Calibration of pixel’s location of a CMOS detector based on Young’s fringes for space-based high accuracy astrometry

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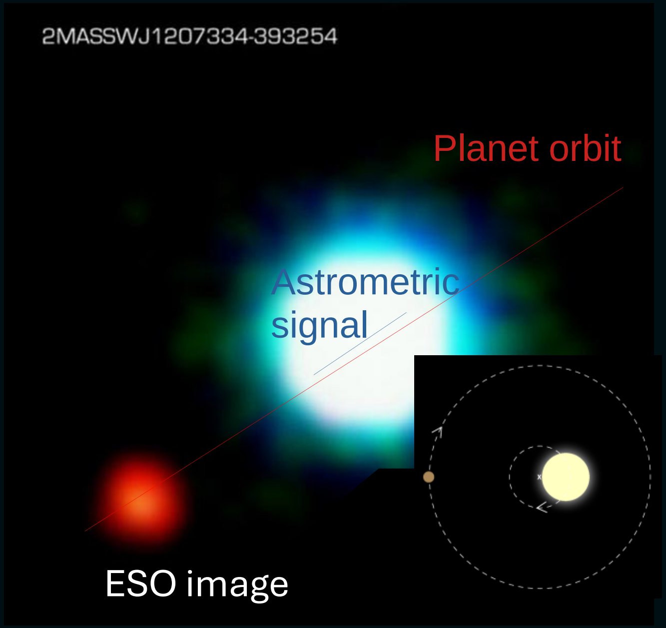
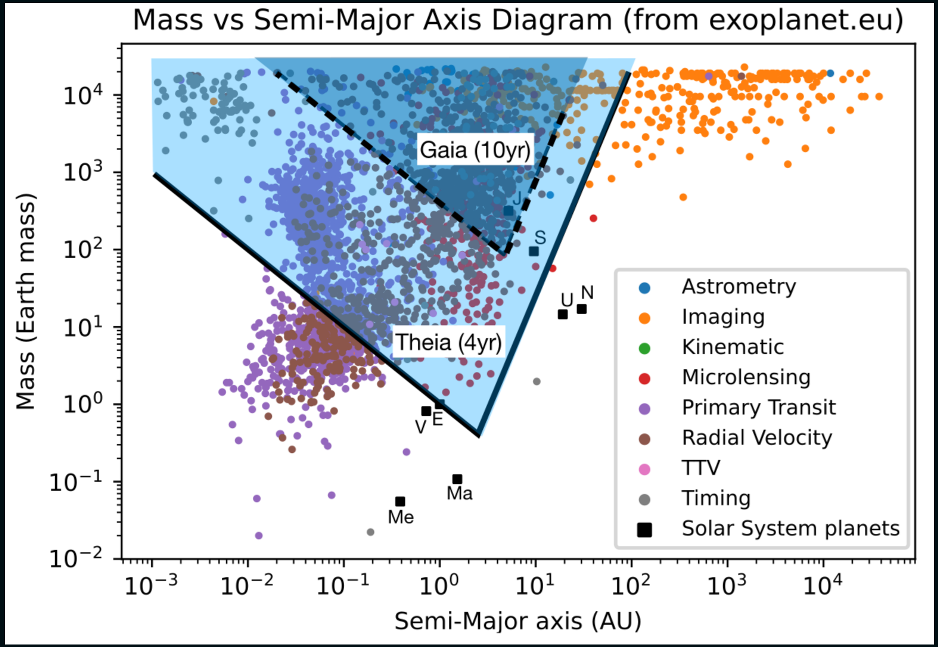
Scientific goal and instrument calibration requirements

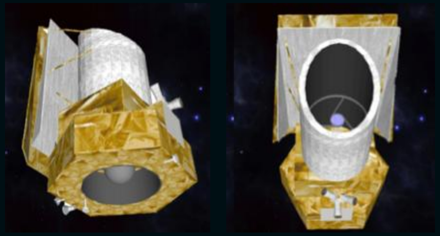


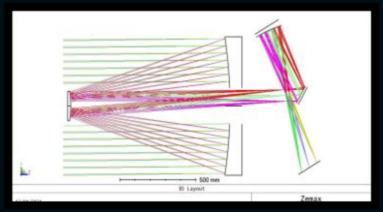


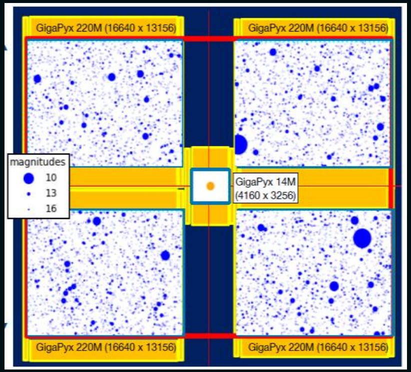
- Relative astrometry to detect Earth-like exoplanets up to 10 parsec away
- 0.3µas accuracy of the star centroïd
- Centroïd precision on detector = 5e-5pix (HWO) – 5e-6pix (Theia) !

$$A = 3\,\mu\text{as} \times \frac{M_{\text{Planet}}}{M_{\oplus}} \times \left(\frac{M_{\text{Star}}}{M_{\odot}}\right)^{-1} \times \frac{a}{1\ \text{AU}} \times \left(\frac{D}{1\ \text{pc}}\right)^{-1}$$

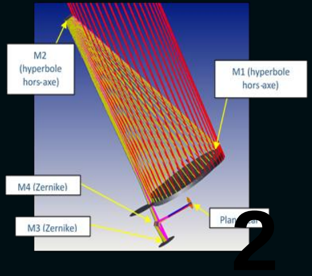
Goal missions – final focal plan

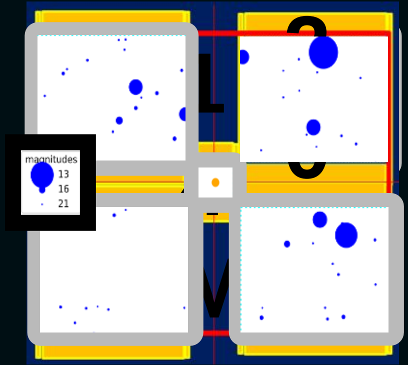






Theia		HWO
ESA	**Agency**	NASA
Medium (M8)	**Mission type**	Habitable World Observatory
0.8 m	**Telescope Diameter**	7 m
~2040	**Launch date**	~2040
L2 lissajous	**Orbit**	L2 lissajous
[450 nm - 900 nm]	**Wavelength domain**	[450 nm - 900 nm]
160 mas	**Diffraction limit**	14 mas
30x30 $arcmin^2$	**Field of View**	4x3 $arcmin^2$
22.500 x 22.500 px^2	**Focal plane size**	34.300 x 25.700 px^2
~500 MP	**#pixels**	~900 MP



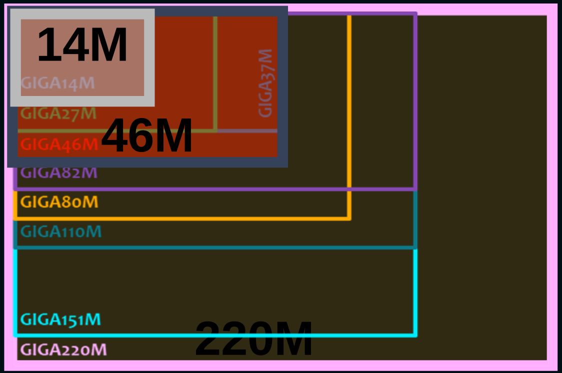


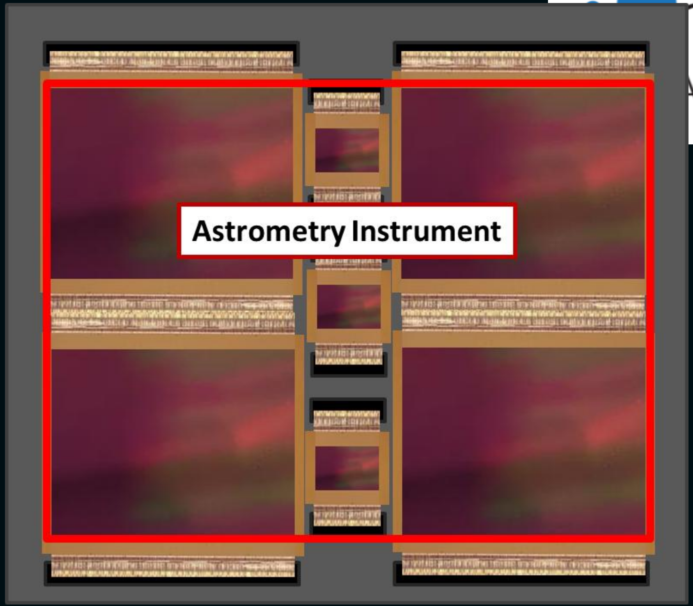
Selected detector

Baseline detector solution:

4 Pyxalis CMOS GigaPyx 220 MP
4.4µm
3 GigaPyx 14 MP at the center
~1 Gigapixel focal plane

Pyxalis GigaPyx sensor family

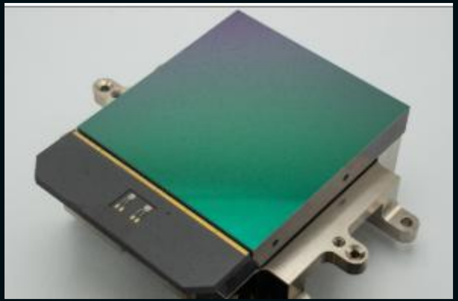




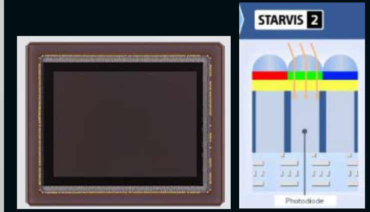
Alternative Detectors:

Teledyne e2V CIS 300: larger pixels (10.0 µm)
Sony IMX 411: micro-lens array (3,8 µm calibration issue)
Gpixel GSENSE 1517: larger pixels (15.0 µm)

Teledyne e2v (81 MP)

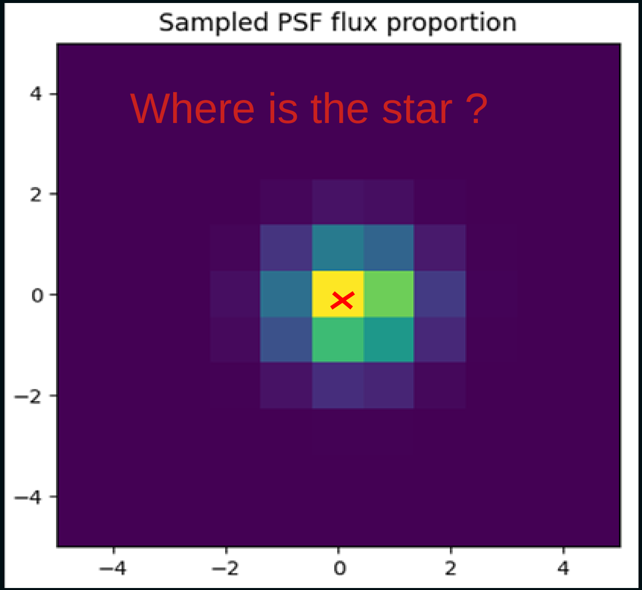


Sony (150 MP)



Gpixel (81 MP)

Where is the star @ 0.00005pix precision?



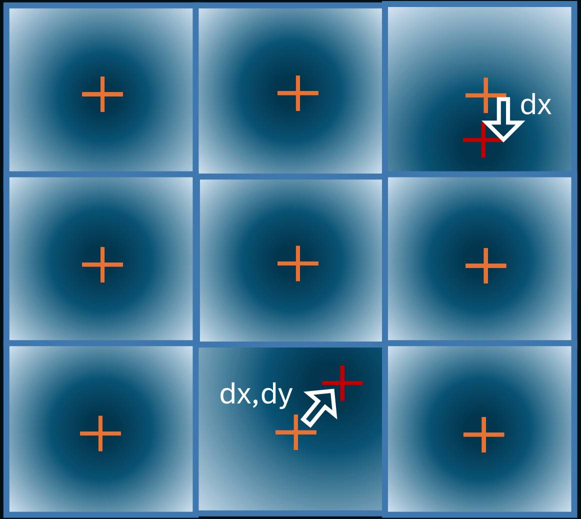
Requirements on instrument knowledge ?

- Great response and dark map (flat, bias)
- Great optical distorsion knowledge
- Lots of frames averaging … (observational strategy)

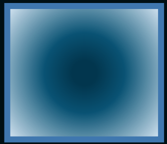
M. Lizzana PhD 2026 (SF2A S08)

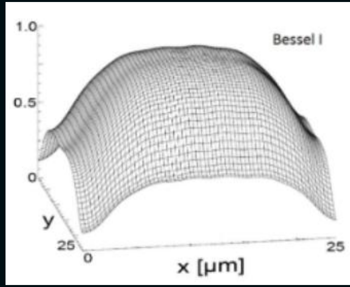
- Pixel's response barycentres (centroïd) : where are the pixels?

« dx,dy » cartography =



Pixel response

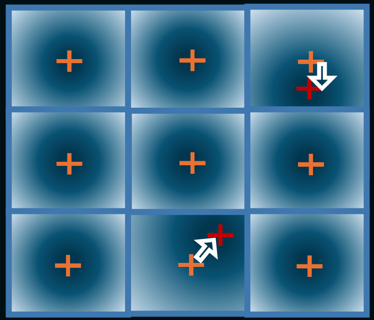




$$(x_c, y_c) = \left(\frac{\iint_{\text{pixel}} x IPRF_\lambda(x,y)dxdy}{\iint_{\text{pixel}} IPRF_\lambda(x,y)dxdy}, \frac{\iint_{\text{pixel}} y IPRF_\lambda(x,y)dxdy}{\iint_{\text{pixel}} IPRF_\lambda(x,y)dxdy} \right)$$

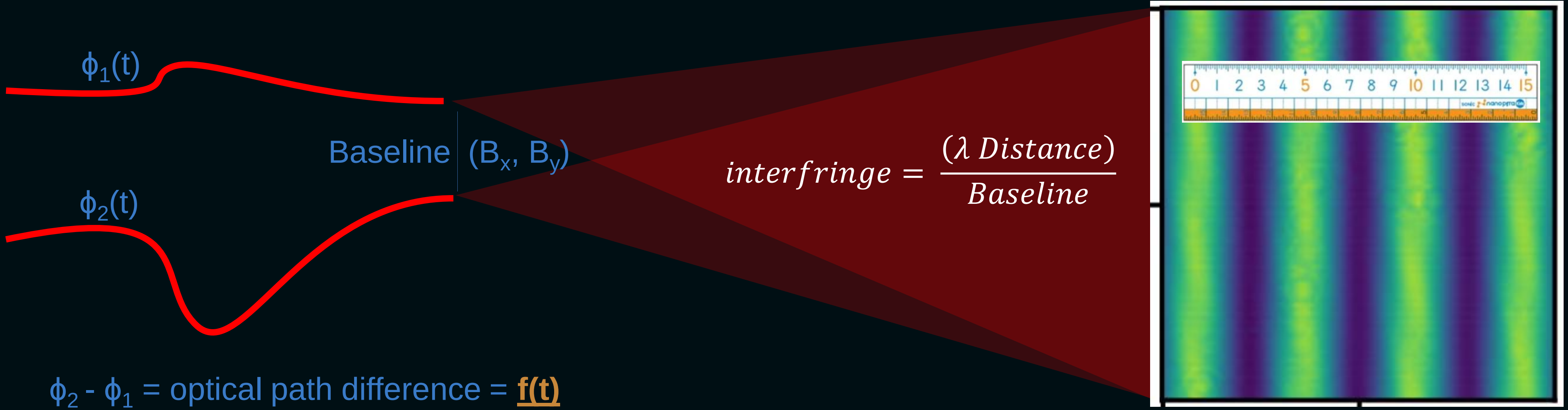
(2019, Vor), (Lizzana PhD thesis)

Measurement principle



The projection of modulated interference fringes on the detector should allow us to measure the photocenters difference w.r.t. theoretical grid.

Shown in (Zhai, 2011)[1], (Nemati, 2011)[1], (Crouzier, 2016)[2], (Shao, 2023)[1] --- [1] JPL [2] IPAG



$$interfringe = \frac{(\lambda\ Distance)}{Baseline}$$

$\phi_2 - \phi_1$ = optical path difference = **f(t)**

The IPAG bench

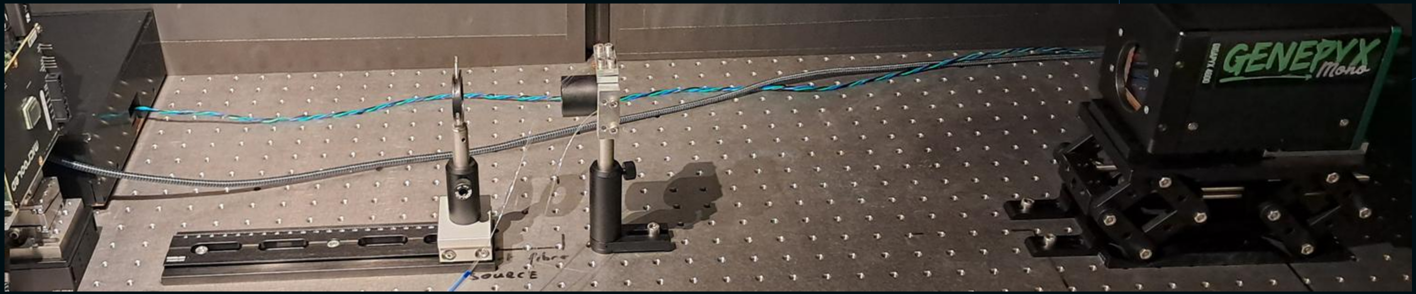
OLED screen for distortion purpuses

2 x 4 opt. fibers
(+ lense for OLED)

Pyxalis' Gigapyx
5456 x 8320pix (44Mpix)

Pyxalis'
Genepyx demo
camera

~40cm



Soler & Co ®

ϕ(t) : Agilent 33522A waveform generator + elec. field phase modulators (lithium niobalt)

Source : HeNe 632nm 21mW (coherent length~30cm)

Fibers : monomode with phase conservation

2 x 6 baselines
Vertical and Horizontal
Corresp. to **7 to 57pix** interfranges

On-board computational requirements

(dx,dy) precision prop. to interfringe/sqrt(#photons)

Those are optimistic results (ideal source, no variation of geometry, etc .)

Mission req. (for perfect contrast @ 50ke⁻):

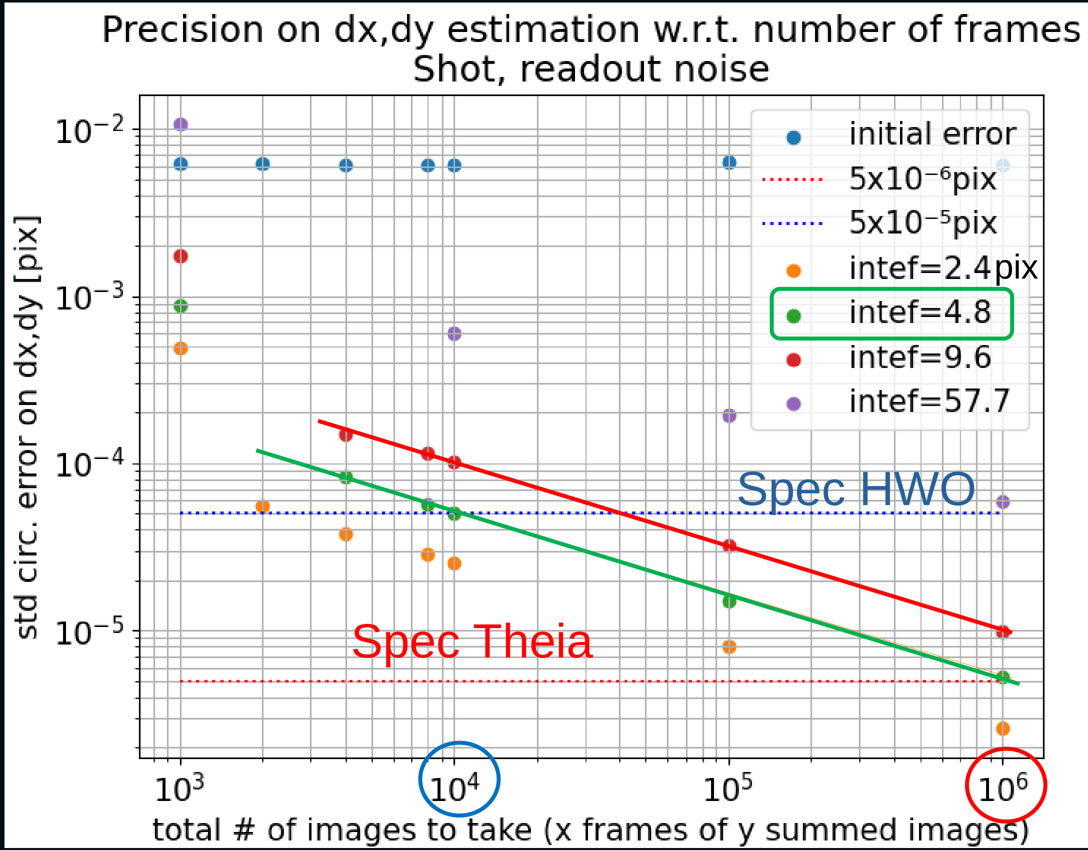
HWO : 3000 – **10.000 images** (5-16min @ 10fps)

THEIA : 3×10^5 – $\mathbf{10^6}$ **images** (8-27h @ 10fps)

Data that must be acquired and treated on board on big 1 Gpix focal plane ...

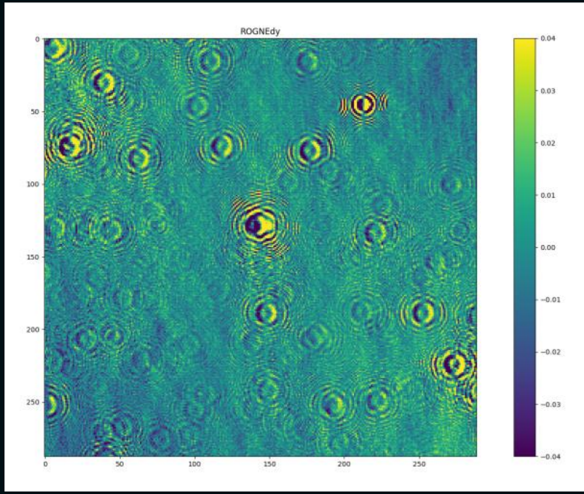
RETINA PEPR Origins

Simulation



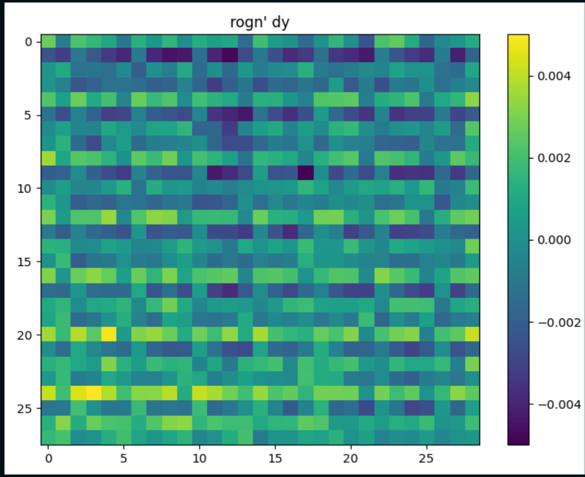
Results

Misalignement of pixels
-4% / +4% pix (~350nm)

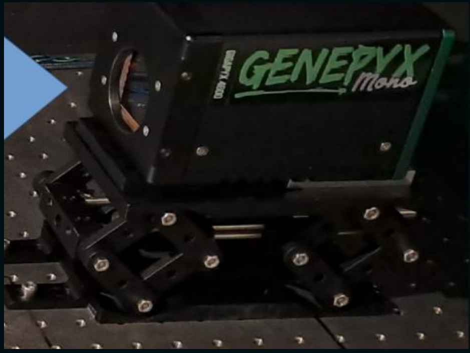


window removal

Misalignement of pixels
-0.5% / +0.5% pix (~44nm)

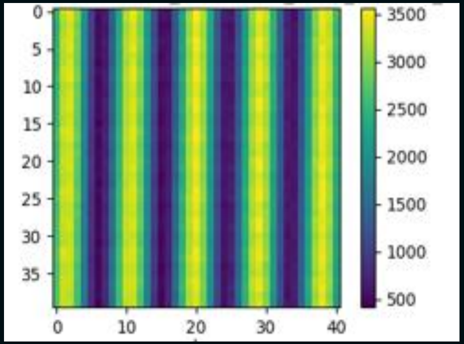


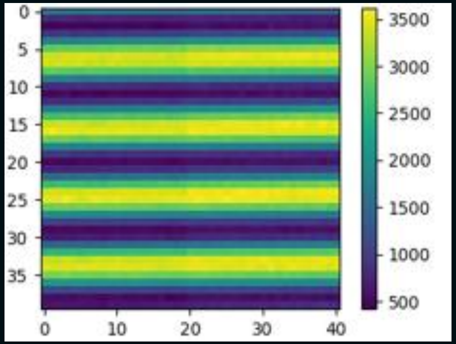
- Relocation of the bench in the white room and window removal
- Removal of the « rain on lake » effect



Results

1000 vertical fringes frames

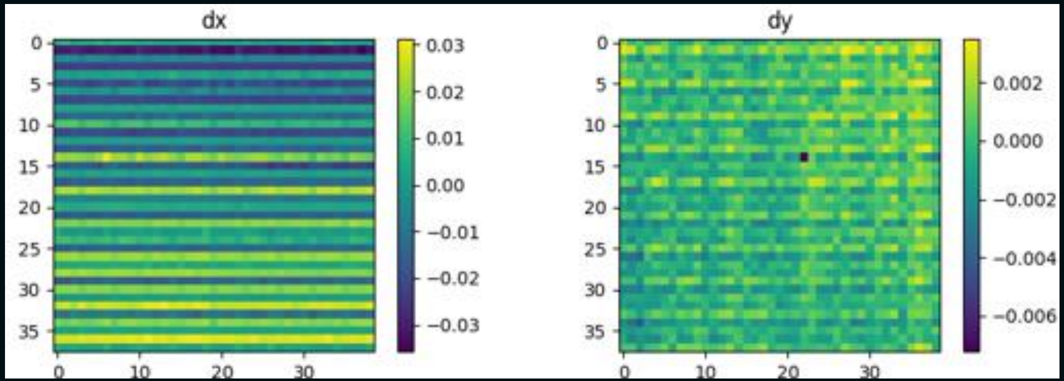




1000 horizontal fringes frames

Estimation algorithm (Crouzier 2016)

Pix misalignments
Maps of « dx,dy »



Unit = pix

We see expected electrical crosstalk (Inter Pixel Capacitance) signature :

characterized apart by hot pixels meas.thiébaut

2 deconvolution algorithm implemented (JWST Donlon 2018), (Thiébaut CRAL)

Pixels misalignments with electrical impacts <3%pix (vertical) <0.5%pix (horizontal)

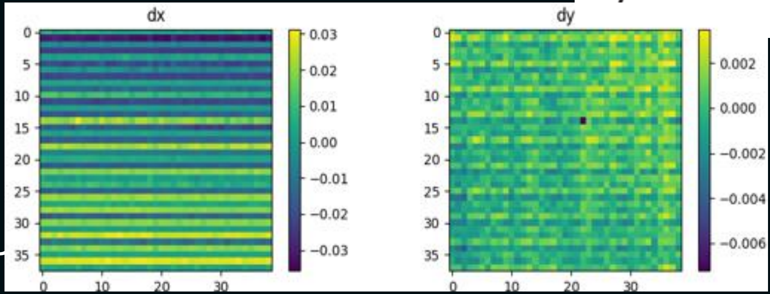
Done

- Full characterization of 2 Pyxalis' 46Mpix incl. IPC (Lizzana paper submitted)
- 2 kernel varying and sparse IPC deconvolution algorithm tested and validated
- Pixel's cartographies coherent with expected electrical effects
- Astrometrical instrument to be proposed @ NASA's HWO w. CEA-IRFU
- 220Mpix under design + fab @ Pyxalis

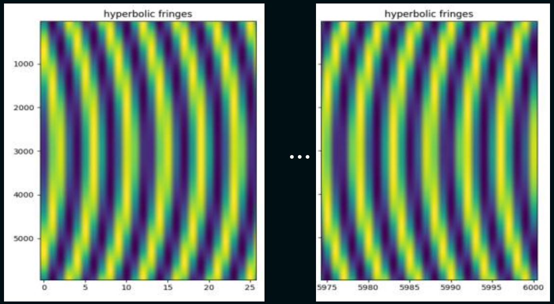
ToDo

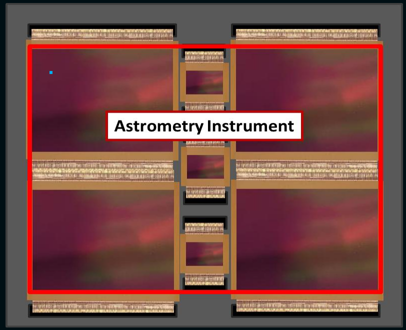
- **Hyperbolic fringes issue** on big focal plane systematics (estimation algorithm issue) – E. Thiébaut (CRAL) + C. Rey (intern)
- **Repeatability** of the measurement w.r.t. ~~time~~ / fibers geometry
- Bench stability requirements
- **Scale-up** to full frame (400x400pix max for now : 300x on 46Mpix, 6000x on full FP)
- Positive impact of dx,dy cartographies **on relative astrometry signal** ? With pseudo-stars moving on bench
- What about other wavelengths?
- **Spatializable hardware** to prove ESA, NASA (HWO) feasability

Pixel's cartographies



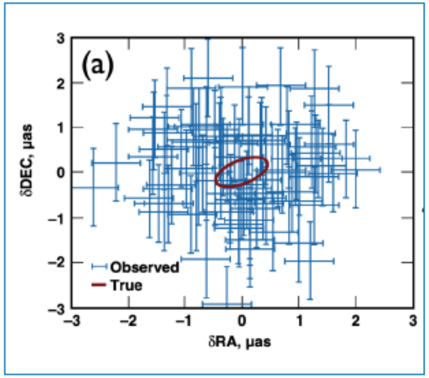
Hyperbolic fringes

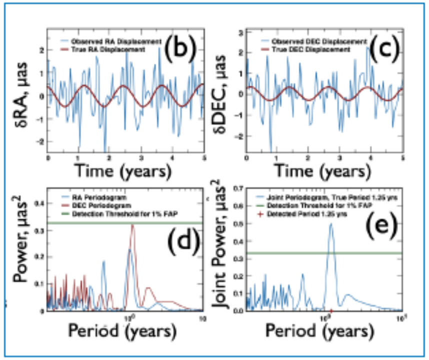




Annexes

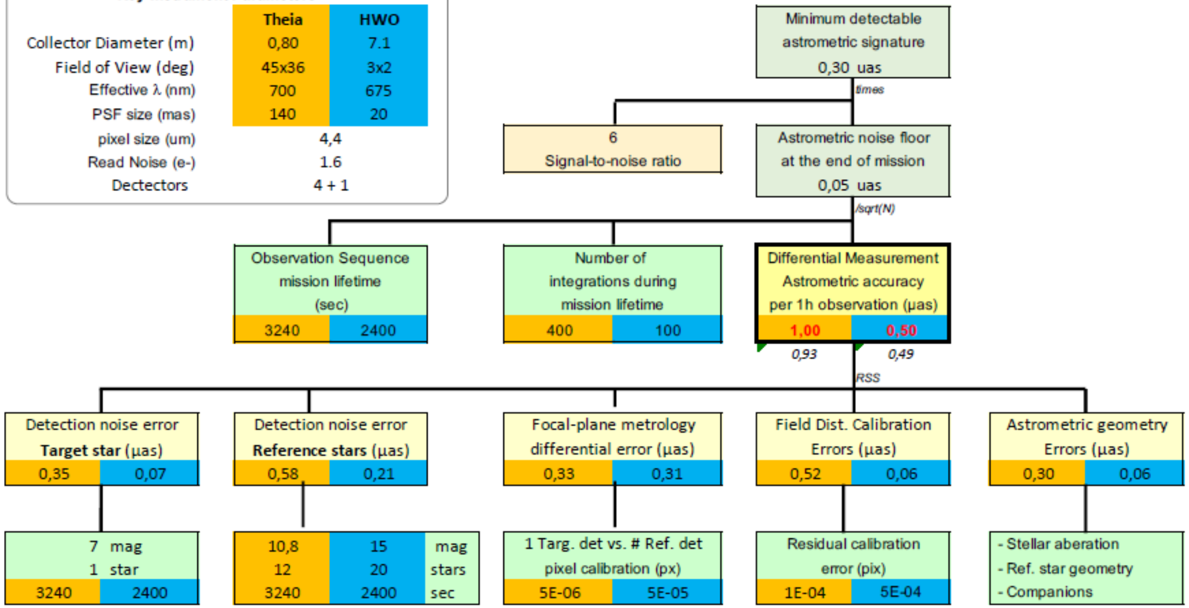
Astrometric error budget for bright targets with Theia and HWO





Key Instrument Parameters

	Theia	HWO
Collector Diameter (m)	0,80	7.1
Field of View (deg)	45x36	3x2
Effective λ (nm)	700	675
PSF size (mas)	140	20
pixel size (um)	4,4	
Read Noise (e-)	1.6	
Dectectors	4 + 1	

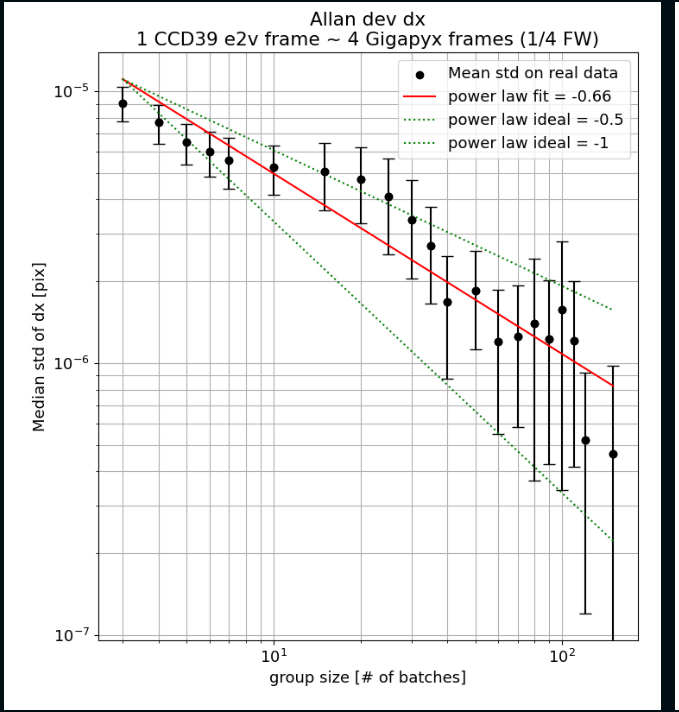


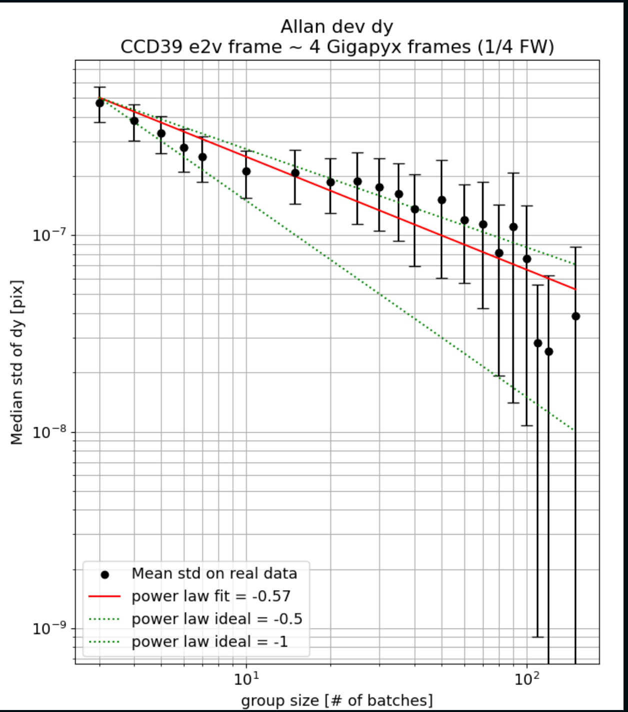
State-of-the-art

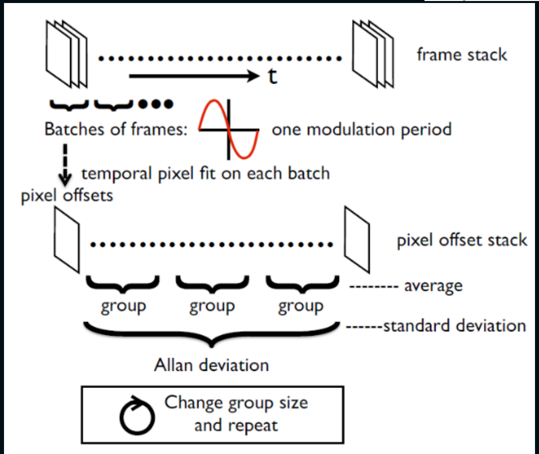
Stabilité du banc : déviations d'Allan

$$\langle (d\bar{x}_{n+1} - d\bar{x}_n)^2 \rangle = \frac{1}{N-1}\sum_{n=0}^{N-1}(d\bar{x}_{n+1} - d\bar{x}_n)^2$$

On converge bien vers un résultat, est-ce le bon résultat ?



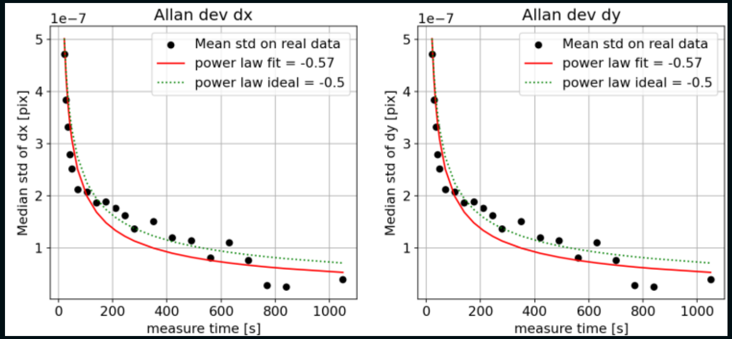




(Crouzier, 2016)

1 batch = 1 dx or dy map = 50 fringes frames (140ms/frame) = 7 secondes

~~Std~~ → Allan variance, median on the 40x40pixels of the window



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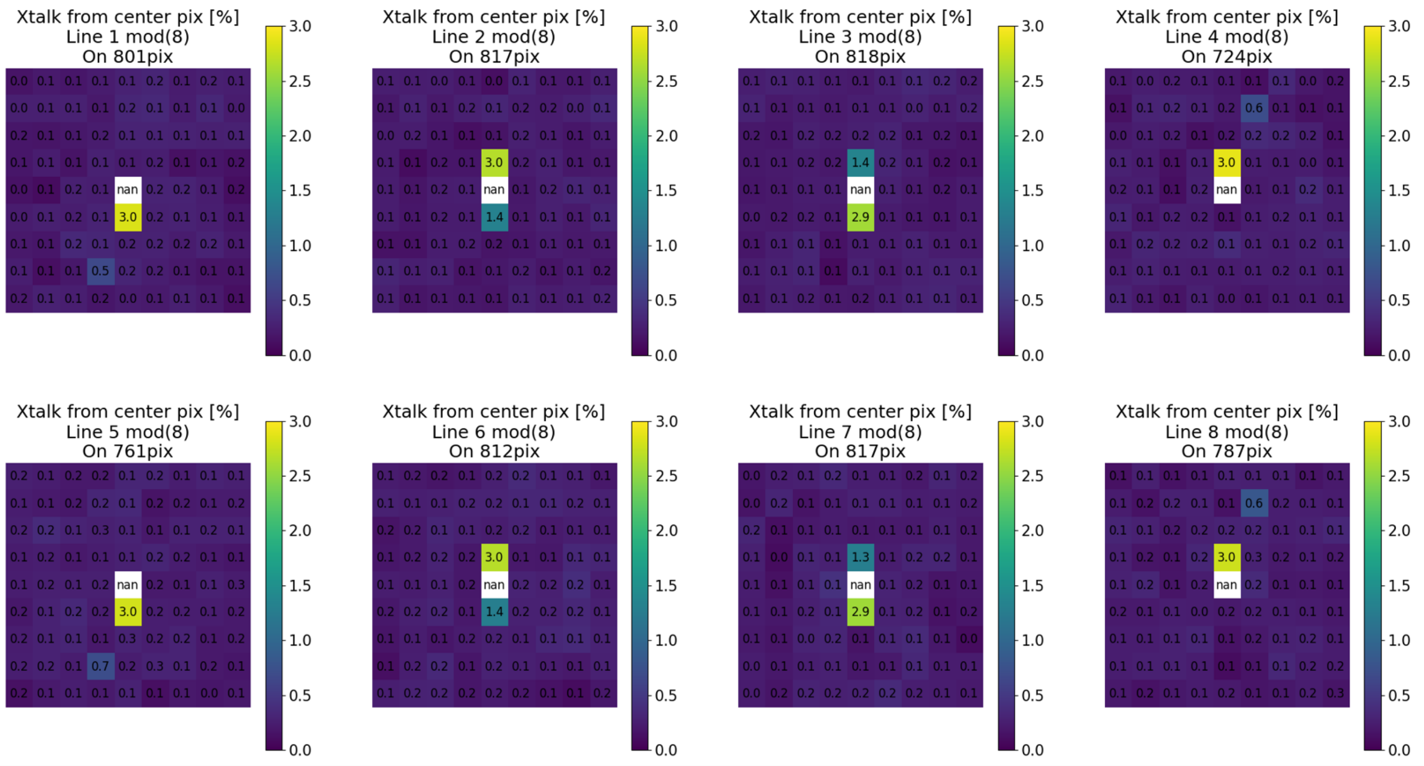
4. Crosstalk / IPC effect

- Show and characterize IPC (Inter-Pixel Capacitance effect (not crosstalk, supposed null for now due to deep trenches)
- Dark frames (tint=10s) : isolate « warm »/hot pixels (higher than average ADU values)
- Regroup / mean by the line number modulo 8 : 8 (or 4?) line repeatability

Each « center warm » pixel impacts 2 pixels

~3% in vertical axis
~0.6% in horizontal axis

→ values are coherent with systematics seen on « dx,dy » maps



4. Crosstalk / IPC effect : deconvolution

Ok let's deconvolve !

Spatially unregular ! No FFT, Wiener filters solutions…

2 algorithms :

Deconvolution on variable kernels (2018, Donlon) on H2RG NIRCam JWST

This results in a fraction, α referred to as the IPC coupling coefficient (Moore et al. 2004), of signal moving from a pixel to each of its neighbors. Expressing this relationship in the discrete form with the convolution expanded we have the following relationship:

$$M(i,j) = S(i,j) + \sum_{m=i-1}^{i+1}\sum_{n=j-1}^{j+1}[\alpha(i,j,m,n)\cdot S(m,n)] - \sum_{m=i-1}^{i+1}\sum_{n=j-1}^{j+1}[\alpha(m,n,i,j)\cdot S(i,j)]. \quad (3)$$

Direct (exact)

Itérations…

$$\hat{S}(i,j) = M(i,j) - \sum_{m=i-1}^{i+1}\sum_{n=j-1}^{j+1}[\alpha(M(i,j),M(m,n))\cdot M(m,n)] + \sum_{m=i-1}^{i+1}\sum_{n=j-1}^{j+1}[\alpha(M(m,n),M(i,j))\cdot M(i,j)].$$

$$\hat{S}_q(i,j) = M(i,j) - \sum_{m=i-1}^{i+1}\sum_{n=j-1}^{j+1}[\alpha(\hat{S}_{q-1}(i,j),\hat{S}_{q-1}(m,n))\cdot \hat{S}_{q-1}(m,n)] + \sum_{m=i-1}^{i+1}\sum_{n=j-1}^{j+1}[\alpha(\hat{S}_{q-1}(m,n),\hat{S}_{q-1}(i,j))\cdot \hat{S}_{q-1}(i,j)], \quad (5)$$

$$\hat{S}_0(a,b) = M(a,b). \quad (6)$$

Deconvolution on variable kernels (2018, Donlon) on H2RG NIRCam JWST

Nous allons résoudre le problème de la déconvolution en minimisant la fonction de coût :

$$\phi(\boldsymbol{x}) = \phi_{\mathsf{data}}(\boldsymbol{x}) + \mu\,\phi_{\mathsf{prior}}(\boldsymbol{x}) \quad (2)$$

Modèle données — Gérer l'augmentation du bruit par la « déconvolution »

avec

Poids

$$\phi_{\mathsf{data}}(\boldsymbol{x}) = (\mathbf{H}\cdot\boldsymbol{x}-\boldsymbol{y})^{\mathrm{t}}\cdot\mathbf{W}\cdot(\mathbf{H}\cdot\boldsymbol{x}-\boldsymbol{y}) \quad (3)$$

$$= \sum_i w_i\,[(\boldsymbol{h}\star\boldsymbol{x})_i - y_i]^2 \quad (4)$$

où $\mathbf{H}$ est l'opérateur de convolution par $\boldsymbol{h}$ et

$$\phi_{\mathsf{prior}}(\boldsymbol{x}) = \|\mathbf{D}\cdot\boldsymbol{x}\|^2 \quad (5)$$

$$= \sum_{i,j}[x_{i+1,j}-x_{i,j}]^2 + \sum_{i,j}[x_{i,j+1}-x_{i,j}]^2 \quad (6)$$

avec $\mathbf{D}$ un opérateur linéaire (de type différences finies).

Gradients conjugés (déconvolution généralisées):

Miniminer ϕ_{data} = minimiser un polynôme de degré 2 ! Donc annuler A(x)=b

Avec $A(x) = H^t\cdot W\cdot H(x) + \alpha\cdot D^t\cdot D(x)$ et $b = H^t\cdot W\cdot y$

IPC : ok on peut « déconvoluer » ! Et ça marche

The 2 algorithms give good and similar results **on dark 10s hot pixels maps**