

High-precision differential astrometry for discovering exoplanets

2026-06-22

Manon Lizzana (IPAG)

Working with : Fabien Malbet, Fabrice Pancher, Sébastien Soler , Hugo Rousset, Alain Leger,
Therry Lépine, Eric Thiebaut

Astrometry and its science cases

Differential astrometry measures the position, the proper motion and the parallax of celestial objects relative to the stars present in the field of view

- Investigate dark matter

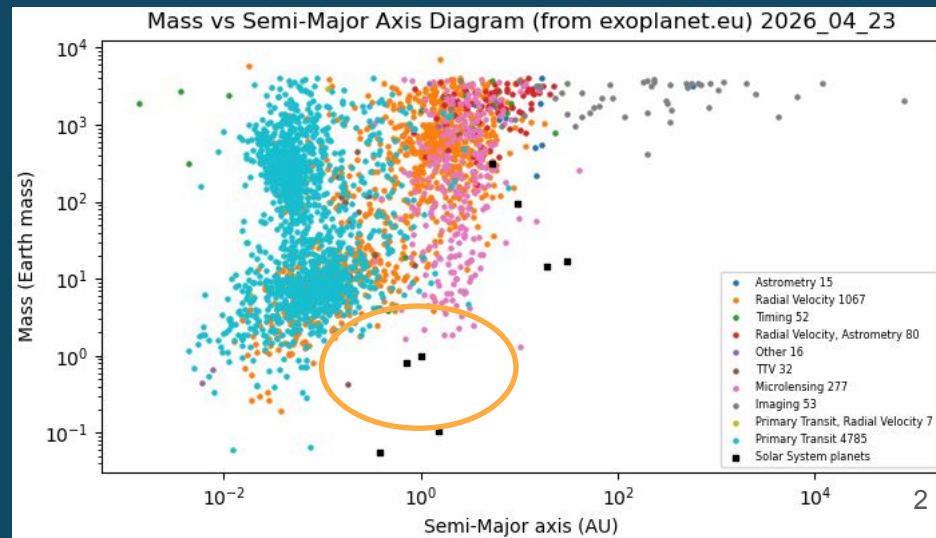
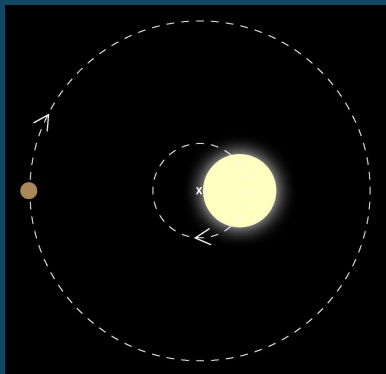
nature of DM, outer Milky way halo, DM subhalos in the galactic disc, substructure population of the DM halo

- Explore planetary systems in the Sun's vicinity

particularly rocky exoplanets in the habitable zone of nearby solar-type systems

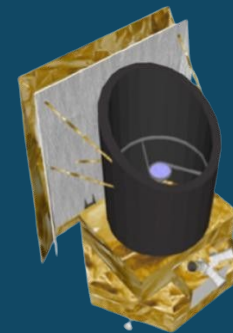
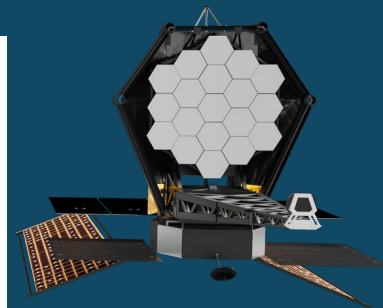
- Study compact objects

...



Comparison Theia and HWO

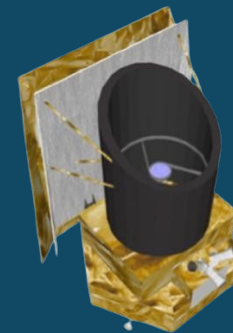
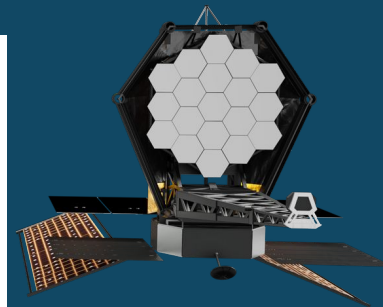
	Theia	HWO
wavelengths	$400 \leq \lambda \leq 900 \text{ nm}$	$100 \leq \lambda \leq 2500$
mission status	proposed project (M8 ESA call)	NASA flagship mission (launch ~ 2040)
telescope diameter	0.8 m	$6 \leq D \leq 8 \text{ m}$
focal length	13 m	$\sim 130 \text{ m}$
FOV	$30 \times 30 = 900 \text{ arcmin}^2$	$3 \times 4 = 12 \text{ arcmin}^2$
PSF size at 550 nm (λ/D)	140 mas	16 mas



Assumptions :
 4.4 μm pixels
 400 observations for Theia
 100 observations for HWO
 SNR=5

Comparison Theia and HWO

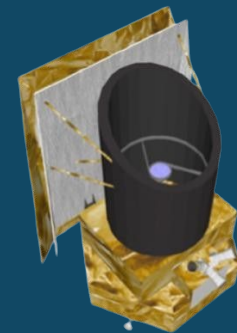
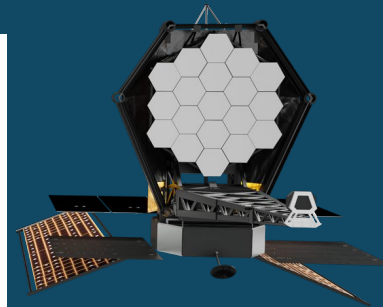
	Theia	HWO
wavelengths	$400 \leq \lambda \leq 900 \text{ nm}$	$100 \leq \lambda \leq 2500$
mission status	proposed project (M8 ESA call)	NASA flagship mission (launch ~ 2040)
telescope diameter	0.8 m	$6 \leq D \leq 8 \text{ m}$
focal length	13 m	$\sim 130 \text{ m}$
FOV	$30 \times 30 = 900 \text{ arcmin}^2$	$3 \times 4 = 12 \text{ arcmin}^2$
PSF size at 550 nm (λ/D)	140 mas	16 mas
signal produced by an exo-Earth ($0.3 \mu\text{as}$)	$2 \times 10^{-11} \text{ m}$ $4 \times 10^{-6} \text{ px}$	$2 \times 10^{-10} \text{ m}$ $4 \times 10^{-5} \text{ px}$



Assumptions :
 4.4 μm pixels
 400 observations for Theia
 100 observations for HWO
 SNR=5

Comparison Theia and HWO

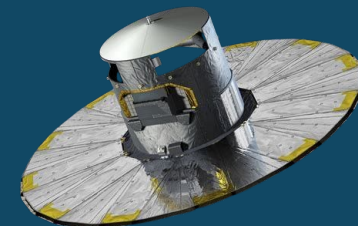
	Theia	HWO
wavelengths	$400 \leq \lambda \leq 900 \text{ nm}$	$100 \leq \lambda \leq 2500$
mission status	proposed project (M8 ESA call)	NASA flagship mission (launch ~ 2040)
telescope diameter	0.8 m	$6 \leq D \leq 8 \text{ m}$
focal length	13 m	$\sim 130 \text{ m}$
FOV	$30 \times 30 = 900 \text{ arcmin}^2$	$3 \times 4 = 12 \text{ arcmin}^2$
PSF size at 550 nm (λ/D)	140 mas	16 mas
signal produced by an exo-Earth ($0.3 \mu\text{as}$)	$2 \times 10^{-11} \text{ m}$ $4 \times 10^{-6} \text{ px}$	$2 \times 10^{-10} \text{ m}$ $4 \times 10^{-5} \text{ px}$
required single measurement accuracy	$0.8 \mu\text{as}$ $1 \times 10^{-5} \text{ px}$	$0.4 \mu\text{as}$ $6 \times 10^{-5} \text{ px}$



Assumptions :
 4.4 μm pixels
 400 observations for Theia
 100 observations for HWO
 SNR=5

Comparison Theia and HWO

	Theia	HWO
wavelengths	$400 \leq \lambda \leq 900 \text{ nm}$	$100 \leq \lambda \leq 2500$
mission status	proposed project (M8 ESA call)	NASA flagship mission (launch ~ 2040)
telescope diameter	0.8 m	$6 \leq D \leq 8 \text{ m}$
focal length	13 m	$\sim 130 \text{ m}$
FOV	$30 \times 30 = 900 \text{ arcmin}^2$	$3 \times 4 = 12 \text{ arcmin}^2$
PSF size at 550 nm (λ/D)	140 mas	16 mas
signal produced by an exo-Earth ($0.3 \mu\text{as}$)	$2 \times 10^{-11} \text{ m}$ $4 \times 10^{-6} \text{ px}$	$2 \times 10^{-10} \text{ m}$ $4 \times 10^{-5} \text{ px}$
required single measurement accuracy	$0.8 \mu\text{as}$ $1 \times 10^{-5} \text{ px}$	$0.4 \mu\text{as}$ $6 \times 10^{-5} \text{ px}$



gaia : $\gtrsim 10 \mu\text{as}$

Assumptions :
 4.4 μm pixels
 400 observations for Theia
 100 observations for HWO
 SNR=5

Comparison Theia and HWO

	Theia	HWO
way	$\lambda < 900 \text{ nm}$	$100 \leq \lambda \leq 2500$
mission	0.5 yr	1.5 yr (in mission)
telescope diameter	0.5 m	1.5 m
focal length	13 m	13 m
FOV	$30 \times 30 = 900 \text{ arcmin}^2$	$3 \times 4 = 12 \text{ arcmin}^2$
	$25000 \times 25000 \text{ px}$	$22000 \times 30000 \text{ px}$
PSF size at 550 nm (λ/D)	140 mas	16 mas
signal produced by an exo-Earth ($0.3 \mu\text{as}$)	$2 \times 10^{-11} \text{ m}$	$2 \times 10^{-10} \text{ m}$
	$4 \times 10^{-6} \text{ px}$	$4 \times 10^{-5} \text{ px}$
required single measurement accuracy	$0.8 \mu\text{as}$	$0.4 \mu\text{as}$
	$1 \times 10^{-5} \text{ px}$	$6 \times 10^{-5} \text{ px}$

S08

Astronomy with super-resolution: Overcoming the λ/D limit

How to overcome the λ/D limit and achieve μas precision ?



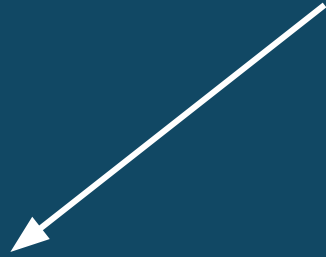
Characterize precisely the focal plane

- Characterize the detectors
- Characterize the pixel centroids

Calibrate the transformation between the positions measured by the camera and the positions of the stars in the sky

- Calibrate optical distortion and plate scale
- Calibrate the star movements

How to overcome the λ/D limit and achieve μas precision ?



Characterize precisely the focal plane

- Characterize the detectors
- Characterize the pixel centroids



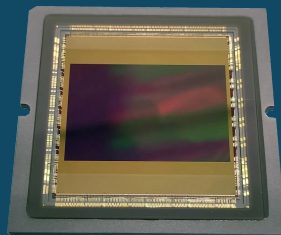
Calibrate the transformation between the positions measured by the camera and the positions of the stars in the sky

- Calibrate optical distortion and plate scale
- Calibrate the star movements

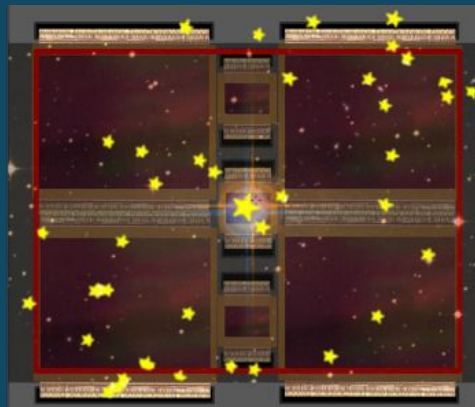
Characterize the detectors

by characterizing a detector in lab :
linearity, dark current, readout noise, gain, pixel
response non uniformity ...

- Current laboratory experiments
Gigapix CMOS from Pyxalis
8320 x 5436 px = 46 Mpx
pixel size : 4.4 μm



- Need for total field of view coverage
 $1 \text{ Gpx} \approx 30\,000 \times 30\,000 \text{ px}$
 $\approx 4 * 220 \text{ Mpx}$



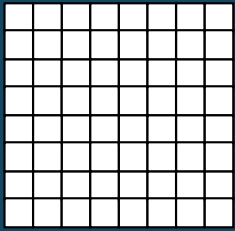
Key figures

readout noise (e-)	12
linearity error (%)	0.9
response non uniformity (%)	1.3
dark current at 35° (e-/s)	36
saturation charge (ke-)	56
bad pixels (%)	0.0004
Inter-pixel capacitance (%)	< 3

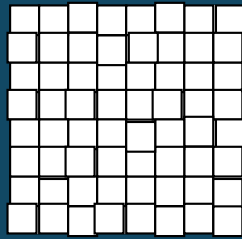
First characterization of such a detector
(compliant with Pyxalis results)

Detector adapted for differential
astrometry

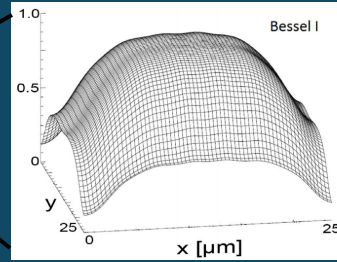
Characterize the pixel centroids



Perfect detector

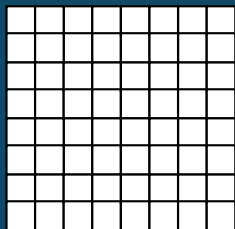


Real detector

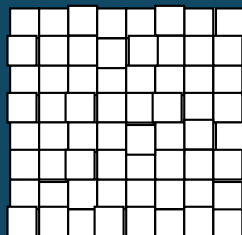


Goal: measure what are the misalignments of the pixels

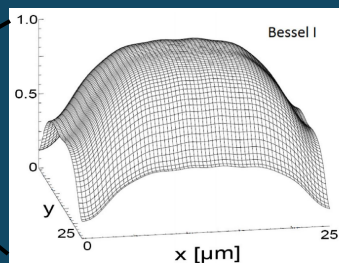
Characterize the pixel centroids



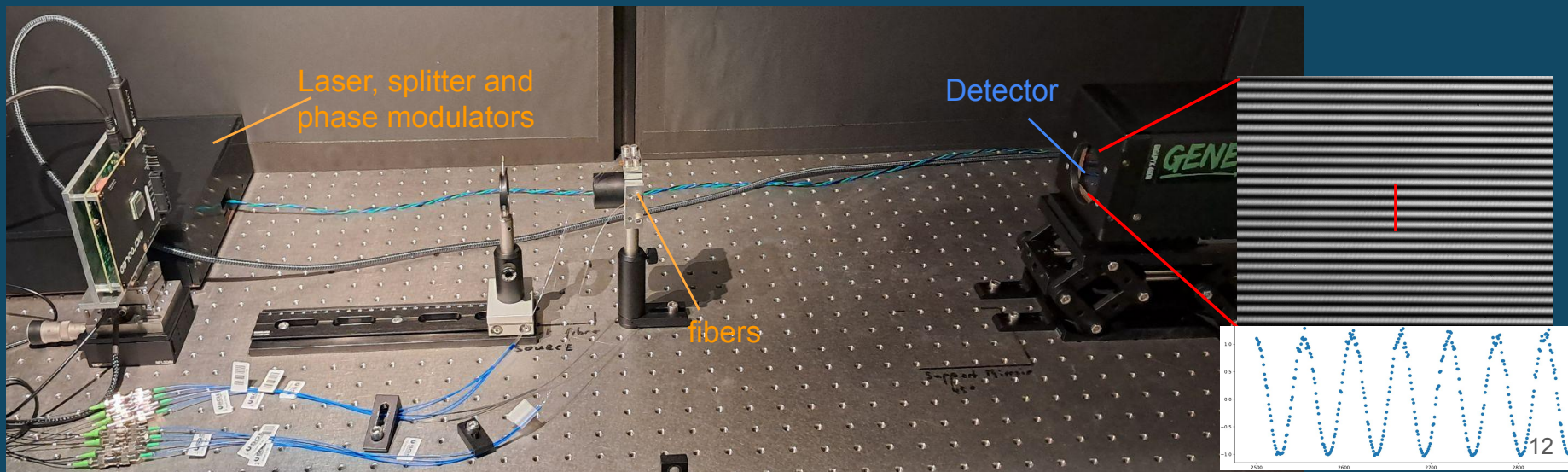
Perfect detector



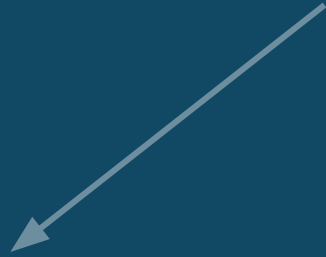
Real detector



Goal: measure what are the misalignments of the pixels



How to overcome the λ/D limit and achieve μas precision ?



Characterize precisely the focal plane

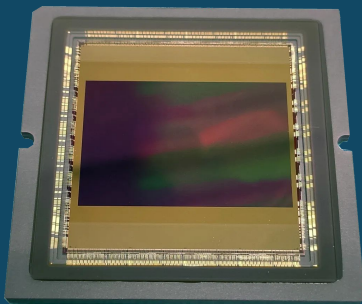
- Characterize the detectors
- Characterize the pixel centroids



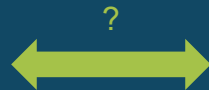
Calibrate the transformation between the positions measured by the camera and the positions of the stars in the sky

- Calibrate optical distortion and plate scale
- Calibrate the star movements

Transformation from detector to sky



(x,y)

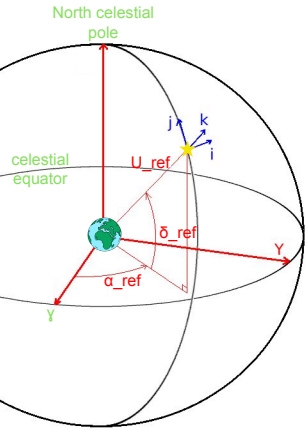


(α, δ)

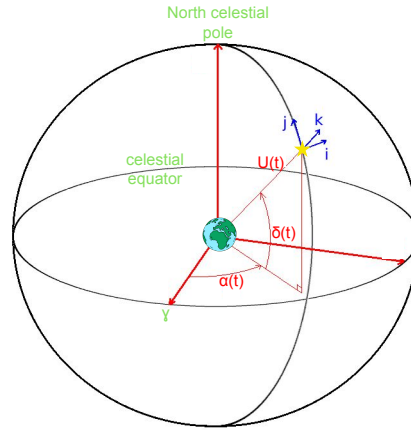
- Plate scale projection
- Movement of the satellite
- Optical distortion
- Relationship between pixels and angular distances
- ...

Transformation from detector to sky

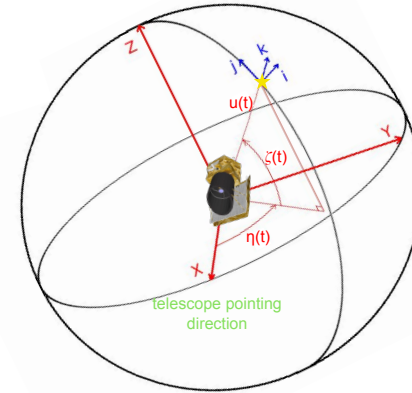
equatorial reference frame



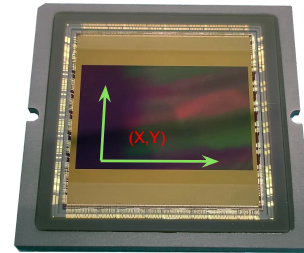
equatorial time frame



intermediate frame

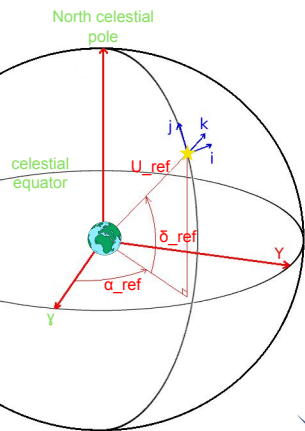


detector frame

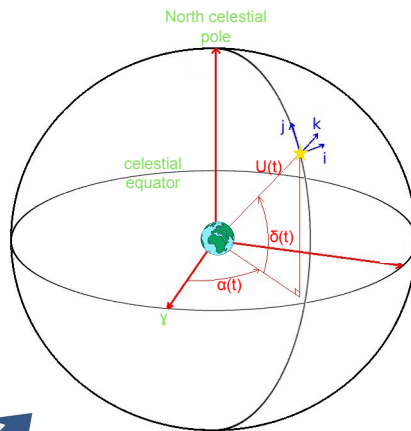


Transformation from detector to sky

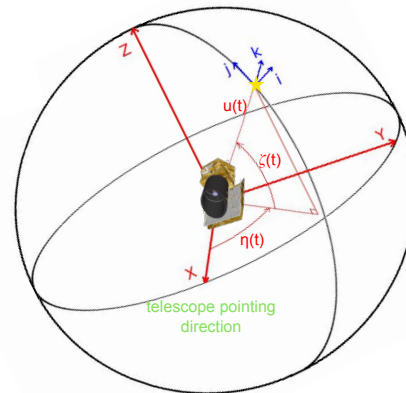
equatorial reference frame



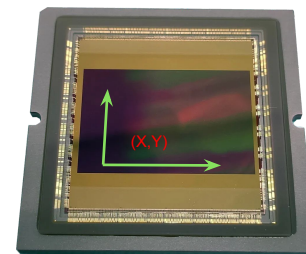
equatorial time frame



intermediate frame

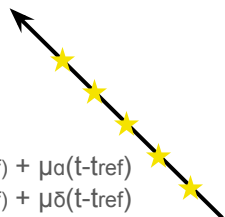


detector frame



s

(astrometric description of the source)

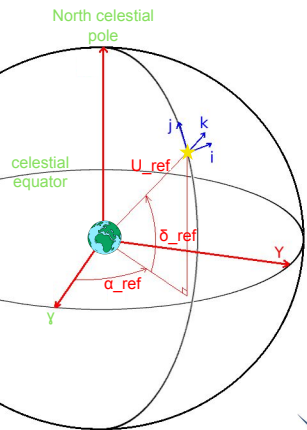


$$\alpha(t) = \alpha(t_{\text{ref}}) + \mu\alpha(t - t_{\text{ref}})$$

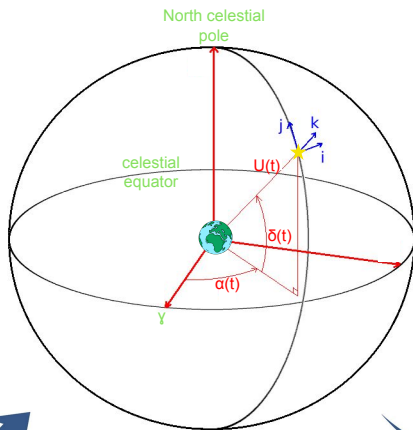
$$\delta(t) = \delta(t_{\text{ref}}) + \mu\delta(t - t_{\text{ref}})$$

Transformation from detector to sky

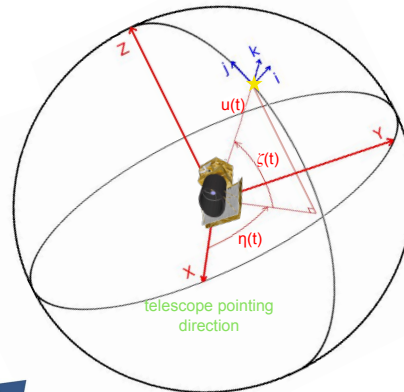
equatorial reference frame



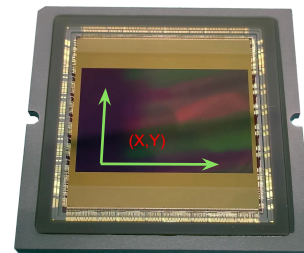
equatorial time frame



intermediate frame



detector frame



s

(astrometric description of the source)

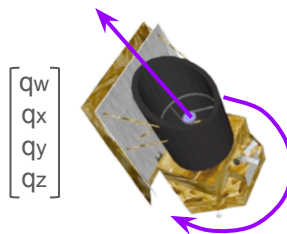
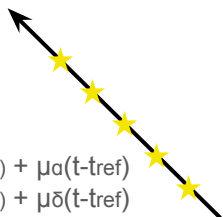


a

(telescope position and orientation)

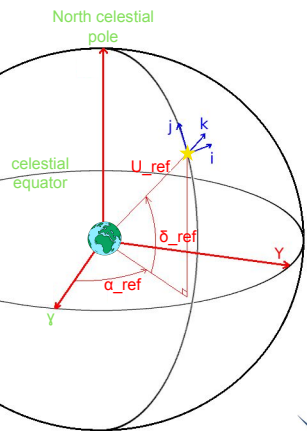
$$\alpha(t) = \alpha(t_{ref}) + \mu\alpha(t-t_{ref})$$

$$\delta(t) = \delta(t_{ref}) + \mu\delta(t-t_{ref})$$

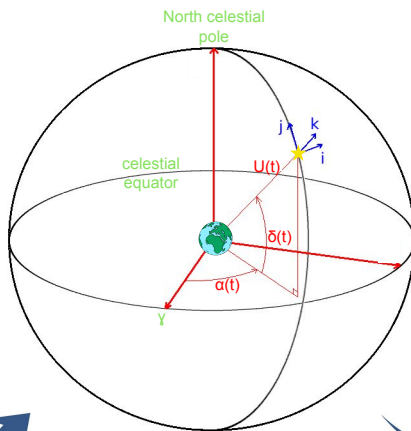


Transformation from detector to sky

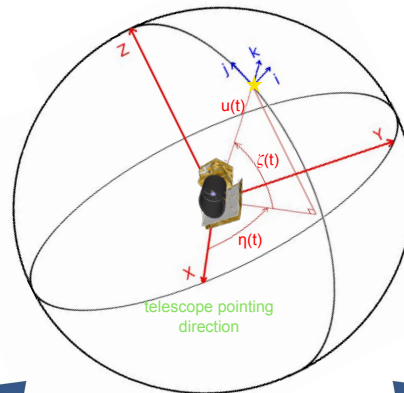
equatorial reference frame



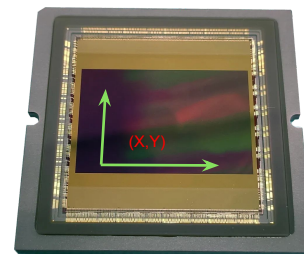
equatorial time frame



intermediate frame



detector frame



s

(astrometric description of the source)

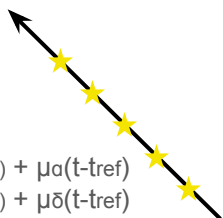
a

(telescope position and orientation)

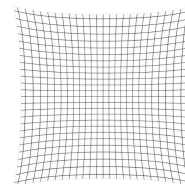
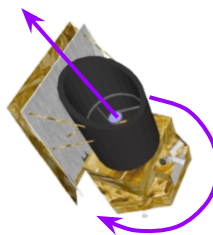
c

(plate scale transformation and optical distortion)

$$\begin{aligned} \alpha(t) &= \alpha(t_{ref}) + \mu\alpha(t-t_{ref}) \\ \delta(t) &= \delta(t_{ref}) + \mu\delta(t-t_{ref}) \end{aligned}$$



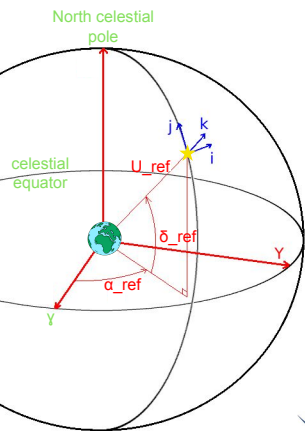
$$\begin{bmatrix} q_w \\ q_x \\ q_y \\ q_z \end{bmatrix}$$



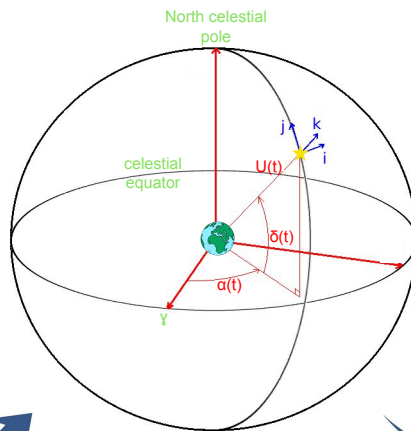
$$\begin{cases} \eta = x + \sum_{ij} c_{\eta ij} x^i y^j \\ \zeta = y + \sum_{ij} c_{\zeta ij} x^i y^j \end{cases}$$

Transformation from detector to sky

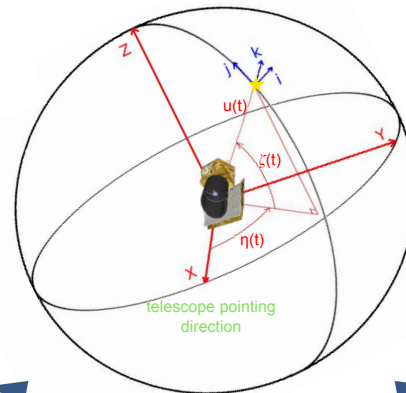
equatorial reference frame



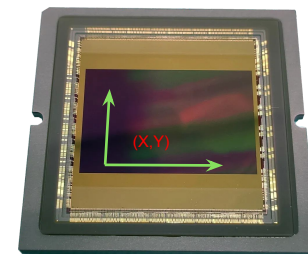
equatorial time frame



intermediate frame



detector frame



s

(astrometric description of the source)

a

(telescope position and orientation)

c

(plate scale transformation and optical distortion)

Fit with an iterative
Levenberg-Marquardt algorithm

$$x = \begin{Bmatrix} s \\ a \\ c \end{Bmatrix} \begin{array}{l} \text{astrometry} \\ \text{attitude} \\ \text{calibration} \end{array}$$

Conclusion and perspectives

The job we have done to overcome the λ/D limit

- We characterized a detector adapted for differential astrometry
- We developed a test bed and algorithms to measure the pixel centroids
- We set up a method to calibrate the telescope attitude, plate scale transformation, optical distortion, and star astrometric parameters simultaneously

Next steps

- We will characterize larger detectors
- We will map the pixel centroids of the adapted detectors into an entire focal plane assembly
- We will evaluate the performance of pointed differential astrometry in simulations and in the lab