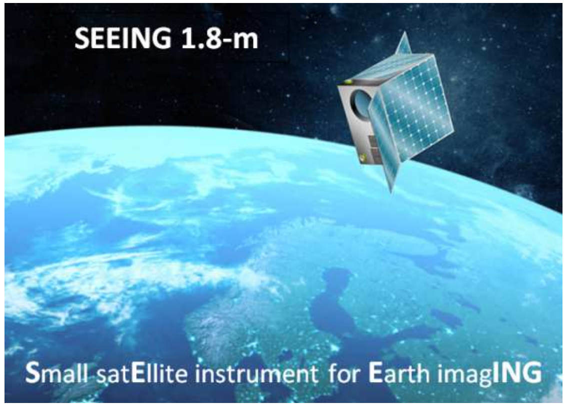
Freeform is a reality



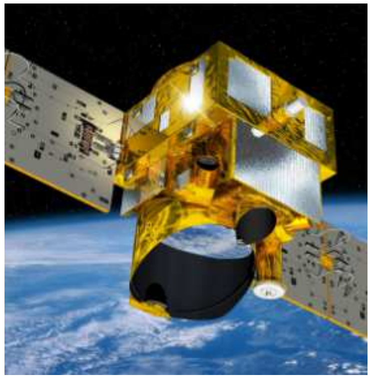
MicroCarb instrument
On Myriades platform

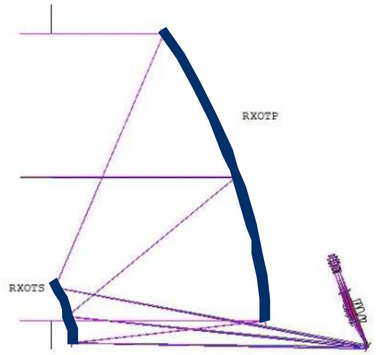
High instrument compactness thanks to freeform optics technology

ELT M1 segments mass-production with freeform technology



1.8-m GSD from 600 km orbit
20x20x25 cm³ payload volume





MERLIN : Receiver fast & large M1

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Outline

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Benefits of freeform

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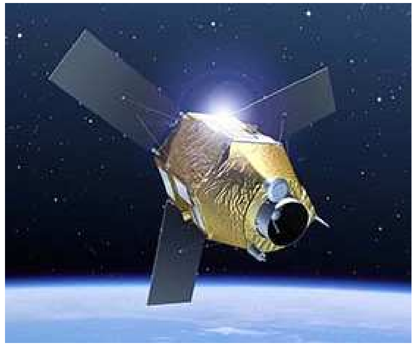
Pleiades telescope freeform version
From smart to agressive freeforms



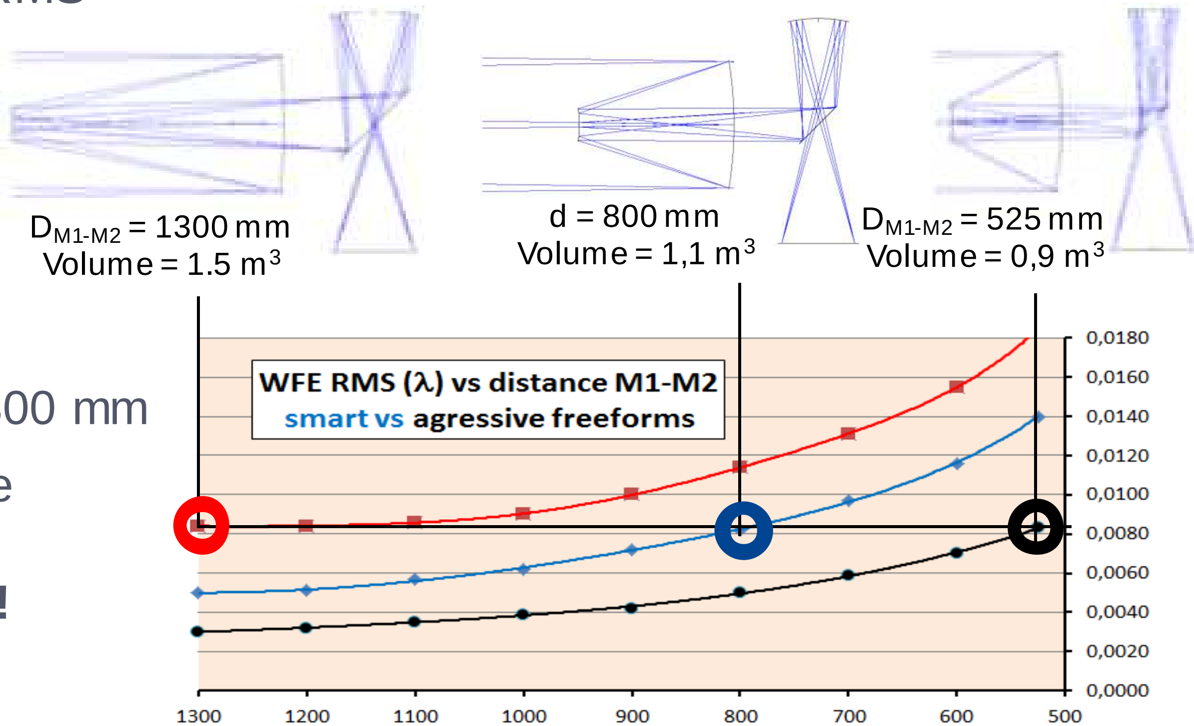
Study case : Pleiades' Korsch type TMA

Aperture - F/#	650 mm - F/20
Linear FoV	1.6° (Y) / 0.1° offset (X)
Dist M1-M2	$D_{M1\text{-}M2}$ = 1300 mm
WFE (worst)	0,0083 λ = λ /120 RMS
Volume	≈1.5 m^3

ESA Workshop on innovative optics
Nov 2015

Introduction of freeform

First smart, then aggressive



Benefits

Increased performance at $D_{M1\text{-}M2}$ = 1300 mm

Reduction of $D_{M1\text{-}M2}$ becomes possible

Gain in volume, mass & inertia !

Nota : also gain in distortion

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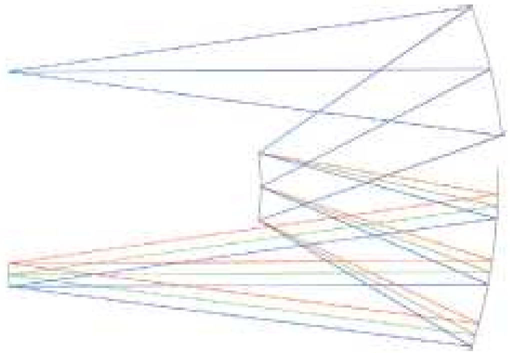
Freeforms also benefits to spectrographs
1: Increasing performances

Recently UoR's scientists published on the subject

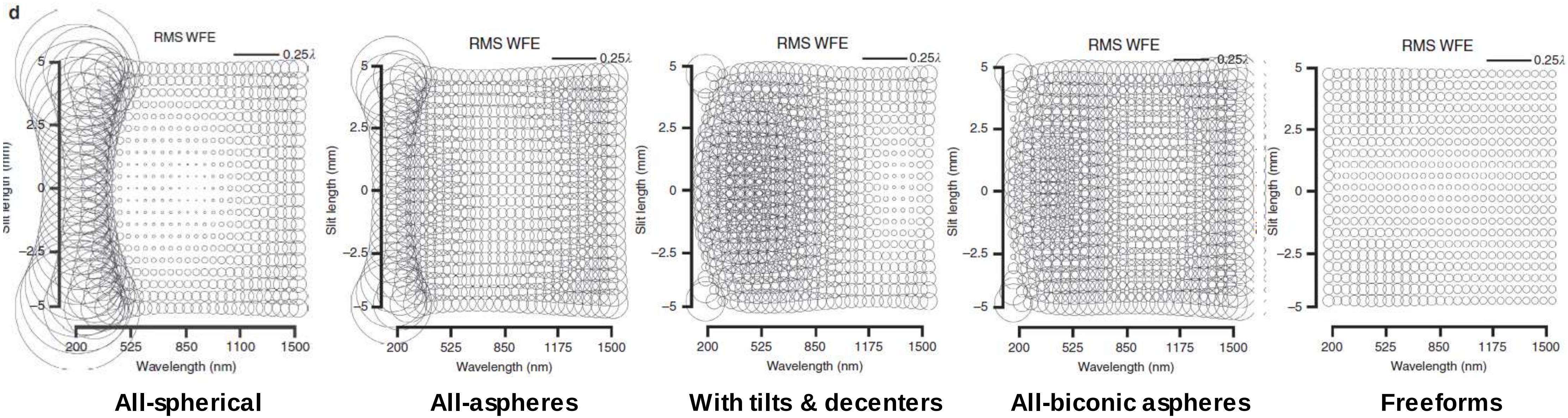
Imaging spectrometer are inherently non-symmetric due to the dispersive element that seperate the wavelengths

Frreform may therefore benefit



Offner-Chrisp spectrometer

Case of an F/3.8 Offner-Chrisp concept



Light; Science & Applications (2017, 6: Freeform spectrometer enabling increased compactness_J. Rolland_K. Thompson

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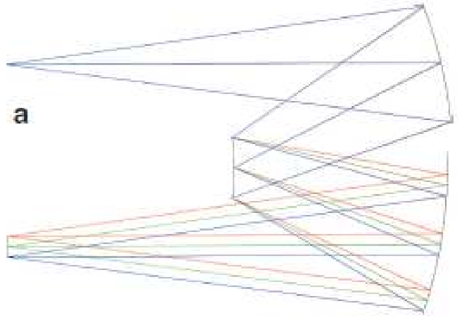
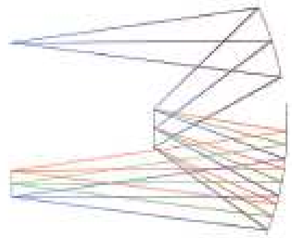
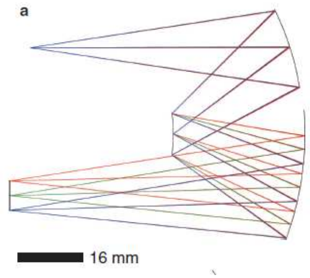
Freeforms also benefit to spectrographs
2: Enabling more compact configurations



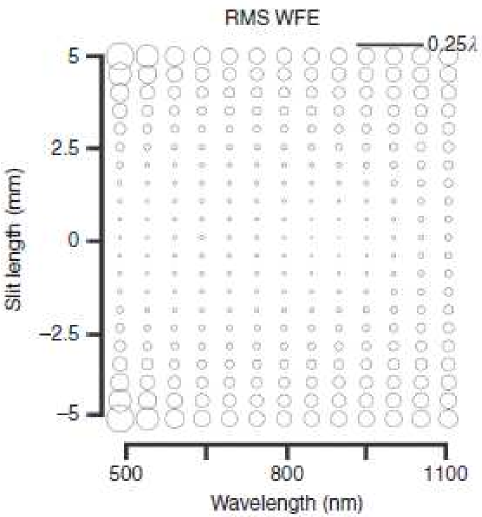


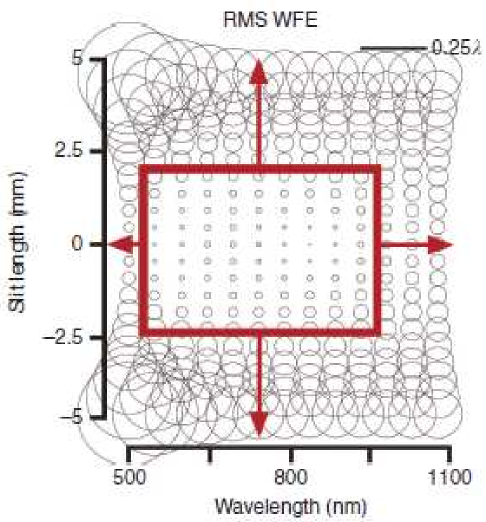


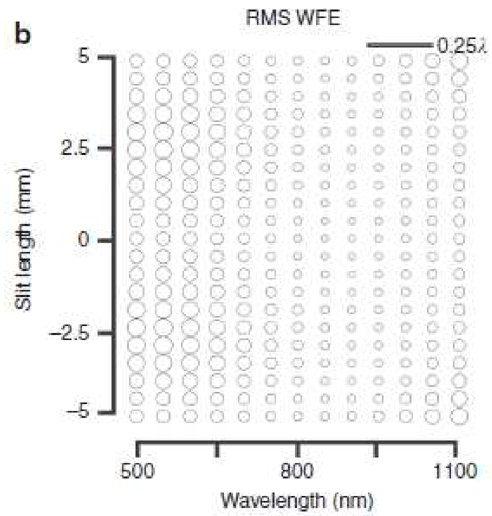
Nominal size / All-spherical

More compact / All-spherical

More compact / All Freeforms







Light; Science & Applications (2017à 6, Freeform spectrometer enabling increased compactness_J. Rolland_K. Thompson

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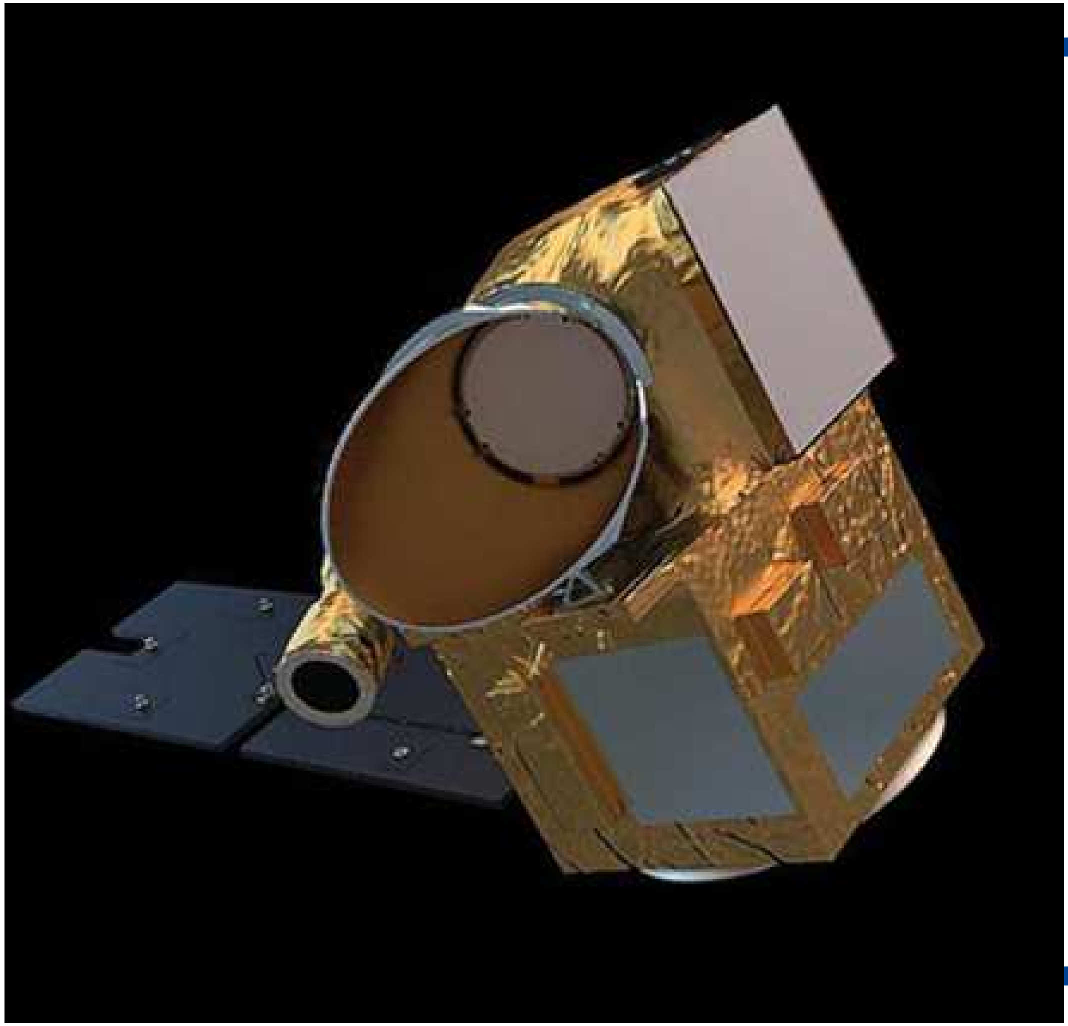

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MicroCarb

The CO_2 cartographer

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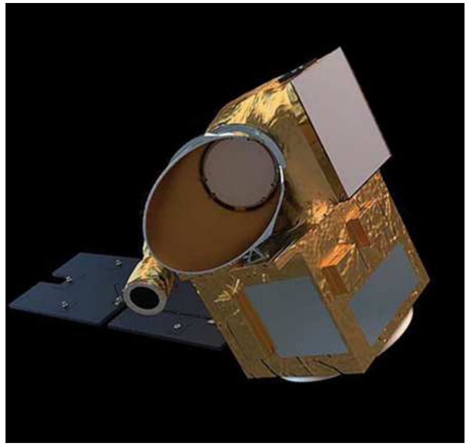
MicroCarb

Program decided in dec 2015 (COP 21)

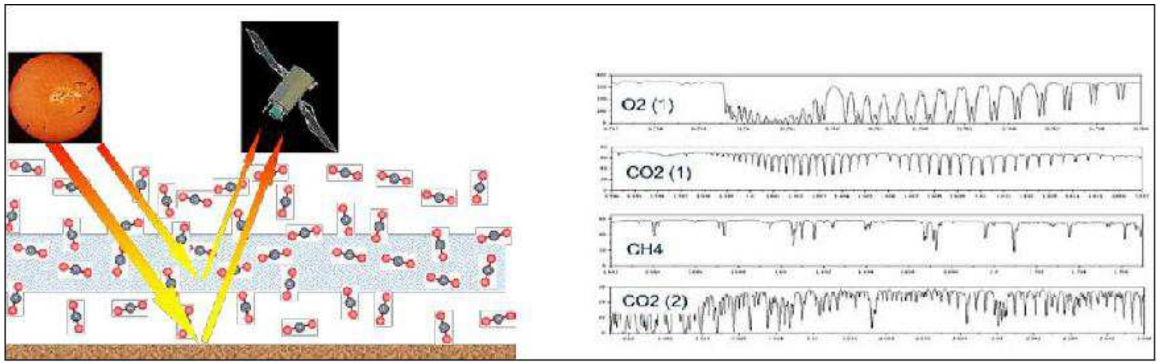
Jan 2016 — Phase B funded
Mar 2017 — Decision of phase C-D funding
Apr 2017 — Partnership France-UK
May 2017 — Kickoff Phase C-D-E
Budget — 75 M€
Launch scheduled for 2020 (orbit 650 km)
Lifetime — 5 years



Mission

Mapping sources and sinks of CO_2, the most important greenhouse gas, on a global scale.
First European program on the subject.
Follows GOSAT (JP) & OCO-2 (US)

High accuracy — ≈ 1 ppm
Bias — < 0,1 ppm
Basic Pixel — 4,5 x 9 km²
Revisit — 1 week



Measurement of absorbed & reflected solar flux in several highly resolved Vis & NIR spectral bands

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MicroCarb: At the peak and cost-effective

Used for PICARD, SSOT, SPIRALE, …

Installed on a Myriade platform

- Microsat platform developed by Cnes
- Classe 100 - 150 kg
- Modular & low cost access to space

Microcarb : compact but high performance

Spacecraft	Mass	Measured greenhouse effect gas	Targeted accuracy on CO_2
GOSAT (launched in 20129	1750 kg	CO_2 + others	4 ppm
OCO-2 (launched in 2014)	450 kg	CO_2	1 ppm
TanSat (launch in Dec. 2016)	500 kg	CO_2	4 ppm
MicroCarb (launch in 2020)	160 kg	CO_2	1 ppm

Thanks to its low global cost, MicroCarb aims to be precursor of a microsat constellation for accurate and continuous carbon monitoring.

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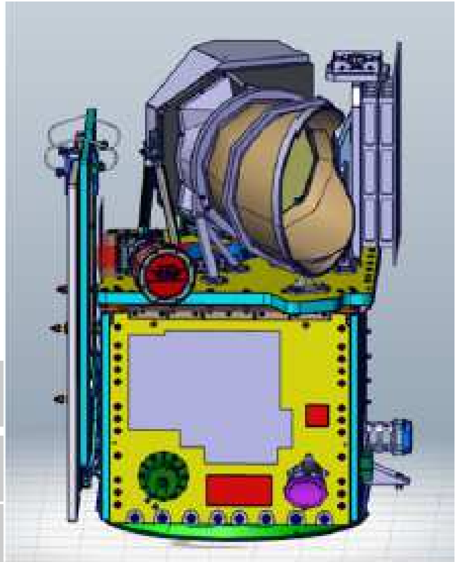
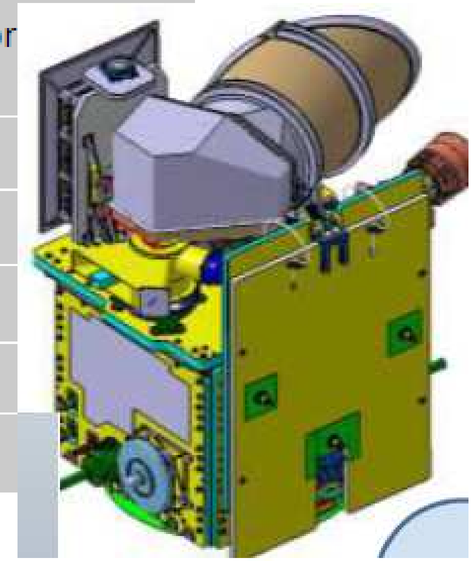
The MicroCarb instrument

CNES selected Airbus for the development of the passive spectrometer instrument



Type	Unique spectrometer with a Grating element
Mass	< 70 kg
Power	< 55 W
Detector	NGP Sofradir (HgCdTe) 1024 x 1024
Imager	Integrated. Cloud detection. 0.625 µm 120 m SSD. FOV=2 x Spectrometer FOV
Data processing	No processing on board : all data are downloaded with lossless compr Data rate: 300 G bits/day
Cooling	Passive : detector (150K), spectrometer : 220 K
Calibration	Calibration devices on board (diffuser, calibration lamps)
Polarization	Scrambler
Pointing:	Scan mechanism 1 axis ±200 km
Structure mirrors	Made of SiC. Free form mirrors



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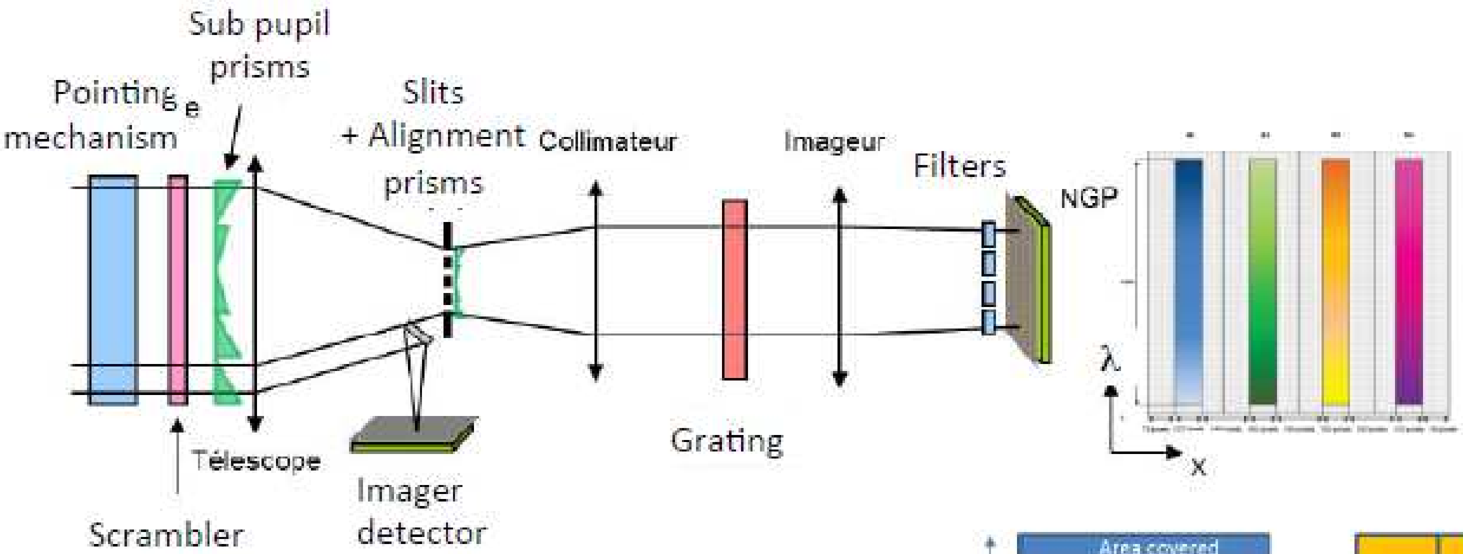
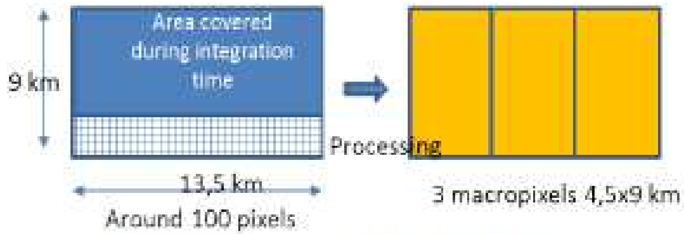
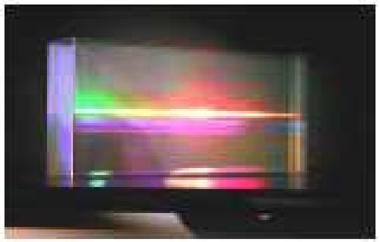
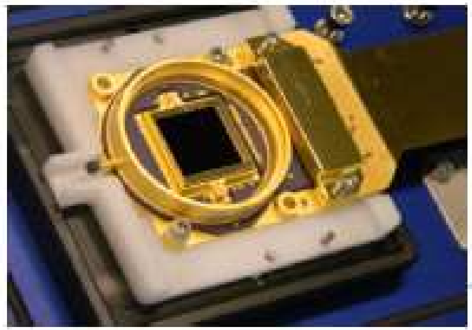
Microcarb: An innovative instrument concept





- Innovative concept permitting the acquisition of the 4 spectral bands with a single telescope, spectrometer and detector (NGP Sofradir)
- Enables to implement a higher number of bands (5- 6)





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Microcarb: Optical principe

Three Mirror Anastigmat

Telescope Principle

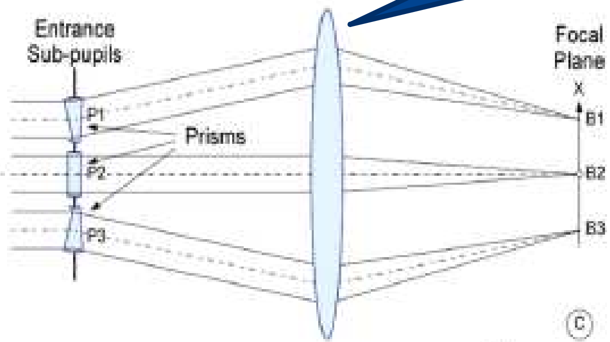
- Split-pupil telescope: Alignment of the spectrometer slits on the same Earth point by 4 Pupil Separation Prisms (PSP), placed at the telescope entrance pupil

Spectrometer principle

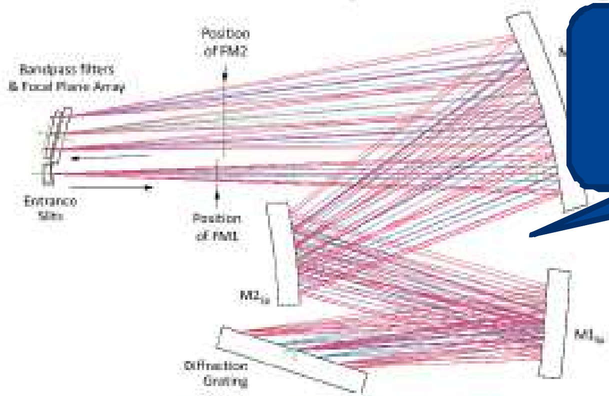
- Spectral bands multiplexing by the grating,
- Echelle grating of ~60 grooves/mm in near-Littrow configuration
- Double-pass TMA compact spectrometer with 4 slits

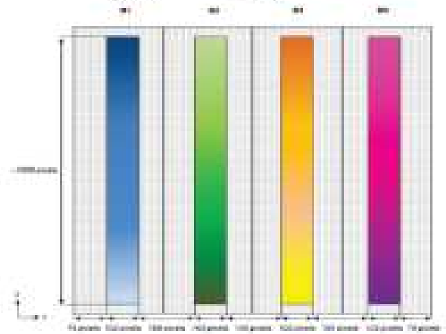
Configuration at detector level

- One spectrum: about 1000 pixels in λ direction
- ACT field: ~100 pixels in the x direction
- Band separation: ~150 pixels in the x direction



Three Mirror Anastigmat





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Spectral characteristics

Spectral characteristics

Performances N1	B1 (O_2)	B4 (O_2)	B2(CO_2)	B3(CO_2)
Central wavelength (nm)	763.5	1273.4	1607.9	2037.1
Bandwidth (nm)	10.5	17.6	22.1	28,1
Spectral Resolution ($\lambda/\Delta\lambda$)	25 500	25 900	25 800	25 900
Signal to Noise ratio @ Lmean (per channel)	285	378	344	177

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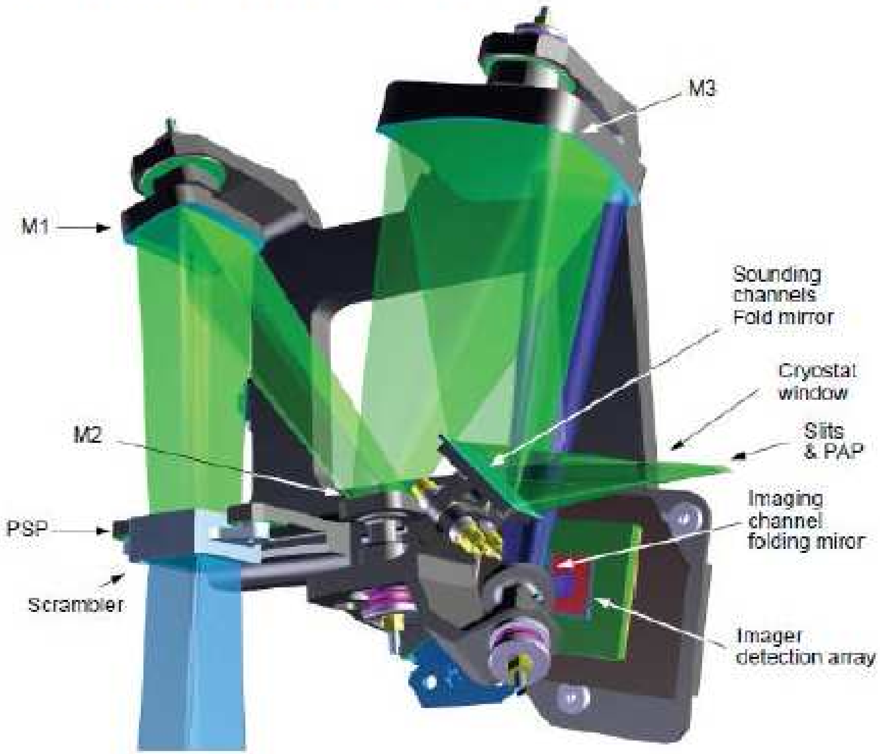
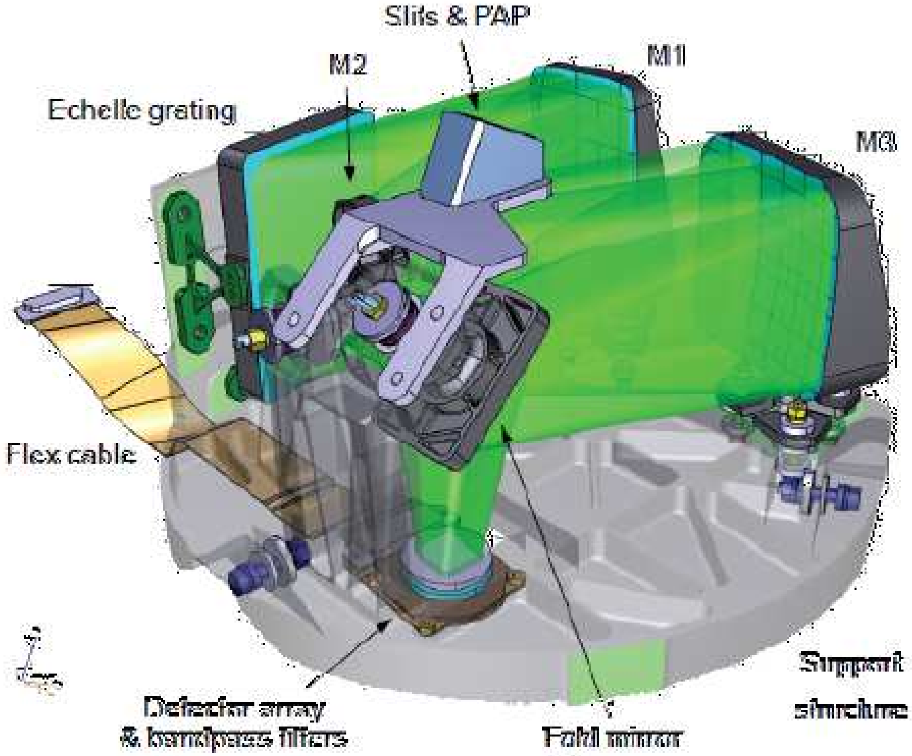
Optical configuration (1)

Telescope assembly: Polarization scrambler, pupils mask, Pupil Separation Prisms, TMA telescope, separation between the sounding and imager channels, imager detector, cryostat window
Telescope optics at 20°C

Spectrometer assembly: Slits, Pupil Alignment Prisms, TMA spectrometer operating in near-Littrow configuration, echelle grating in the pupil plane, filters and detector
Spectrometer optics at 220 K, array at 150 K





ICSO 2016 – The MicroCarb instrument
19 Octobre 2016
8
AIRBUS DEFENCE & SPACE

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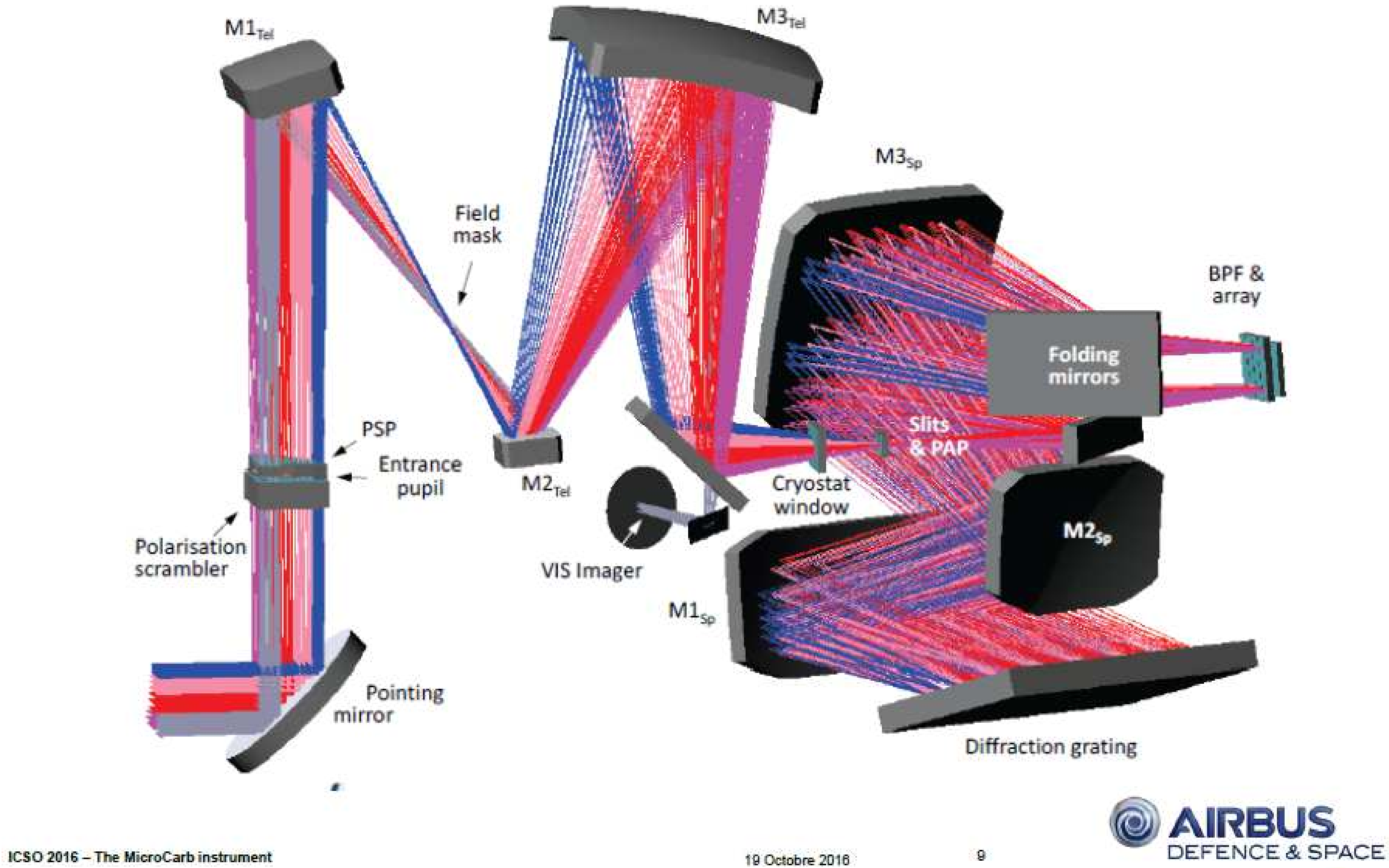
Optical configuration (2)



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Joint design work with Airbus

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Work share

Airbus

- Instrument optical design
- Mecano-thermal architecture
- Spec evolution during Phase B
- Final decision

Safran Reosc

- Optical manufacturing
- Optical metrology
- Risk assessment & mitigation
- Commitment on specifications

Agreement to be found on

- Mirror type of definition (Zernike vs Polynomials)
- Feasability vs asphere departure
- Commitment on the WFE spec (15 nm RMS WFE)
- Commitment on schedule
- Edge effects and edge margin needed
  - => Compactness

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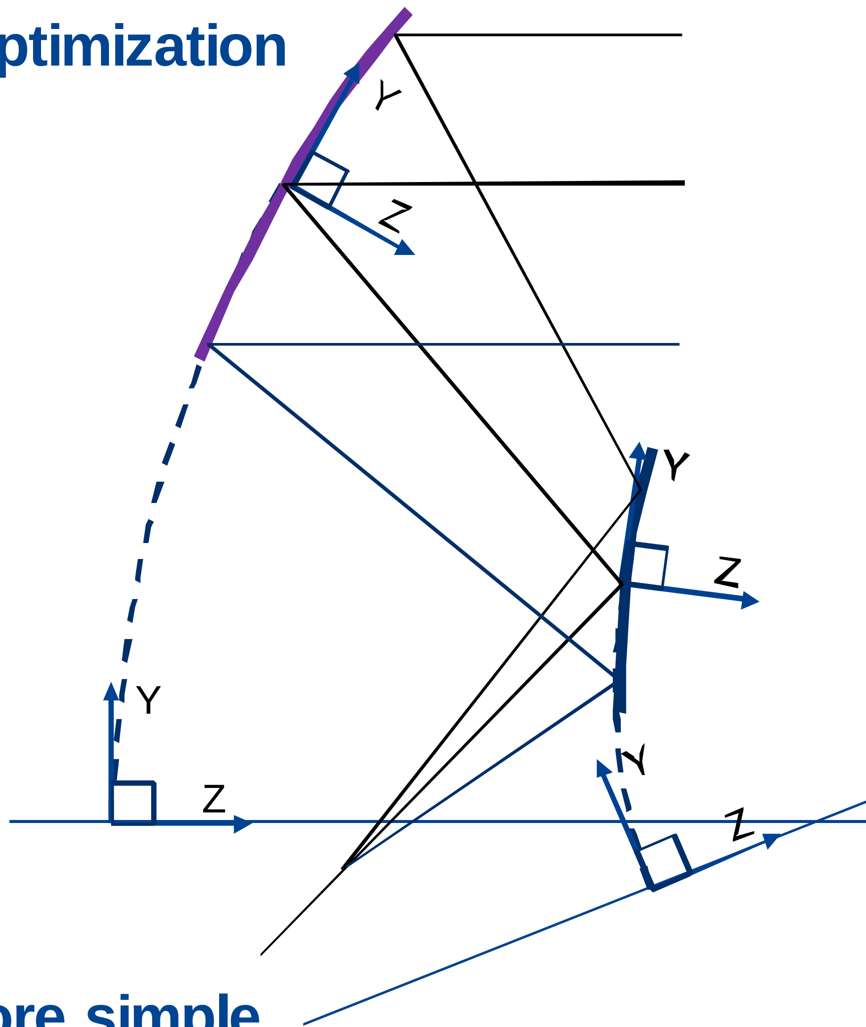
Optical elements referential

Building the reference system for an easier optimization

Option 1 : Classical referential

Parent conic axis of first mirror
Tilts & decenters of next mirrors
Asph + freeform terms



Option 2 : Local referential on each mirror

Incidence vs « main chief ray » of each mirror
Radius at center of usefull area
Freeform terms

Other options also possible

All give same results

=> Option 2 selected because it is more simple

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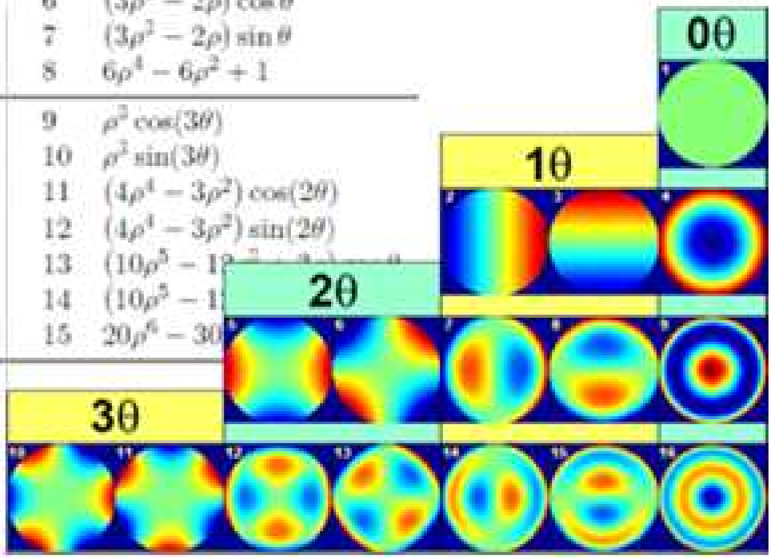
Zernike vs Polynomials

Zernike polynomials

Preferred by Safran Reosc

Wyant		HOS			
n	m	n	m	n°	Polynôme
0	0	0	0	0	1
1	1	1	1	1	$\rho\cos\theta$
				2	$\rho\sin\theta$
	0	2	0	3	$2\rho^2-1$
2	2	2	2	4	$\rho^2\cos(2\theta)$
				5	$\rho^2\sin(2\theta)$
	1	3	1	6	$(3\rho^3-2\rho)\cos\theta$
				7	$(3\rho^3-2\rho)\sin\theta$
	0	4	0	8	$6\rho^4-6\rho^2+1$
3	3	3	3	9	$\rho^3\cos(3\theta)$
				10	$\rho^3\sin(3\theta)$
	2	4	2	11	$(4\rho^4-3\rho^2)\cos(2\theta)$
				12	$(4\rho^4-3\rho^2)\sin(2\theta)$
	1	5	1	13	$(10\rho^5-1$
				14	$(10\rho^5-1$
	0	6	0	15	$20\rho^6-30$



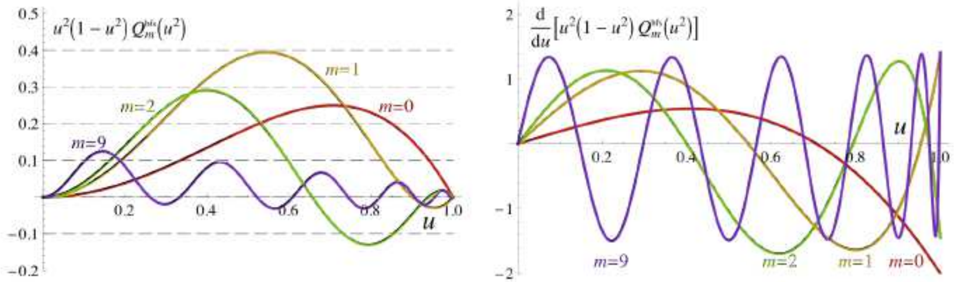
Taylor expansion polynomials

Initially preferred by Airbus

$$Z(x,y)=\sum_{n,m} X^nY^m$$

Forbes polynomials

$$z(\rho)=\frac{c_{\text{bfs}}\,\rho^2}{1+\sqrt{1-c_{\text{bfs}}^2\,\rho^2}}+\frac{s\,(1-s)}{\sqrt{1-c_{\text{bfs}}^2\,\rho_{\max}^2\,s}}\sum_{m=0}^{M} a_m\,Q_m^{\text{bfs}}(s)$$



And many others, …

Chebychev, Legendre, NURBS, …

Reosc's polishing & testing NC chain is based on Zernike.

Similar performance obtained in all cases

=> Zernike representation selected

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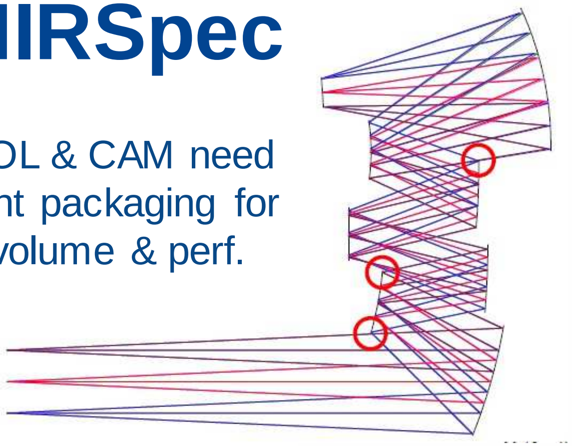
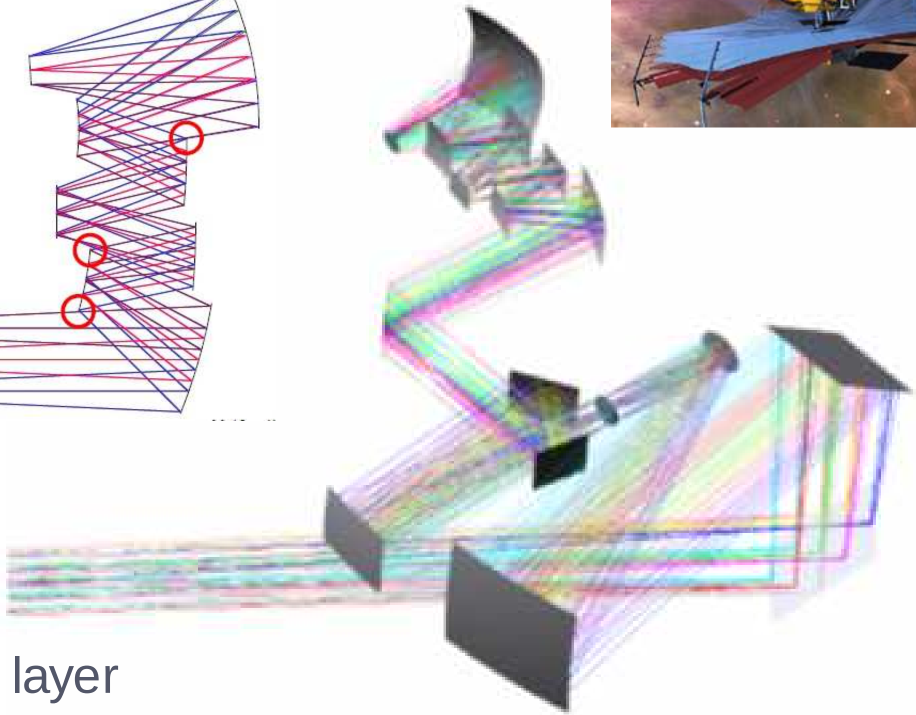
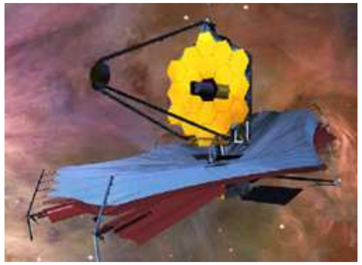
Aspheric departure: NIRSpec



COL & CAM need tight packaging for volume & perf.



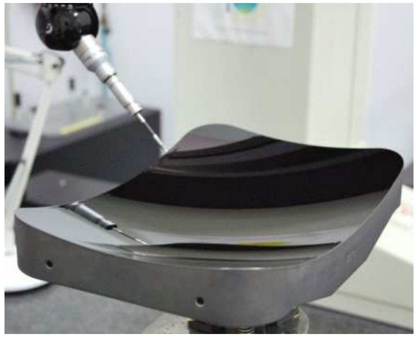


Three successive TMA

1. Relay the JWST image
2. Collimator
3. Camera

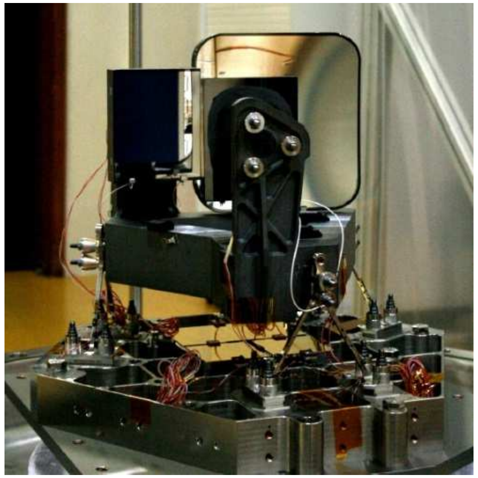
Average characteristics

Dimension	10x10 to 30x30 cm
Asphere sag	10 to 400 µm
Substrate	RB SiC+ CVD SiC polishing layer
WFE quality	< 130 nm RMS for all train
Edge margin	≈ 1 mm



CAM mirrors

Integrated CAM TMA



Integrated COL TMA

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Aspheric departure

Various designs submitted by Airbus during Phase B

Mirror size in the range of 100x100 mm only

Some cases highly aspheric :

- Aspheric departure up to 1,5 mm
- Slopes up to 30 mrd
- Zernike up to Z36

Only M3-Tel is similar to NIRSpec

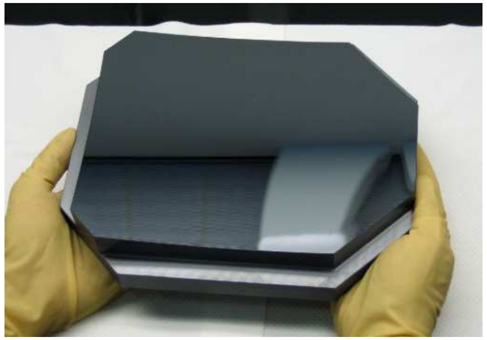
All others mirrors are significantly more aspheric

- **Asph departure = 450, 600, 1300 µm PTV**

Polishing requirements : 15 nm RMS WFE

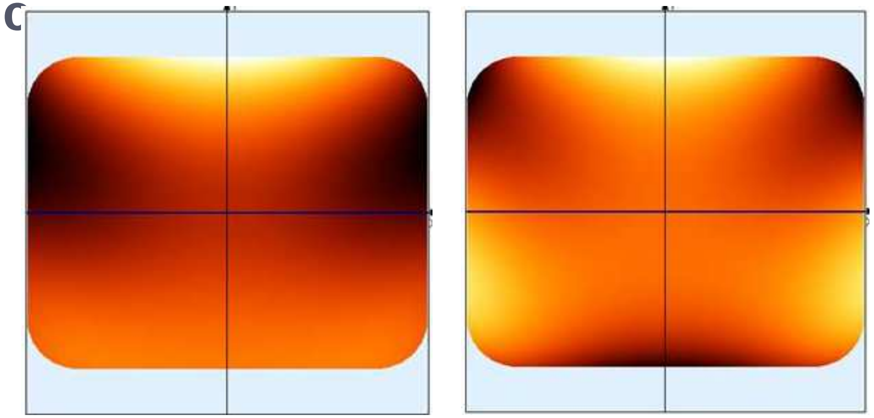
Discussion and exchanges

Agreement on most reasonnable values



EUV ellipsoid mirror

Size	230x155 mm
Margin	18 mm
Asph	2.8 mm PTV
Slope	70 mrad PTV
WFE	25 nm RMS



Ex: M2 Spectro TMS

Clear aperture	100 x 75 mm
Asph wrt best sphere	590 µm
Asph wrt best cylinder	320 µm

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Edge margin

1 mm margin only achieved on NIRSpec but :

More tooling, work and schedule involved

Risks on polishing layer (CVD or R-SiC)

Airbus edge margin wish : < 5 mm

Safran Reosc initial wish : > 15 mm

Final edge value agreed : 12 mm for freeforms

(less for plano and spherical)

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PREPARATION FOR MANUFACTURING

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CVD SiC or R-SiC ?

Due to short schedule constraints Airbus has selected R-SiC as baseline for MicroCarb

CVD SiC

MERSEN-Boostec has a 1.3-m CVD furnace
Operation remains long and risky

Schedule

- Preparation before CVD
- CVD deposition & inspections
- Profile restoration after CVD
- 10X more difficult polishing than glass

Risks

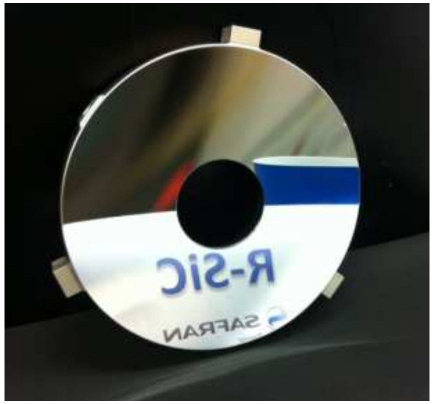
Deposition process
Chips along edges
Passing through the CVD during polishing

Safran Reosc R-SiC: Faster – Safer - Larger

Up to 1.6-m and more
Fast polishing like glass - Low roughness – Low BRDF
Easy removal & redeposition in case of passing trhough
Self funded intense R&T since several years

- Demonstrator piece made for ADS (SPOT-6 mirror)

ESA Qualification on C-SiC and RB-SiC
Capability up to 1600 mm in our large coater
Large size demonstration under OTOS – TANGO program



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SAFRAN

Robotic polishing for small optics

EUCLID M1

In the past years, focus was given on large optics.

ELT M1 segments & large space optics

But small size freeform optics demand is growing

New space optic: MicroCarb, IASI NG, M2 mirrors of larger projects, etc…
Astro instrumentation
Petawatt laser optics

Safran Reosc has developped its small size robotic polishing solution

Capacity	0-500 mm
Technology	Full freeform
	Glassy / SiC
Interface	Same for all robots

3 units recently implemented

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IBF finishing

IBF Technology mastered since 2 decades

USION-130 equipment
Themis solar telescope de 1-m primary (1998)

Technology scaled up for GTC 1.8-m segments

USION-250 equipment Installed in 2001
Used since for many large astro & space optics
3 **USION-150** set-up for ELT M1 segments

Technology scaled down for litho optics

USION-30 Installed in 2005
For 35 – 350 mm aperture optics
Few mm only small footprint
Extreme accuracy down to 0.3 nm RMS

Tooling preparation for handling MicroCarb optics within our Usion 30 equipment .

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Coating on the IR detector

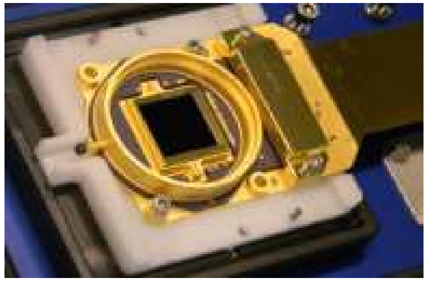


Image Sofradir

MicroCarb focal plane is also innovative

New Generation Panchromatic (NGP) detector from Sofradir

HgCdTe array hybridized on a silicon CMOS ROIC

Baseline of Sentinel-5 1024 x 1024 pixels

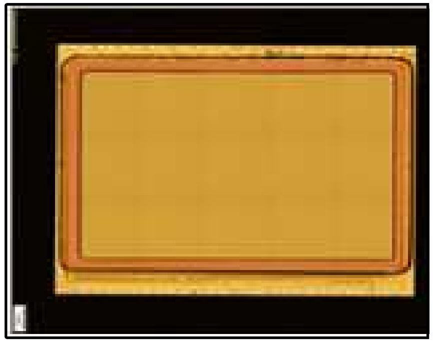
Optimized for detection from vis to 2.5-µm

Coating on sensor strongly enhances throughput

About 40% light lost by reflection on the detector surface

An AR coating on the detector strongly reduces these losses:

- Losses ≈ 15% only with monolayer
- Losses < 5% with multilayer



AR coated sensor

Various developments conducted on the subject

First AR coating on detector in 2013

Proto 350-2500 nm AR coating in 2015

Sentinel-5 space qualification in 2016

MicroCarb AR coating development in progress

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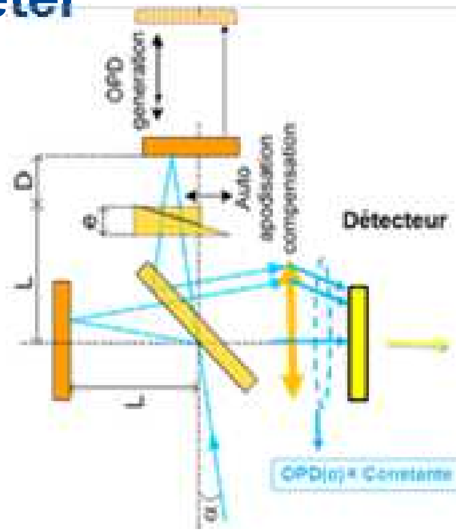
IASI NG Freeform Mirrors

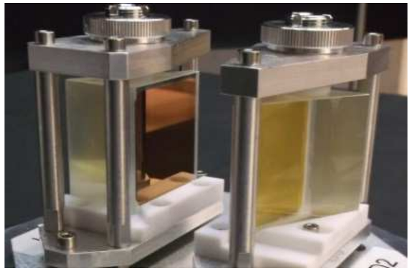
New Generation of the IR Atmospheric Sounding Interferometer

- Onboard METOP SG
- T°, Humidity, 25 atmospheric components
- Better (x2) SNR and spectral resolution with MERTZ FTI design
- Spectral range: 3,6 to 15,5 µm



Mertz prisms made of KBr

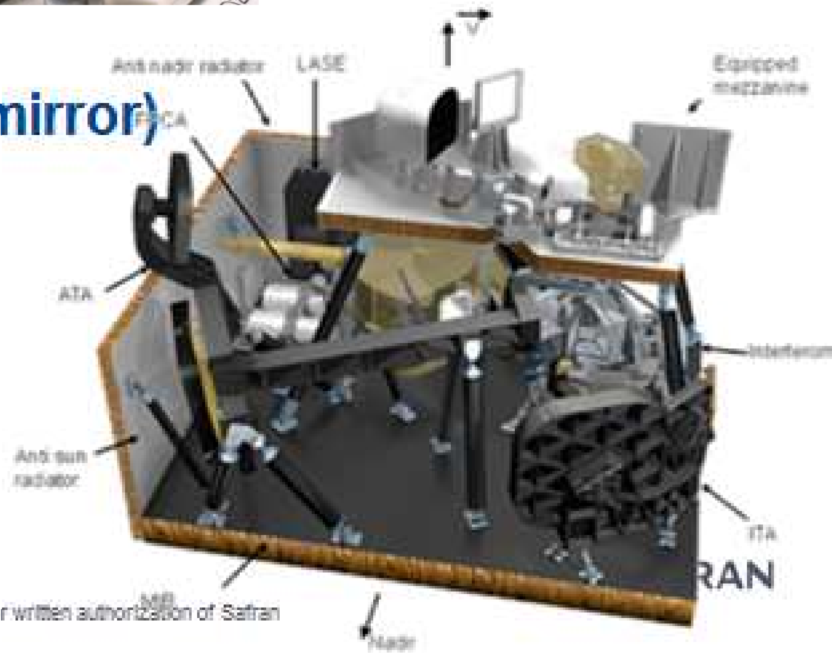
- High transmission over wide spectral range
- But hygroscopic
- Prisms polished by Safran Reosc



Afocal telescope & Imager Telescope (+ Scan mirror)

- Feed the interferometer system
- Imager companion of the interferometer

Use of freeform surfaces
Easyer IR specification
Polished by Safran Reosc



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Conclusion

Freeform optics offer new key system performance factors

- Performance, Volume, Mass, … Cost
- Example shown with compact Pleiades or sprecto-imager design (K. Thompson)

Manufacturability and testability are the key enablers

- Freeform capability available at Safran Reosc since more than 2 decades
- Need tight interactions between designer & manufacturer

MicroCarb is EU first ‘serious’ instrument fully based on freeform

- A high return / low cost mission thanks to the use of freeforms
- Safran Reosc selected by Airbus
- Efficient concurrent engineering done for manufacturability
- Refined technology applied: small robots, small IBF, metrology SiC polishing layer, …
- AR coating on detector
- First SiC surbstrate arriving early Jan 2018

Safran Reosc is entering full speed in the era of freeform optics

Thanks to Cnes, Airbus … and Safran Reosc team

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