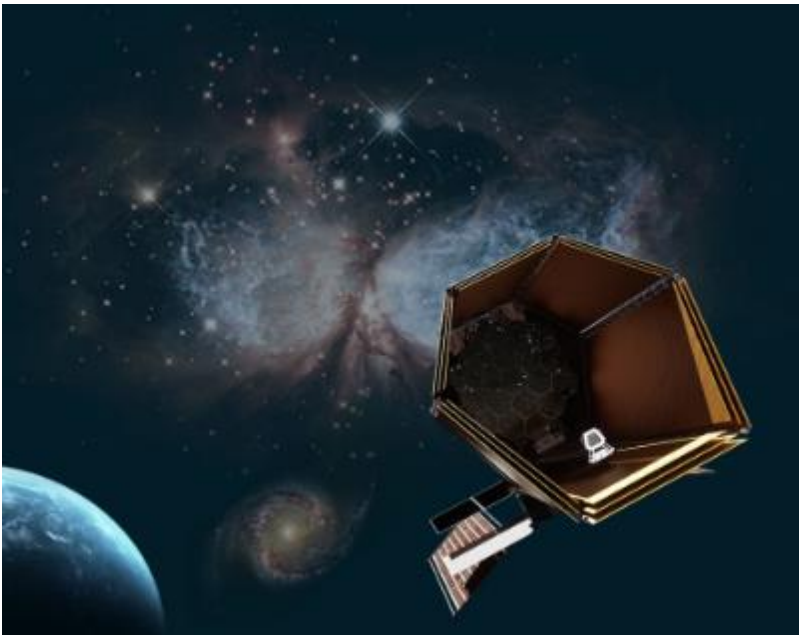




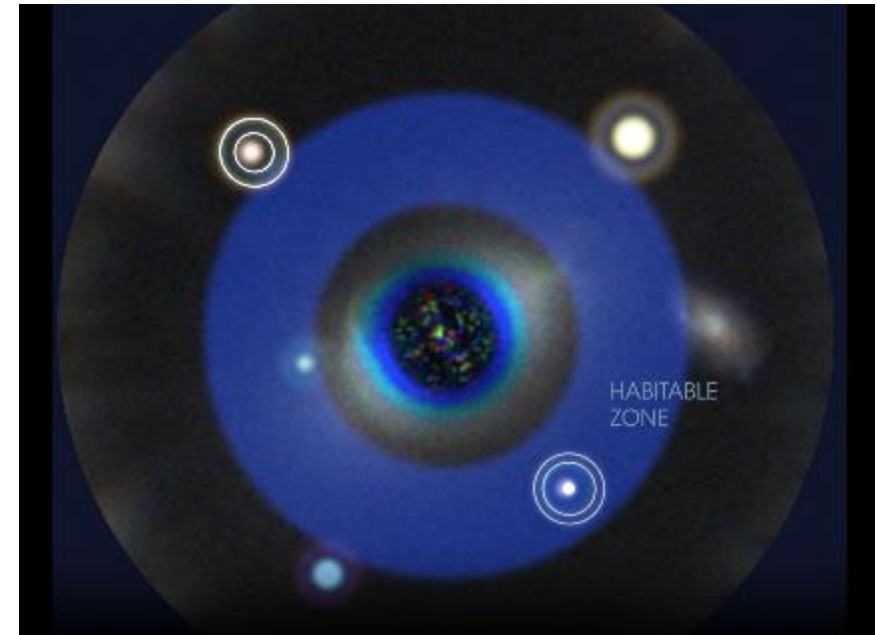
Astrometry with the Habitable World Observatory

the challenge of on-board processing



Séminaire CEA-DEDIp
24/09/2026

Jerome Amiaux (CEA-DAP - France)



Current Large Space Observatory

James Webb Space Telescope

- launched in 2021
- 6 m telescope
- Small field (some arcmin²)
- IR [0,6 – 28,5] μm
- 4 instruments
 - NIRCам
 - NIRSpec
 - MIRI
 - FGS / NIRISS



Euclid Mission

- launched in 2023
- 1.2 m telescope
- Large field (0.5 deg²)
- Visible and NIR (2.3 μm)
- 2 instruments
 - VIS
 - NISP



Nancy Grace Roman Space Telescope

- launched in 2026
- 2.4 m telescope
- Large field (0.3 deg²)
- NIR
- 2 instruments
 - Wide Field Instrument
 - Coronagraph



Current Large Space Observatory

James Webb Space Telescope

- 60 Mega-pixels IR sample up the ramp
- Downlink: 50 GB/day (400 Gbit/day)
- Storage: 65 GB
- Low level on board processing

×8



Euclid Mission

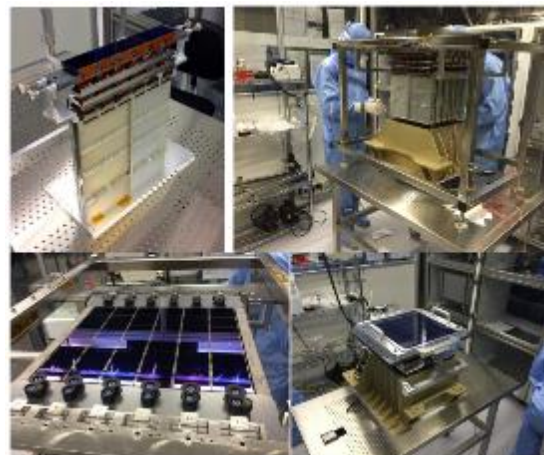
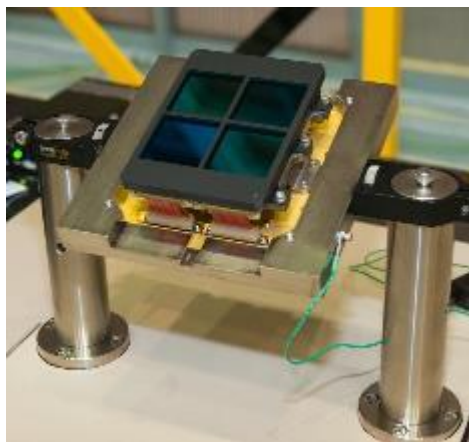
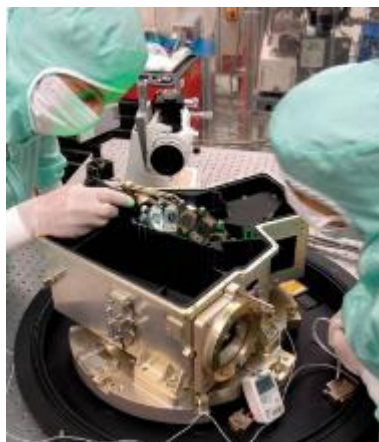
- 600 Mega-pixels VIS
- 60 Mega-pixel IR onboard slope
- Downlink: 100 GB/day (800 Gbit/day)
- Storage: 500 GB
- High level on board processing (slope)

×8



Nancy Grace Roman Space Telescope

- 300 Mega-pixels sample up the ramp
- Downlink: ~1 TB/day (10 Tbit/day)
- Storage: 4 TB
- Low level on board processing (average)



Current Large Space Observatory

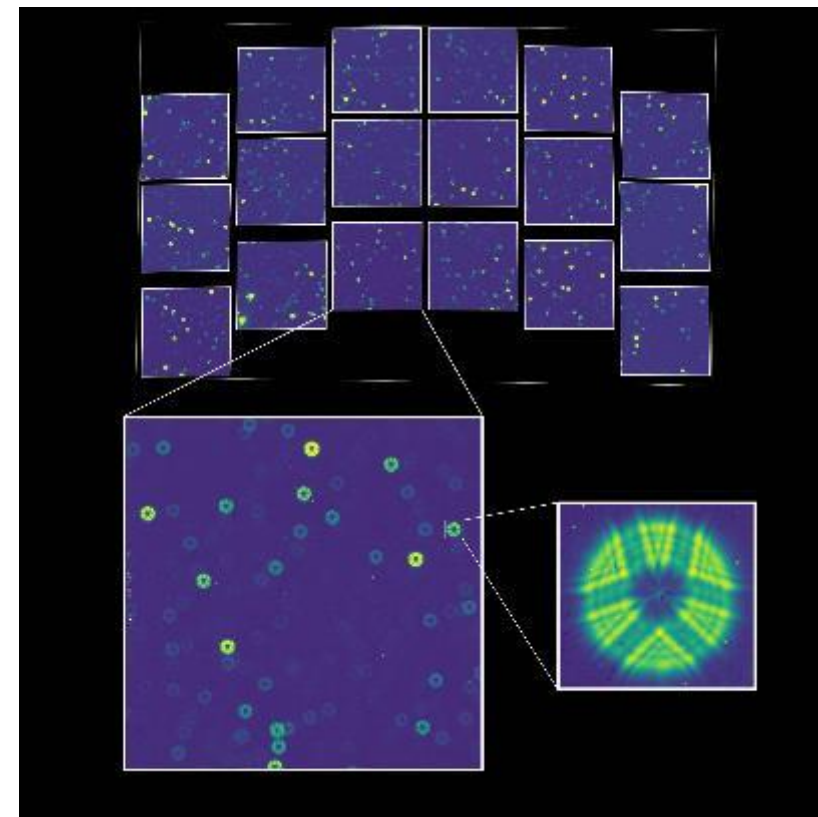
James Webb Space Telescope



Euclid Mission



Nancy Grace Roman Space Telescope

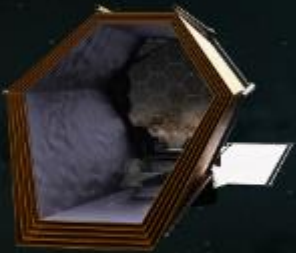
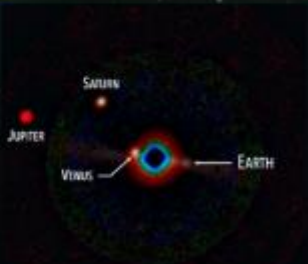


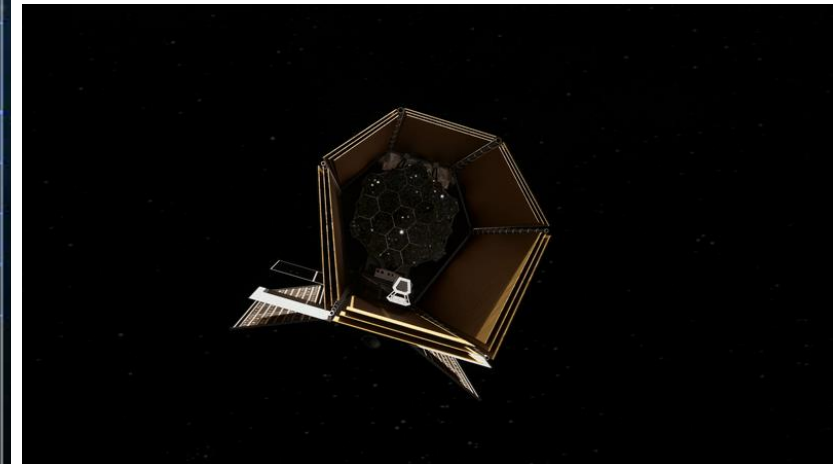
Next Generation Largest Observatory

HWO is the next flagship mission recommended by Astro 2020 Decadal Survey following on:

- JWST (6,5 m IR telescope launch 2021)
- Nancy Grace Roman Telescope (2,4 m VIS / IR telescope launch 2027)

HWO will be 7 to 8 m UV / VIS and IR telescope dedicated to search for signs of life on planets outside our solar system: launch first half of 2040

Telescope	Coronagraph	High-Resolution Imager	UV Multi-Object Spectrograph
Diameter ~6.0 m (inner)	High-contrast imaging and imaging spectroscopy	UV/Vis and NIR imaging	UV/Vis multi-object spectroscopy and FUV imaging
Bandpass ~100-2500 nm	Bandpass ~200-1800 nm	Bandpass ~200-2500 nm	Bandpass ~100-1000 nm
	Contrast $\lesssim 1 \times 10^{-10}$	Field-of-View $\sim 3' \times 2'$	Field-of-View $\sim 2' \times 2'$
	R ($\lambda/\Delta\lambda$) Vis: ~140 NIR: ~70, 200	60+ science filters & grism	Apertures $\sim 840 \times 420$
		High-precision astrometry?	R ($\lambda/\Delta\lambda$) ~500-60,000
			
Fourth Instrument To be defined			

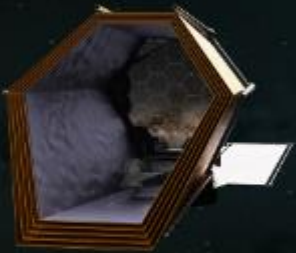
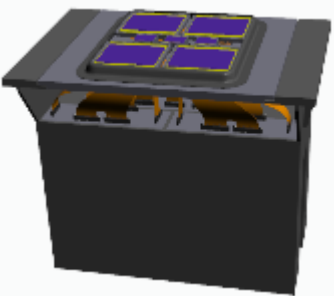


Next Generation Largest Observatory

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	R ($\lambda/\Delta\lambda$) Vis: ~140 NIR: ~70, 200	60+ science filters & grism	Apertures ~840 x 420
		High-precision astrometry?	R ($\lambda/\Delta\lambda$) ~500-60,000
			
Fourth Instrument To be defined			

Current proposal CEA/IPAG under discussion with HWO office:

Astrometric instrument either on the High Resolution Imager or as a stand alone camera at the telescope focal plane.

**First Review end 2029:
Mission Consolidation Review:
design of telescope baseline and
selection of instruments.**

Goal and Sizing Case for Astrometry instrument

Measuring the **mass of the Earth-like** exoplanets orbiting in the habitable zone of Sun-like stars detected and characterized by direct imaging with the Coronagraph instrument

“Mass is the **most fundamental property of a planet**, and knowledge of a planet’s mass (along with a knowledge of its radius) is essential to understand its bulk composition and to interpret spectroscopic features in its atmosphere.”

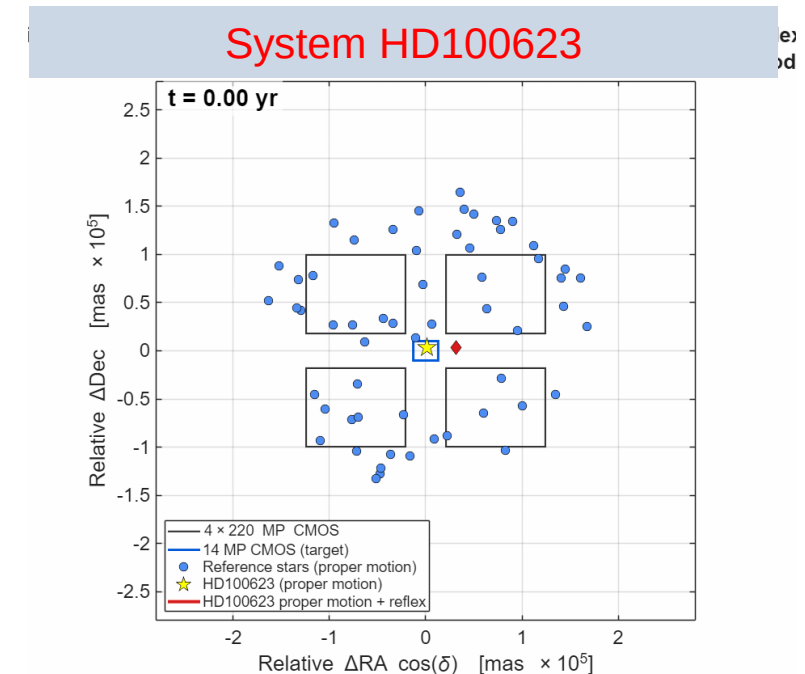
-National Academy of Sciences Exoplanet Survey Strategy Report.

Principle of relative astrometry measurements:

Determination of the angular displacement of the photocenter of the [target star + planet] around the barycenter of the system in the relative frame of the reference calibration stars.

Large Variability of systems:

Design analysis based on a sample ~160 Potential HWO targets and their close environment (from GAIA survey)
(Mamajek & Stapelfeldt 2024)



Astrometry Budget

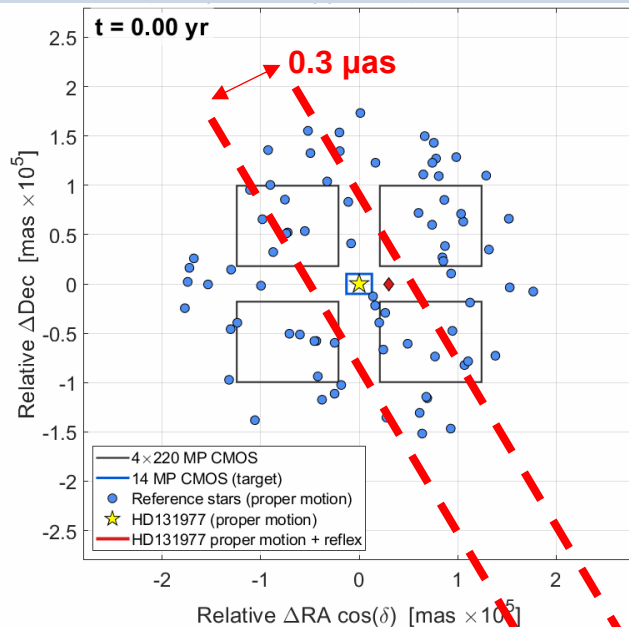
Sizing Case: exo-Earth signature @ 10pc signal:

Astrometric Signal $0.3 \mu\text{as}$

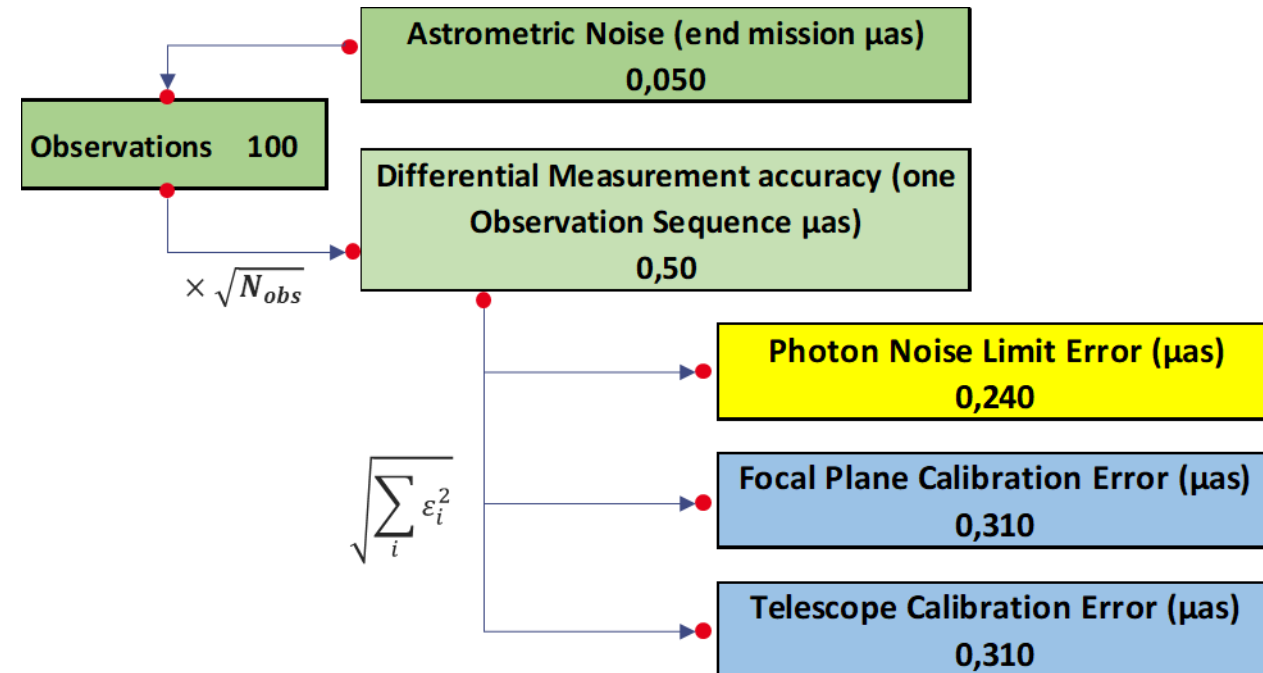
Single measurements astrometric noise requirement:

- **$0.500 \mu\text{as}$**
- **Typical revisit 100 over >1 year**

System HD131977



Below μas error means astrometry is mainly be about controlling systematics and calibration



Designing for Statistical limit

Large dynamics of target:

- Target system stars: magnitude [3 to 7]
- Calibration Star: magnitude [15 to 20]

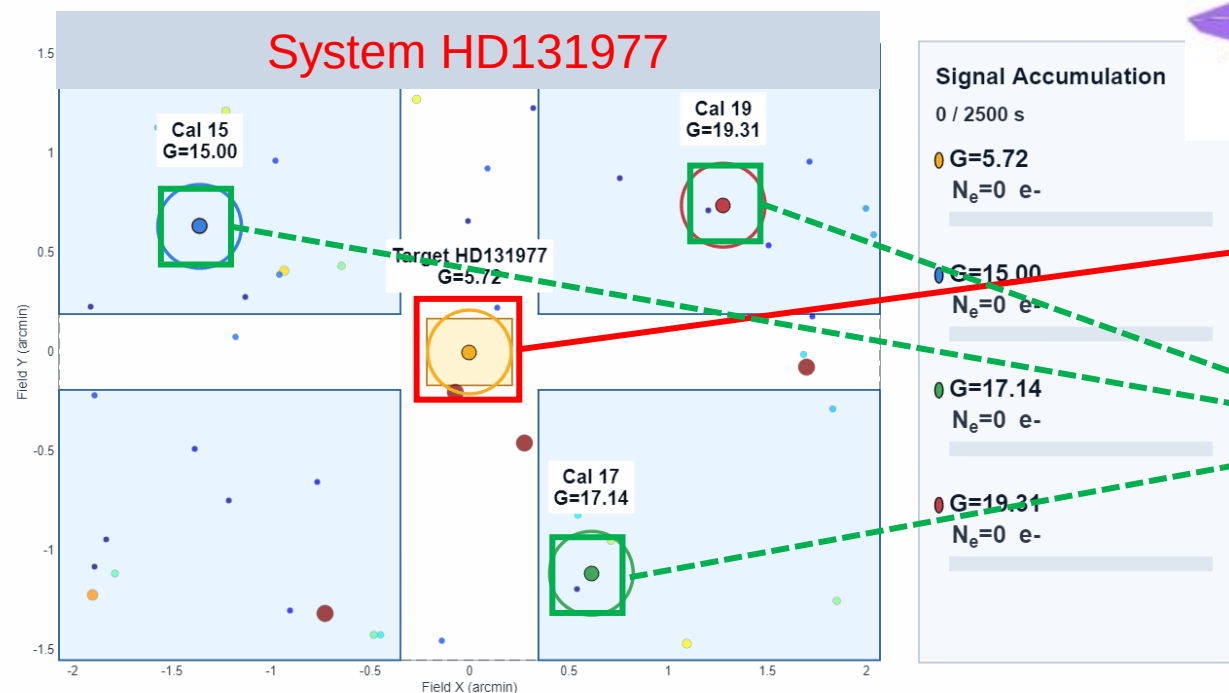
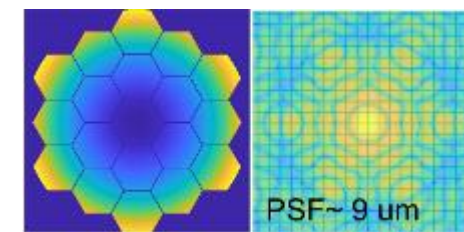
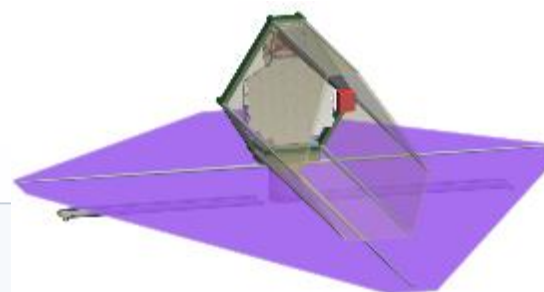
Integration time: **2500 s**

- Fast read on target (window): 1000's fps
- Longer read on calibration: 10 fps

Benefits from HWO:

large mirror: 33 m² collecting area

small PSF: ~20 mas



$$\sigma_{ast_target} = \frac{FWHM_{PSF}}{2\sqrt{N_{photo-e-}}}$$

$$\sigma_{ast_cal} = \frac{1}{\sqrt{N_{cal_star}}} \times \frac{FWHM_{PSF}}{2\sqrt{N_{photo-e-}}}$$

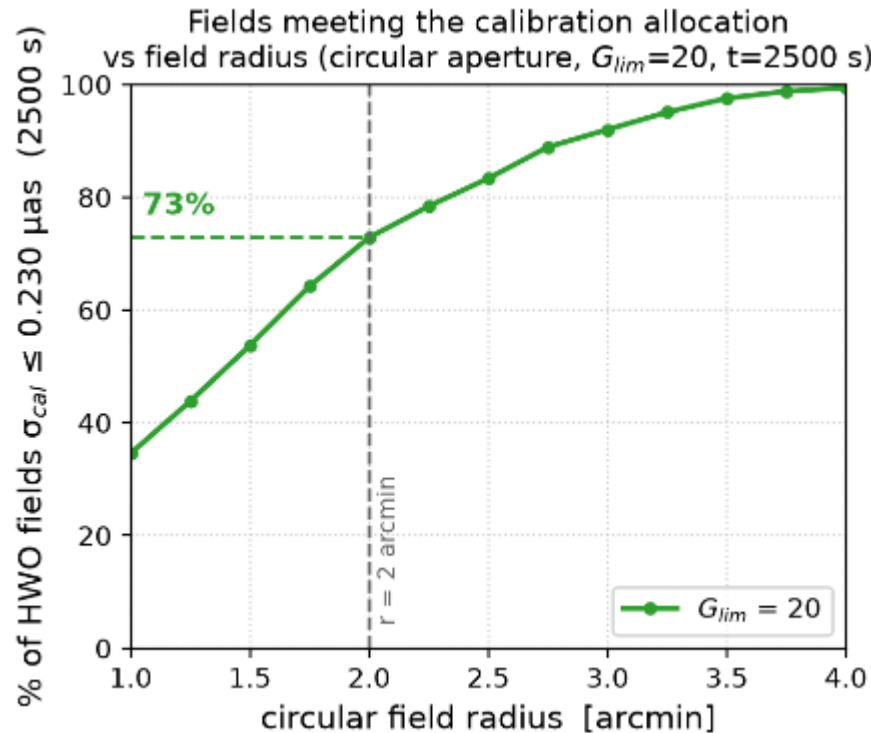
< 0.240 μas

get statistical floor noise **<0,240 μas in 2500 s**

Trade off for Field of View

Study performance **Statistical astrometric noise on both target star and calibration grid stars** over 160 targets with a 2500-s exposure time:

- Reaching close to 100% would require 36 arcmin²
- Reaching in >70% of HWO targets with 12 arcmin²

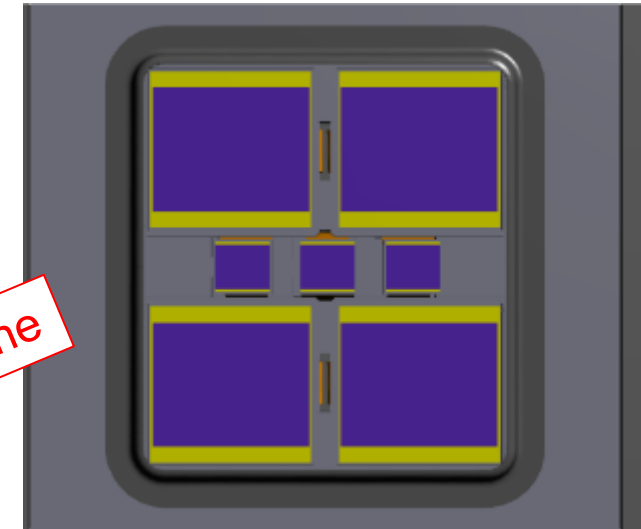


DEDIp seminar: HWO astrometry Data Challenge



Baseline

Giga-pixel Focal Plane



Status of Design Baseline

EAC5 Instrument C: HRI-A Astrometry and Guiding

Directly at telescope focal plane

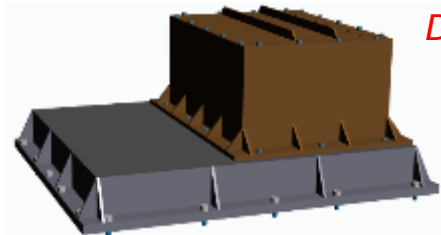
Focal Plane Assembly: 4×3 arcmin² with 1 Gigapixel

- 4 large 220 MegaPixel CMOS
- 1 small 14 MegaPixel CMOS (+redundancy)

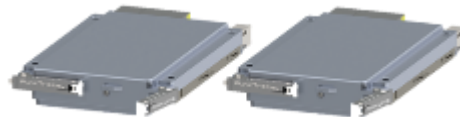
3 Electronics Modules



*Power Supply Unit (PSU)
Total Consumption 310 W*



*Data Processing Unit (DPU)
5 PFLOPs of operations*

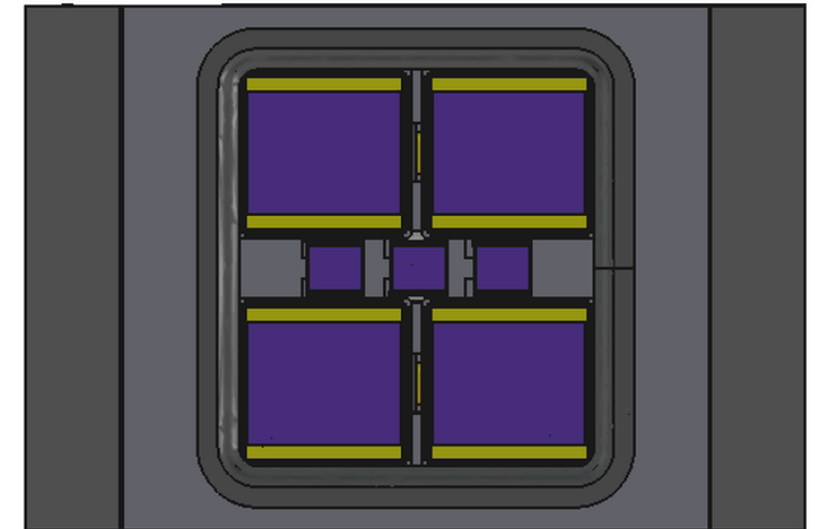
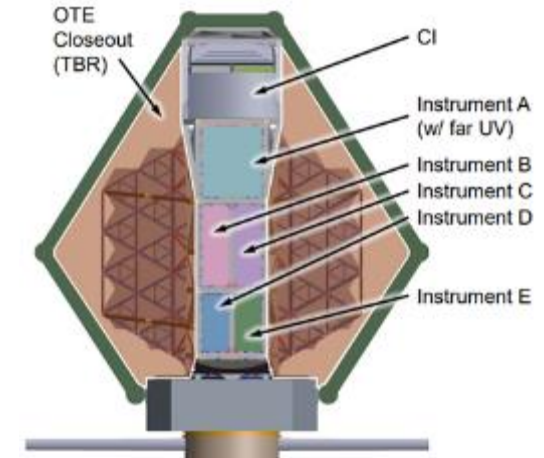


*Memory Unit (MEU)
29 Tbits of storage*

Calibration Units:

- Laser Metrology for pixel grid calibration

Total Mass Instrument 80 kg



Challenges (toward TRL5)

1. Development of a new CMOS detector with a specific **thermal-mechanical-electrical package**.

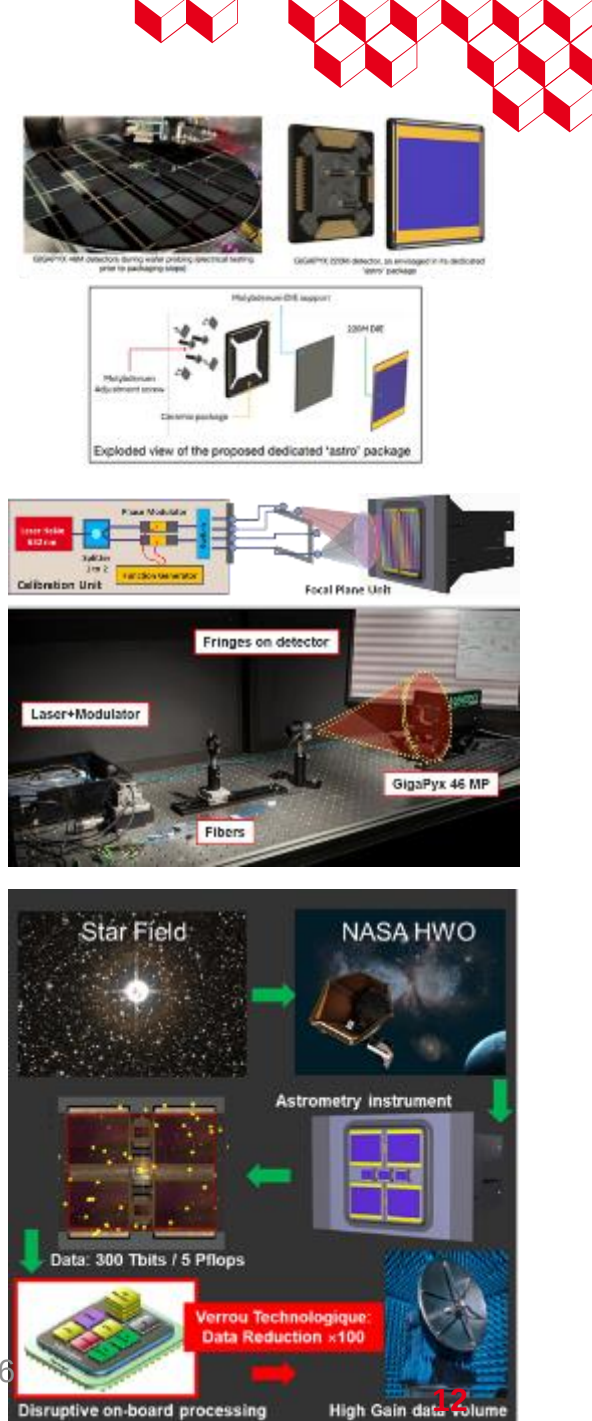
RETINA project funded (PEPR – France 2030 4 M€) for development of 220 MP format CMOS compatible with flight mission

2. **On-board Calibration** of pixel grid and **optical PSF Calibration** at 50 μ -pixel (5x10-5 pixel) level need to be validated on ground

Mitigation: development of dedicated test bench with IPAG for detector and optical effects calibration

3. **Large Volume of Data:** Gigapixel focal plane will generate data volume that cannot be downloaded to ground. Typically will require $\times 100$ in data reduction.

Mitigation: On going work for complex on-board processing implemented close to pixel

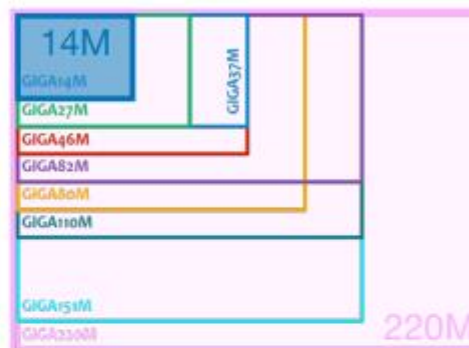


Large Format CMOS toward TRL5

Instrument for relative Astrometry Measurement

- **Baseline detector solution:**
 - 4 Pyxalis CMOS GigaPyx 220 MP
 - 3 GigaPyx 14 MP at the center
 - ~1 Gigapixel focal plane

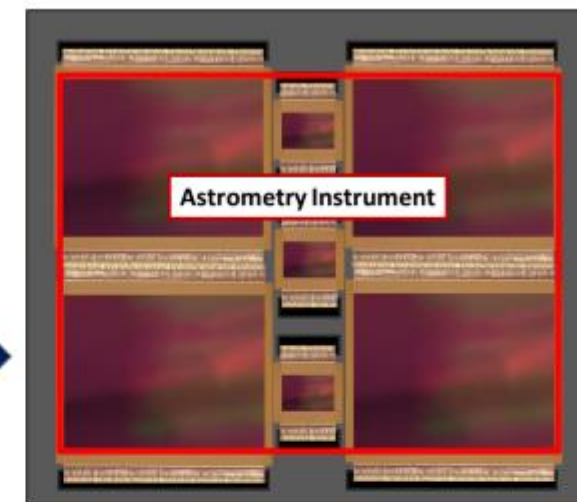
**Pyxalis GigaPyx
sensor family**



GigaPyx (220 MP)

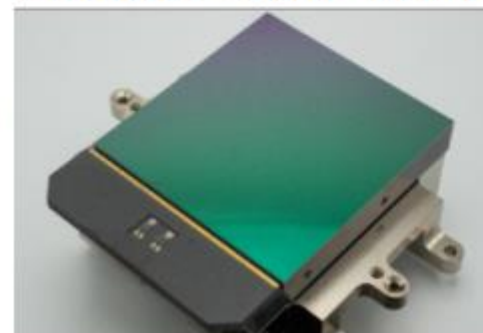


4x



- **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)



Calibration Pixel Grid

Focal Plane Calibration Error (μs)
0,310 50 $\mu\text{-pixel}$

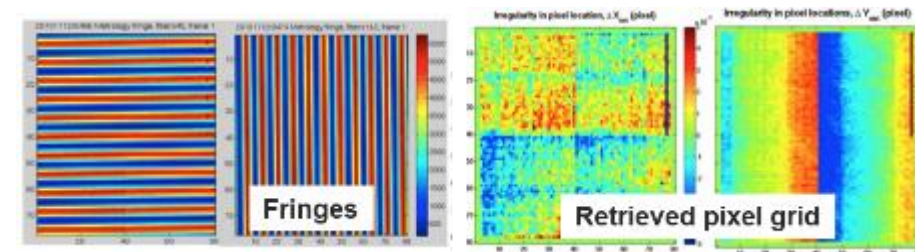
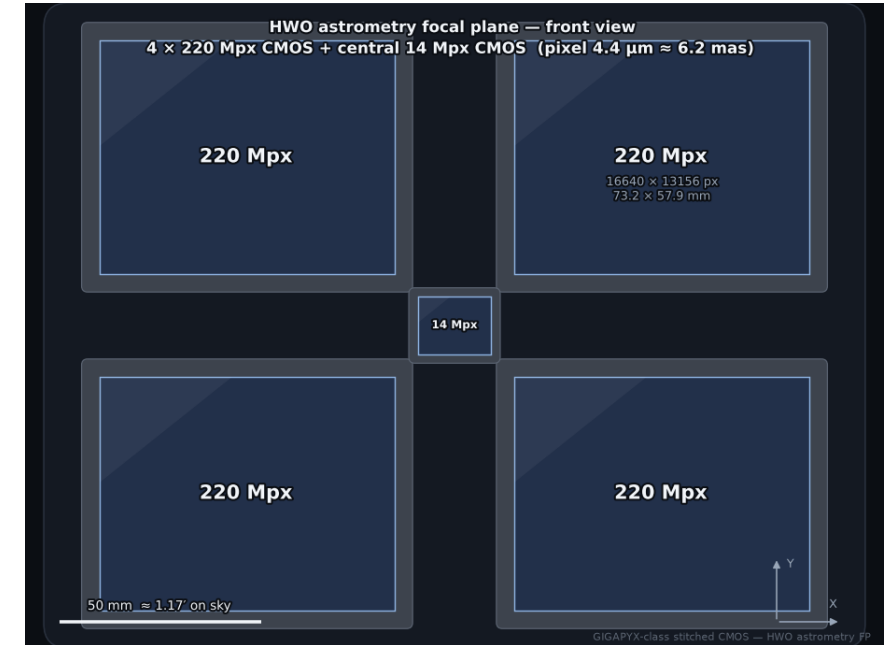
Pixel grid vary spatially (mainly due to manufacturing mask process) and need to be calibrated using an **in-flight calibration Unit**

- Project Young's fringes pattern on the focal plane from pairs of monomode fibers connected to HeNe Laser
- Based on integrated optical components largely developed for optical communication (including space communication)
- Calibrate pixel photocenter grid $\delta x(i, j)$ and $\delta y(i, j)$ offsets

Best result on ground:

- IPAG/CNES: 6×10^5 pixels (Crouzier et al. 2016)
- JPL/VESTA: 3×10^5 pixels (Shao et al. 2023)

On going work at IPAG to extend to larger focal plane and to define a reference algorithm for data processing



In Flight Calibration error budget is reached in a sequence of calibration of 1500-s

Calibration Pixel Grid

Focal Plane Calibration Error (μas)
0,310 50 $\mu\text{-pixel}$

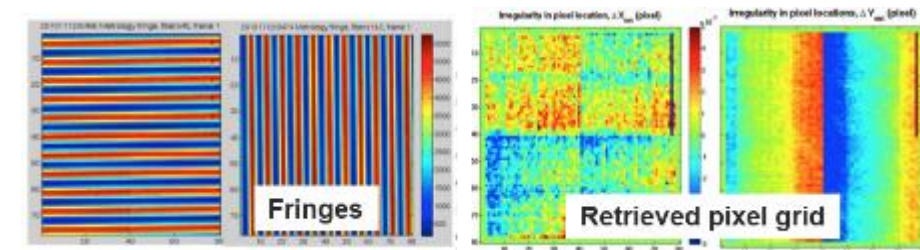
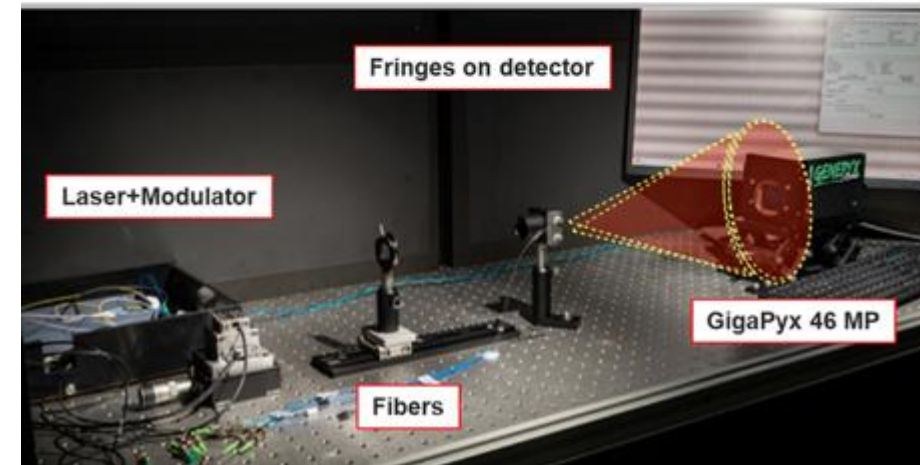
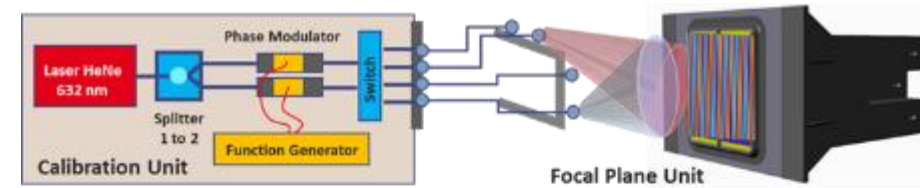
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In Flight Calibration error budget is reached in a sequence of calibration of 1500-s

Calibration Telescope Optical Grid

Telescope Calibration error (μas)
0,310 50 $\mu\text{-pixel}$

Optical Path calibration impacted by two main effects:

- Optical distortion grid
- Effective PSF (optical + intrapixel) field dependance

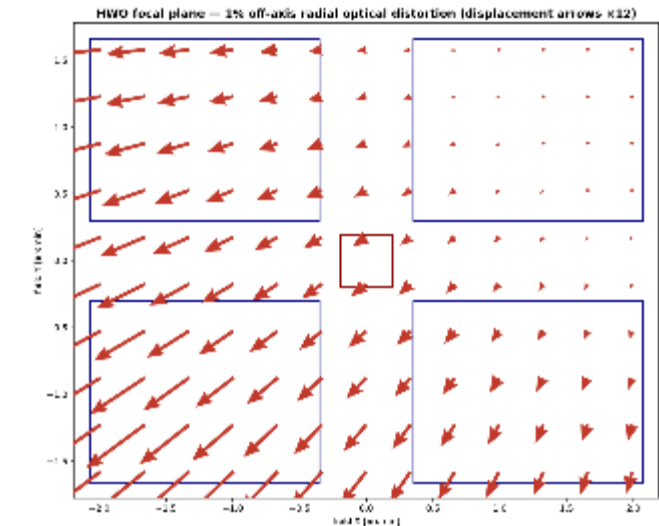
Those are leading to calibration of WFE to the **10-100 pm** level.

Calibration strategy is being developped and wait for EAC5 telescope model for simulations but benefits from HWO design and will rely on:

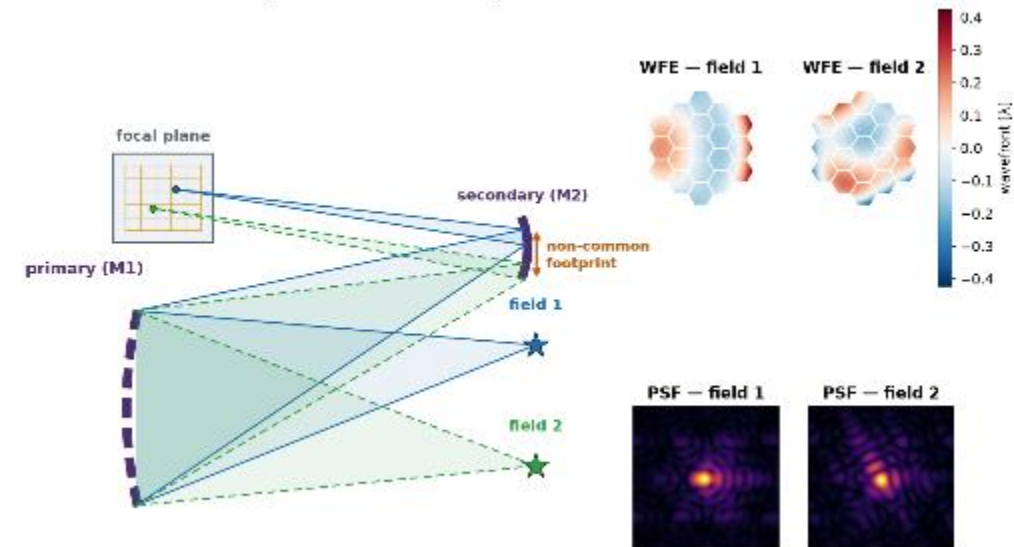
- **Mirror-only** design up to instrument: no chromatism (best telecentric)
- **High thermal stability** for all mirrors (M1-M4): <10 pm (similar to CI)
- **Dense Star field calibration** (GC) + dither for distortion and PSF model
- **Self Calibration** of in-field stars (1000's of frames, large SNR)
- Optional WFS at star location (jointly with refocusing mechanism)

Optical In Flight Calibration Allocation 10 000-s

DEDIp seminar: HWO astrometry Data Challenge



Non-Common Optical Path: two field positions see different WFE $\rightarrow$ different PSF



Calibration Telescope Optical Grid

Telescope Calibration error (μas)
0,310 50 $\mu\text{-pixel}$

Optical Path calibration impacted by two main effects:

- Optical distortion grid
- Effective PSF (optical + intrapixel) field dependance

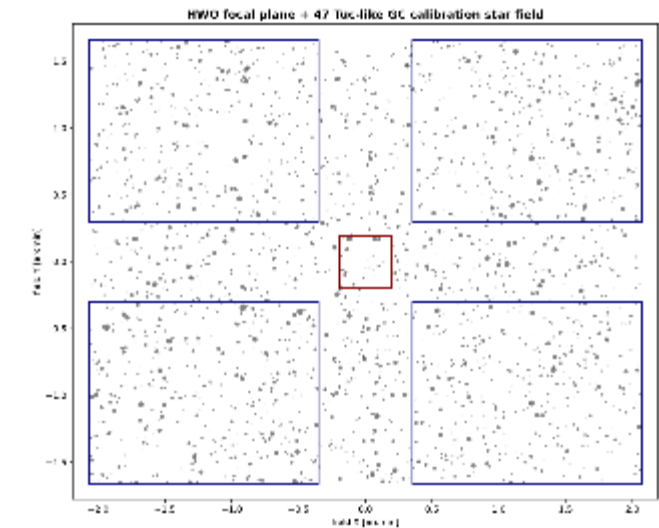
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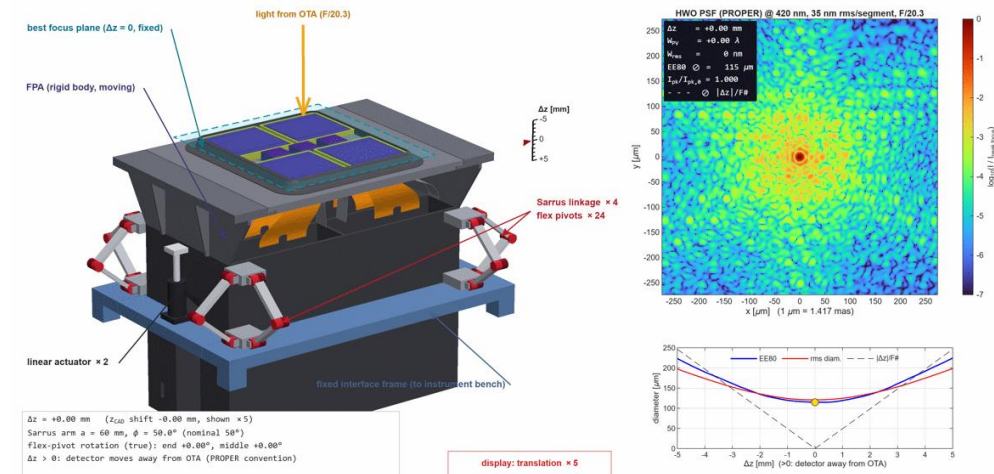
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Optical In Flight Calibration Allocation 10 000-s

DEDIp seminar: HWO astrometry Data Challenge



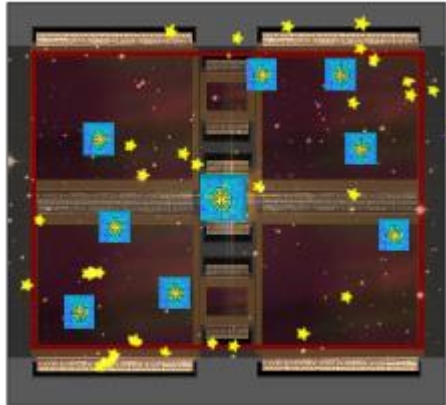
HWO focal plane - focus mechanism: Sarrus linkages with flex pivots, rigid FPA translation $\Delta z = \pm 5$ mm along the optical axis



Observation and Calibration Sequence

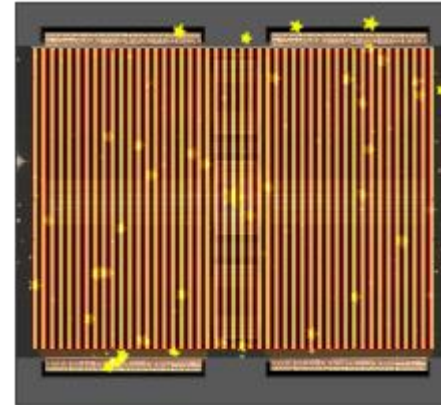
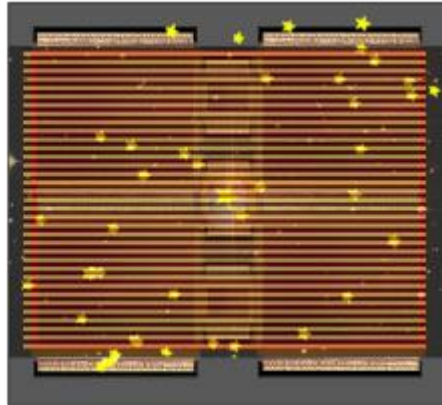
Relative Astrometric Observation of star HD100623

Science: star window extraction



GAIA DR3
HD100623
Crateris A

Calibration: Young's fringe scanning (time varying) horizontal and vertical

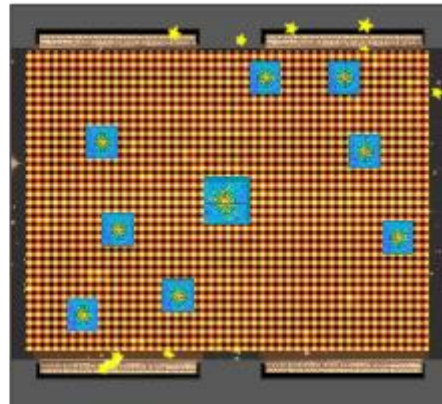


Sequence of observation:
2500-s: science data
1500-s: Calibration data
+
10 000-s Optical Calibration

200 Tbits
100 Gbits/s

250 Tbits
150 Gbits/s

GAIA DR3
HD100623
Crateris A



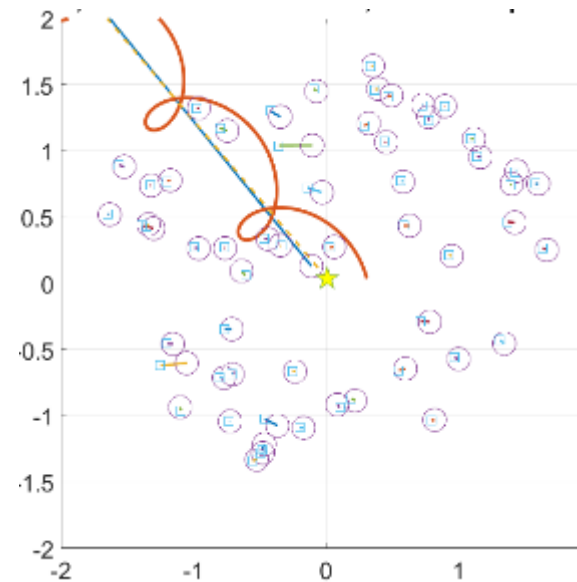
download

< 3 Tbits



On-board processing:
stars thumbnail are
referenced to optical
« interferometric accuracy »
grid

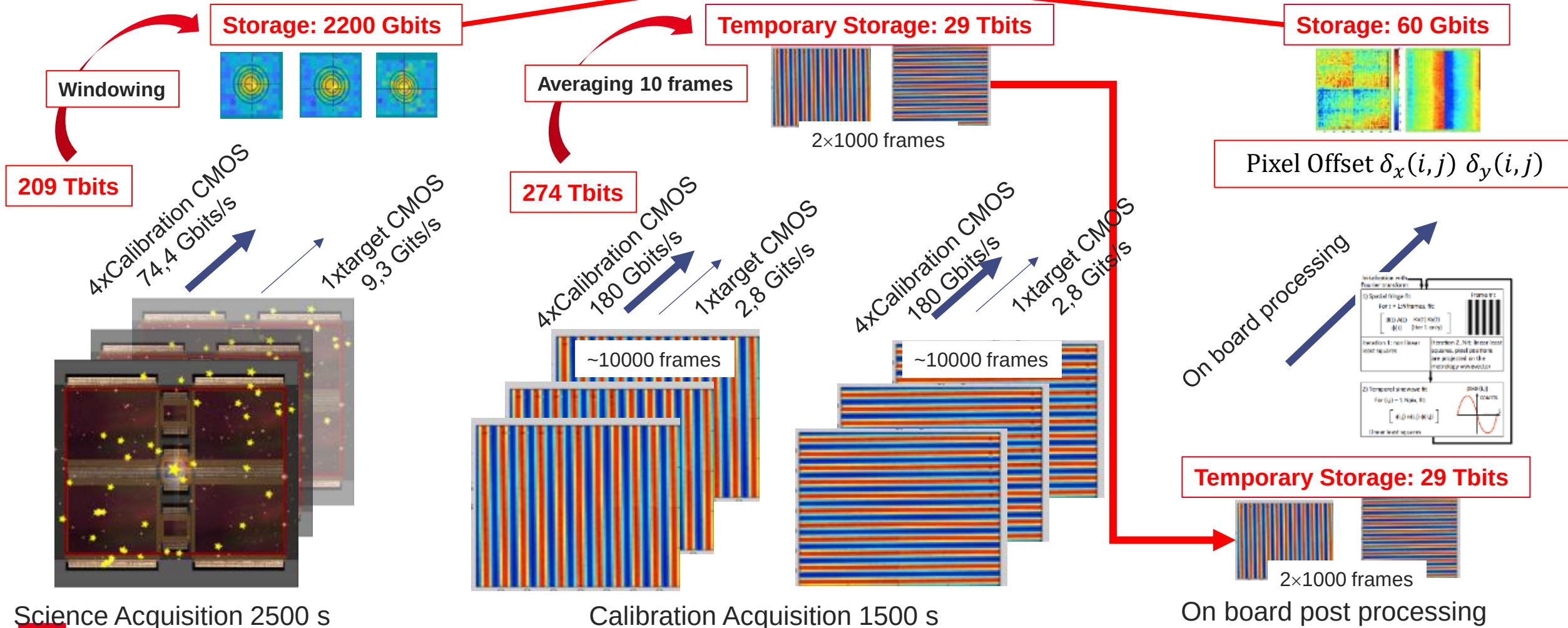
5 Pflops per observation cycle



On-ground:
From accurately referenced
relative stars astrometry,
retrieval of exoplanet-star
reflex motion

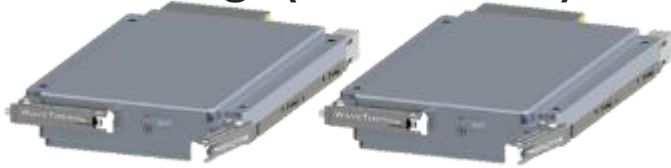
The Data Challenge

Data transmitted to HRI processing Unit: <3 Tbit per observation sequence before compression



Calibration On-board Processing

2 × RH304T (72 Tbit) MEU
storage (need 29 Tbit)



Complex Processing (5 PFLOP)
Bottlenecks:

- Computation intensive
- Large Memory Transfer (29 Tbit)
- Organization of data (spatial / temporal)



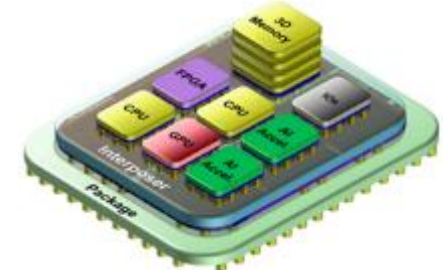
Current Architecture (TRL 5)



CPU-centric (PIC64 HPSC or GR765) +
Accelerator (FPGA)

- Serial processing by SW
- Require multiple access to mass memory of large amount of data (bottleneck)
- Can handle 5 PFLOP in 20 hours
- 200 W ⇔ 4 kWh

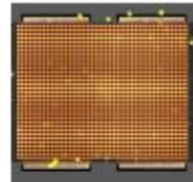
Disruptive Architecture (TRL 3)



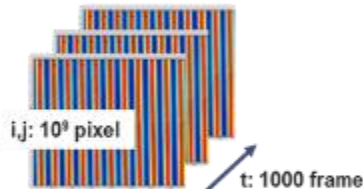
Fabric-centric (Chiplet + CGRA)

- Parallel processing in HW fabric
- Load once, compute and store locally
- Require HW/SW co-design
- Can handle 5 PFLOP in 2.5 hours
- 200 W ⇔ 0,5 kWh

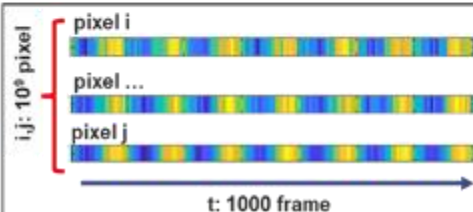
4 parameters × 10⁹ pixels
Set of images $I(i,j,t) = f(i,j) \times g(t)$
5 parameters × 1000 frames



STEP01:
Frame-major data for i=1:1000 frames
• Spatial intensity fringe fit
• [Non-linear / linear] least square



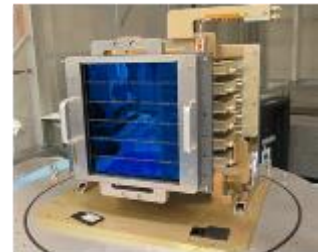
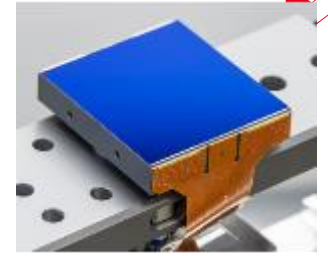
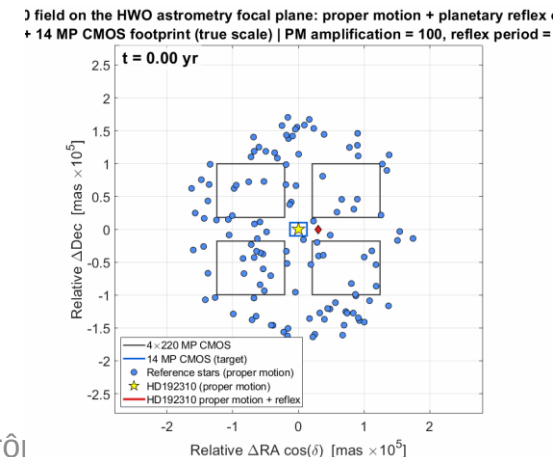
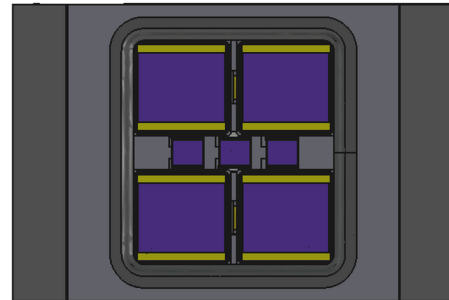
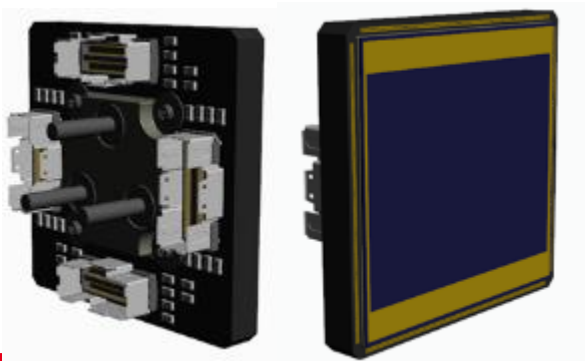
STEP02:
Pixel-time vector for (i,j)= 10⁹ pixels
• Temporal sinewave fit:
• Linear least square



Iteration × 4

Conclusion on Astrometry Instrument for HWO

- Astrometry at the level required to detect signal from Earth-like Planet is **challenging** (as is direct imaging of those planets)
- HWO is a unique opportunity to benefit from the **very large aperture – very stable environment** for Astrometry measurement
- Challenge for the 3 coming years include on board processing for large (100 Tbit) or data.
- Instrument team is relying on successful experience of building missions with NASA (JWST-MIRI) and complex large focal plane (Euclid) and preparing for larger European cooperation toward Gigapixel Astrometry Instrument AGATE



Thank you for your attention



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Project management



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