

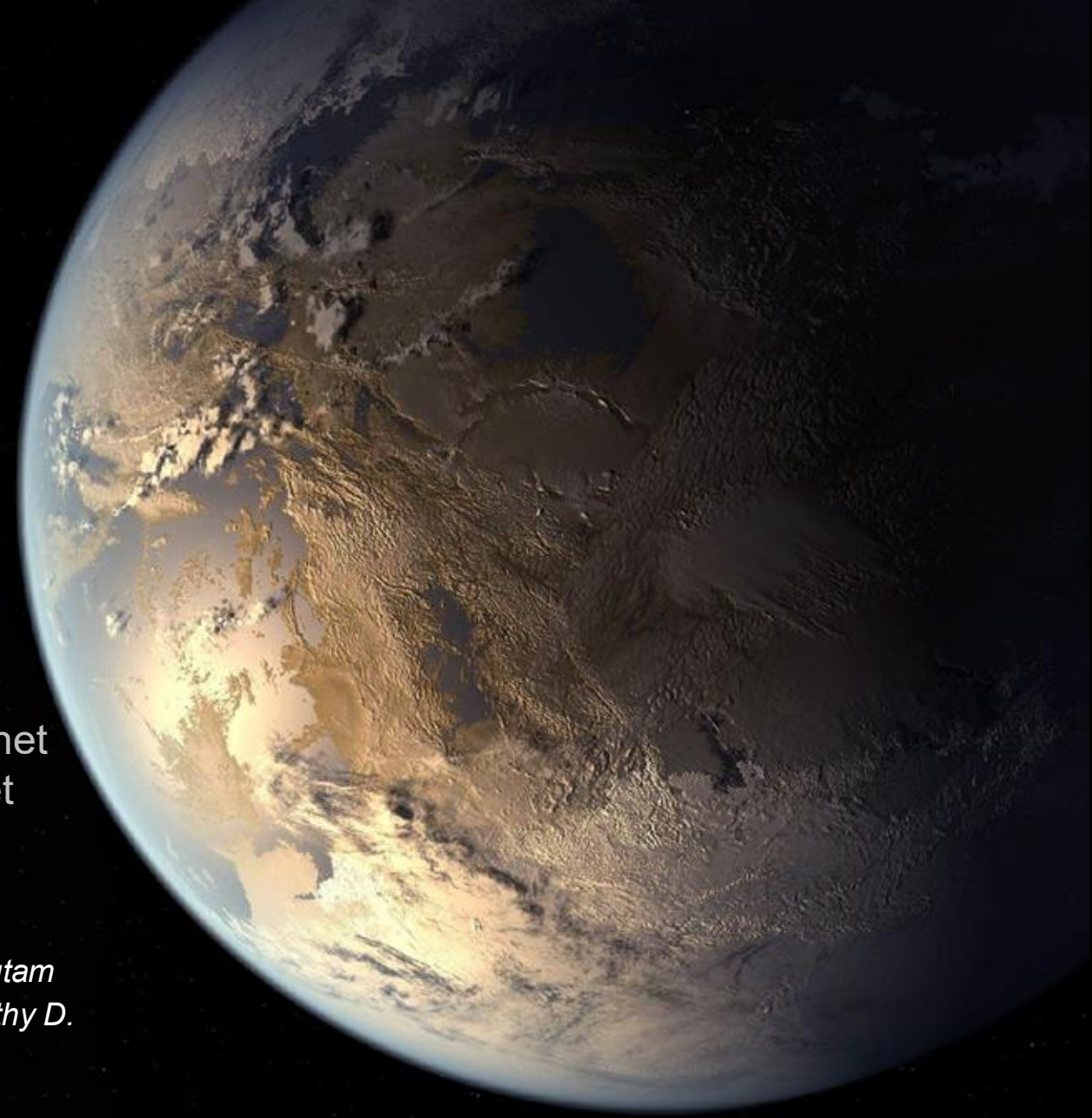
ASTRA MISSION CONCEPT

ASPECT

*Astrometric Space Probe for Exoplanet
Characterization and True-mass*

Sub-microarcsecond stellar astrometry for true exoplanet masses, complete Keplerian orbits, and the cold-planet population.

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Background & Why Now

What ASPECT is?

***ASPECT** is a probe/strategic-class space astrometry mission to detect and measure masses of exoplanets delivering a foundational a fundamental building block for exoplanet science.*

Why now

- **Measuring masses** is essential to continue advancing exoplanet science.
- **The decadal questions remain open.** Astro2020 questions E-Q1, E-Q1a, and E-Q1e are unanswered for the nearest Sun-like stars.
- **Value for HWO increases the earlier ASPECT flies.** Partial prior knowledge raises direct-imaging yield and re-phases later visits.
- **Gaia won't provide the information needed** (20 to 30 μ as, against the 0.3 μ as needed.)
- **Enabling technologies are maturing to TRL 4 to 6.** Diffractive-pupil calibration and large-format detectors



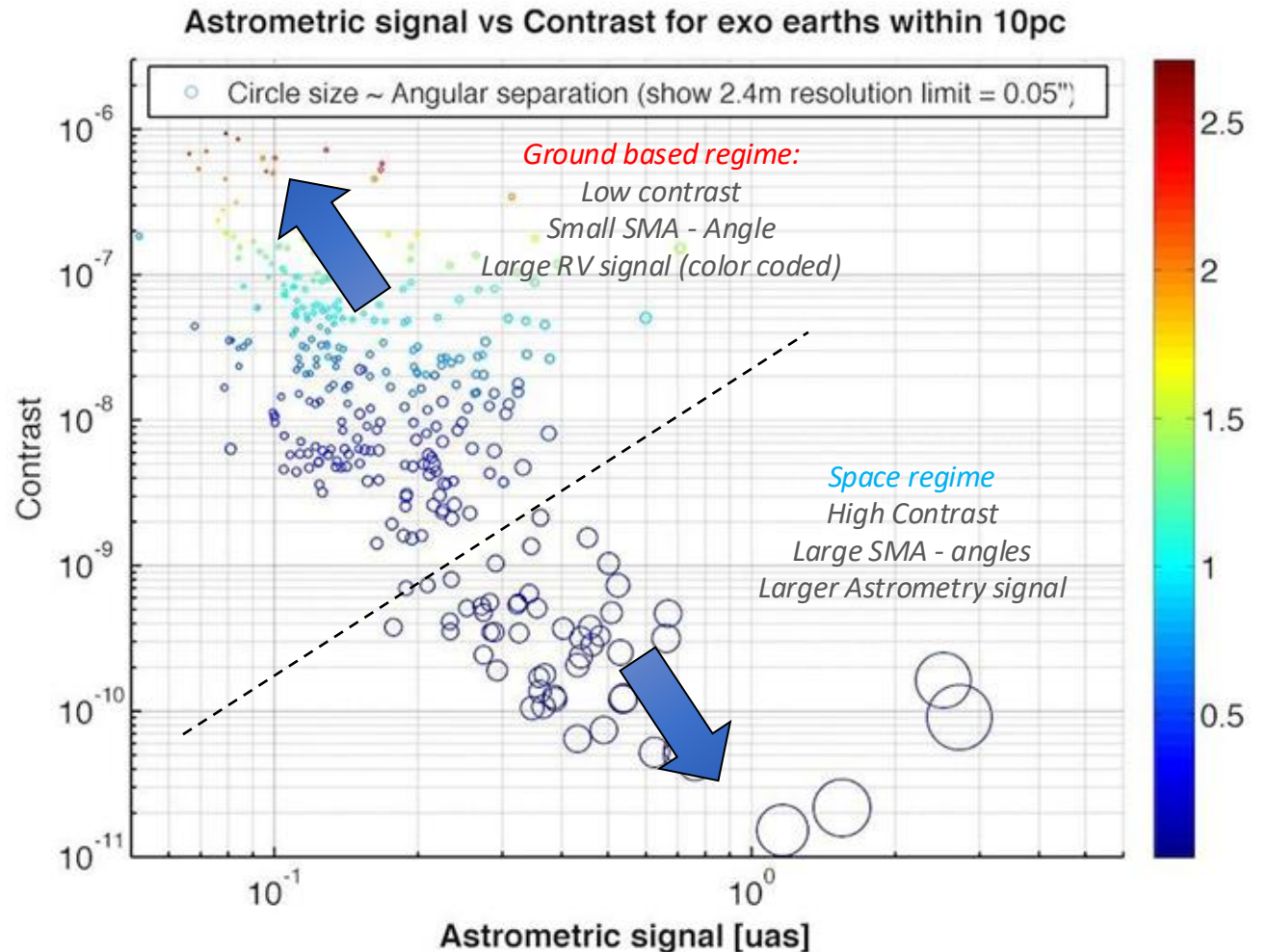
Why we do astrometry from space?

Ground based regime:

- Low contrast
- Small SMA - Angle
- Large RV signal

Space regime

- High Contrast
- Large SMA - angles
- Larger Astrometry signal



Science Cases and Astro2020 Traceability

SO-1 True masses of habitable-zone planets

- Mass sets structure, atmospheric retention, habitability
- Surface gravity prior breaks retrieval degeneracies
- Precursor catalog: Reduces blind search for HWO

Astro2020: E-Q1e; *Pathways to Habitable Worlds* priority area

SO-3 Complete Keplerian architectures

- Full orbital element set for new and known planets
- Eccentricity sets time spent outside the habitable zone
- Mutual inclinations: stability and formation history

Astro2020: E-Q1: *is the Solar System configuration common*

SO-2 Cold and long-period demographics

- Signal grows with separation; inverse of RV and transit
- Temperate to ice line: least explored regime unreachable now
- Tests the role of the snow line in formation

Astro2020: E-Q1a, supporting E-Q1

SO-4 Cepheid parallaxes for the Hubble constant

- Parallax zero point limits the anchor rung
- Bright calibrators: Gaia saturation-limited
- Geometric; independent of the photometric chain

Astro2020: Panel on Cosmology, Hubble tension; secondary objective

Science Table

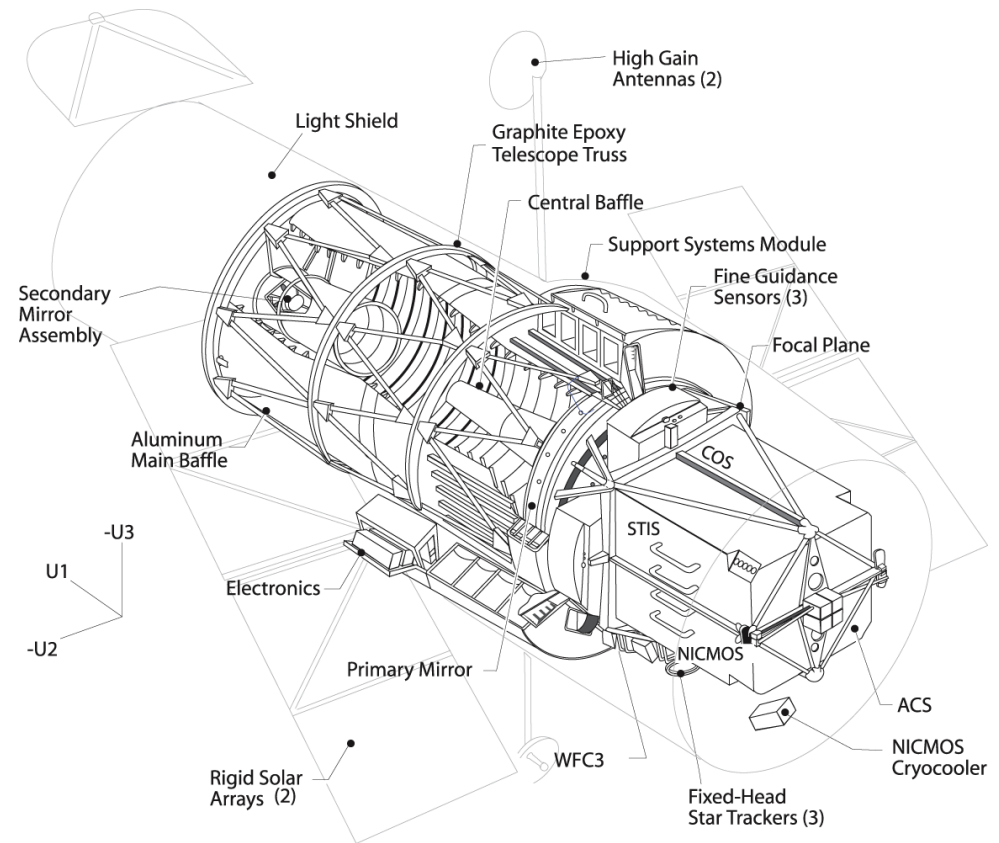
Science Objective	Astro2020	Physical Parameters	Observables and performance	Challenges
<i>SO-1 Earth analogs masses; HWO and LIFE precursor catalog</i>	E-Q1e	Planet mass (5σ); inclination; semi-major axis; phase at HWO epoch	$\alpha = 0.3 \mu\text{as}$ for Earth analog, 10 pc, 5σ $0.2 \mu\text{as} \Rightarrow 0.03 \mu\text{as}$ for 50 epochs 100 to 200 FGK dwarfs within 20 pc	Time-variable distortion, detector calibration. Photocenter jitter 0.1 to 1 μas Catalog fraction at HWO start
<i>SO-2 Temperate and colder demographics</i>	E-Q1a, with E-Q1	Occurrence rate; semi-major axis and mass distribution	1 - 3.6 AU; 3 AU at 5 yr, 3.6 AU at 7 yr Wider companions as accelerations on the 20-year Gaia arc available	Period coverage set by baseline completeness versus separation
<i>SO-3 Complete Keplerian orbits</i>	E-Q1	Full orbital parameters; siblings mutual inclinations	Orbit fits over 30 to 100 epochs Multi-planet solutions Combined radial-velocity and astrometric	Phase-coverage degeneracies Radial-velocity activity floors Ground-campaign scheduling
<i>SO-4 Cepheid parallaxes</i>	Panel on Cosmology; secondary	Absolute parallax; distance; period-luminosity ZP	0.2 μas or better Visual magnitude 4 to 12 Tie to the ICRF-linked frame	Point-spread-function wings Crowded low-latitude fields Transfer to the extragalactic rung

Single-epoch accuracy: Guyon et al. 2012. Occurrence rates: Bergsten et al. 2022. Jitter: Makarov et al. 2010.

Why a probe-Class (\$1.0–1.5 B)

Why ASPECT is proposed as Probe and not Explorer or PI-class mission:

- **Strategic science return:** a foundational, community-wide true-mass and orbit catalog answering fundamental exoplanet questions and supporting HWO and LIFE beyond the reach of smaller
- **Probe-grade payload & data system:** 2.0 m TMA, $0.3^\circ \times 0.3^\circ$, Nyquist sampled $\sim 42,000$ pix/side $\Rightarrow 1.75$ Gpix, and a sub- μ s centroiding.
- **Sub- μ s per-epoch accuracy ($\lesssim 1 \mu$ s)** 0.2μ s, $\sim 100\times$ better than Gaia's 20–30 μ s bright-star floor requires a dedicated, thermally stable L2 platform.
- **In-situ, targeted distortion metrology** (diffractive pupil + detector calibration) drives a bespoke optics/detector subsystem rather than heritage instruments.
- **Dedicated 5-yr (goal 7 yr) survey at L2** of ~ 100 – 200 FGK dwarfs at ~ 50 Fisher-information-optimized epochs each, with an ICRF3 reference-frame tie.



Sketch of the Hubble Space Telescope as proxy for a future ASPECT: Adapted from Space Telescope Science Institute

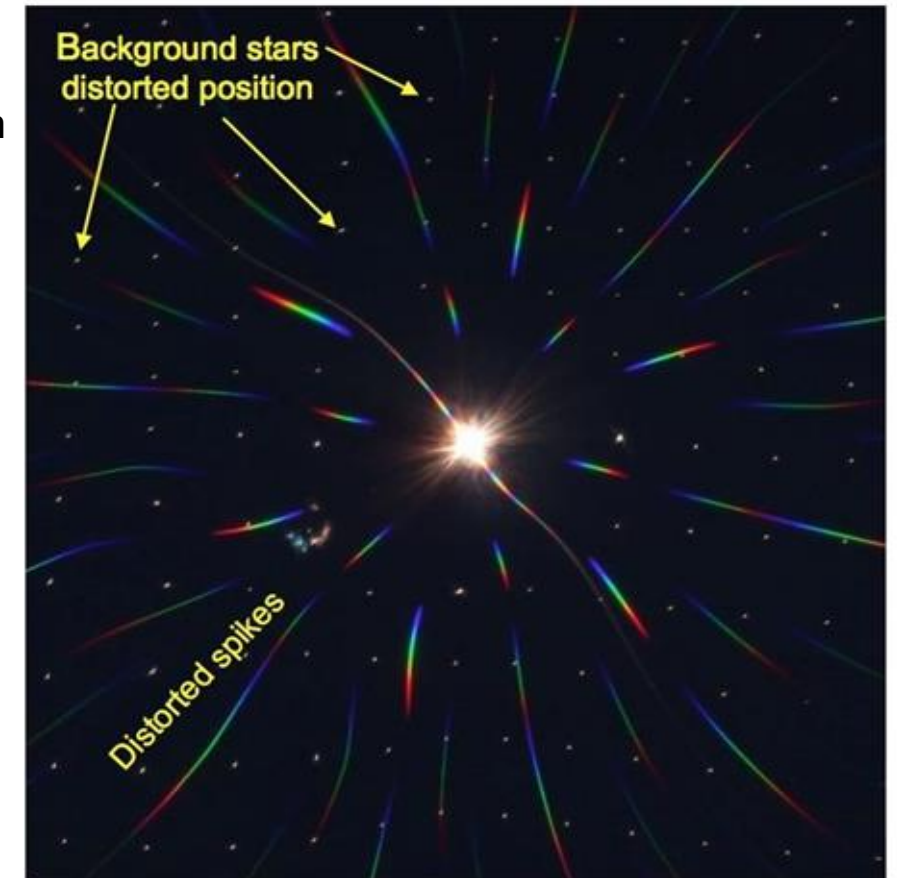
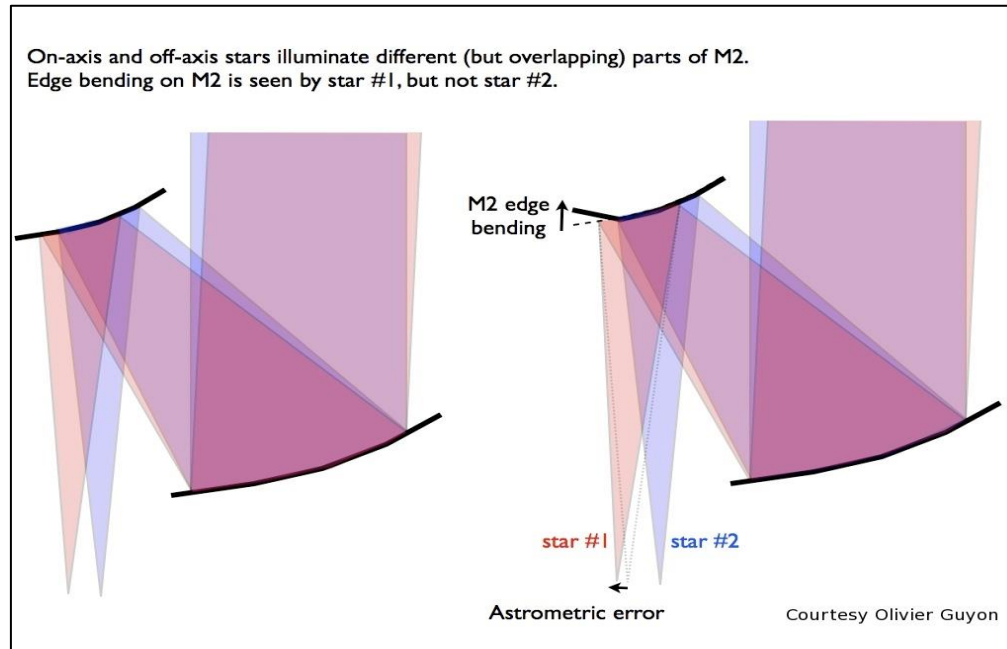
Challenges (Some of them)

- **Stellar photocenter jitter.** Spots, granulation and magnetic-cycle variability and chromaticity together with stellar companions perturb the apparent stellar centroid at the sub- μ as level. => Need larger FoV to get more background stars to average noise.
- **Sub- μ as distortion stability.** A $1e-5$ pixel calibration needed; thermal, radiation-induced and quasi-static wavefront errors must be calibrated in situ.
- **Detector Calibration.** While the Diffractive Pupil is capable of calibrating pixel errors of bkg stars by rolling the telescope. A properly calibrated detector simplifies observations and improves performance for faint fields science case.
- **Systematics-limited sensitivity.** Covariance from correlated residuals (distortion, activity, photocenter) sets the floor, not white-noise averaging; ~ 30 – 100 epochs required.

Key technology –Diffractive Pupil Calibration

Dynamic distortions is one of the key limitations for high-precision astrometry

- Causes local plate scale changes
- Bias the astrometric measurements
- Impact on multi-epoch astrometry
- A solution is to use dots on the primary to generate a diffraction pattern

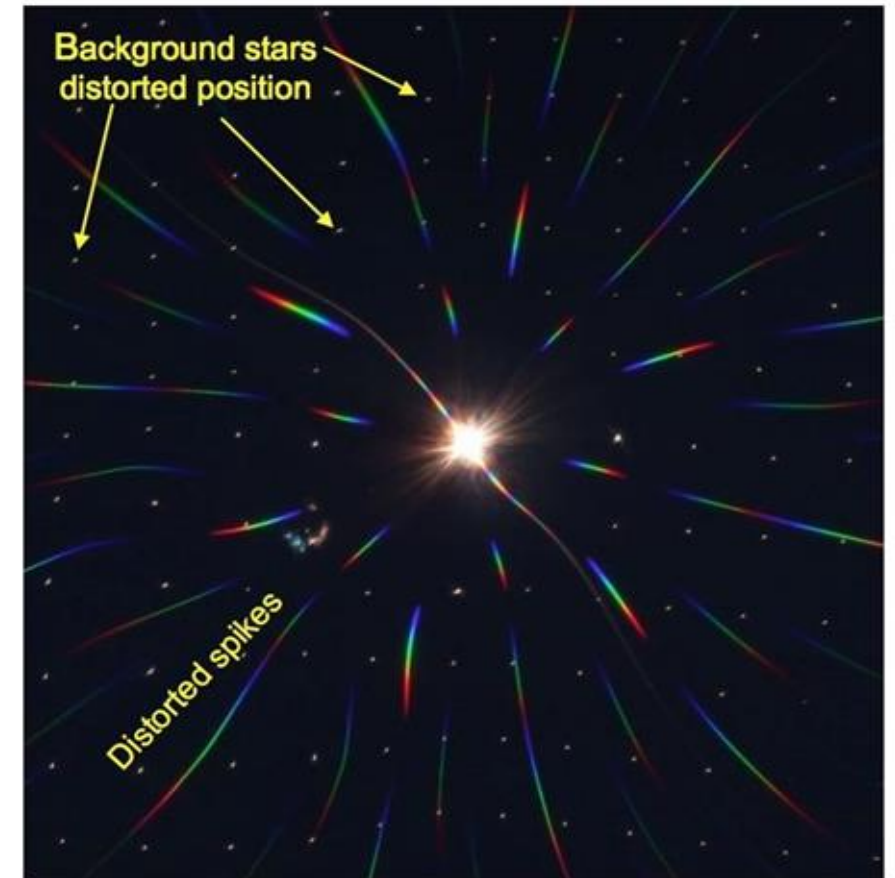


Distortion and the use of a diffractive pupil to calibrate it.

Key technology –Diffractive Pupil Calibration

Dynamic distortions is one of the key limitations for high-precision astrometry

- **Calibrates optical system** distortions end-to-end relaxing telescope stability requirements
- **Averages detector errors** by spreading the target light on $\sim 100,000$ px where the spikes are imaged.
- **Solves the target/background dynamic** range (typically 7-10 mag) by spreading the target light on the spikes
- Detector error of background stars is averaged rolling the telescope around its boresight
- Delivers low-resolution stellar spectrum



Distortion and the use of a diffractive pupil to calibrate it.

Key technology –Diffraction Pupil Calibration

Dynamic distortions is one of the key limitations for high-precision astrometry

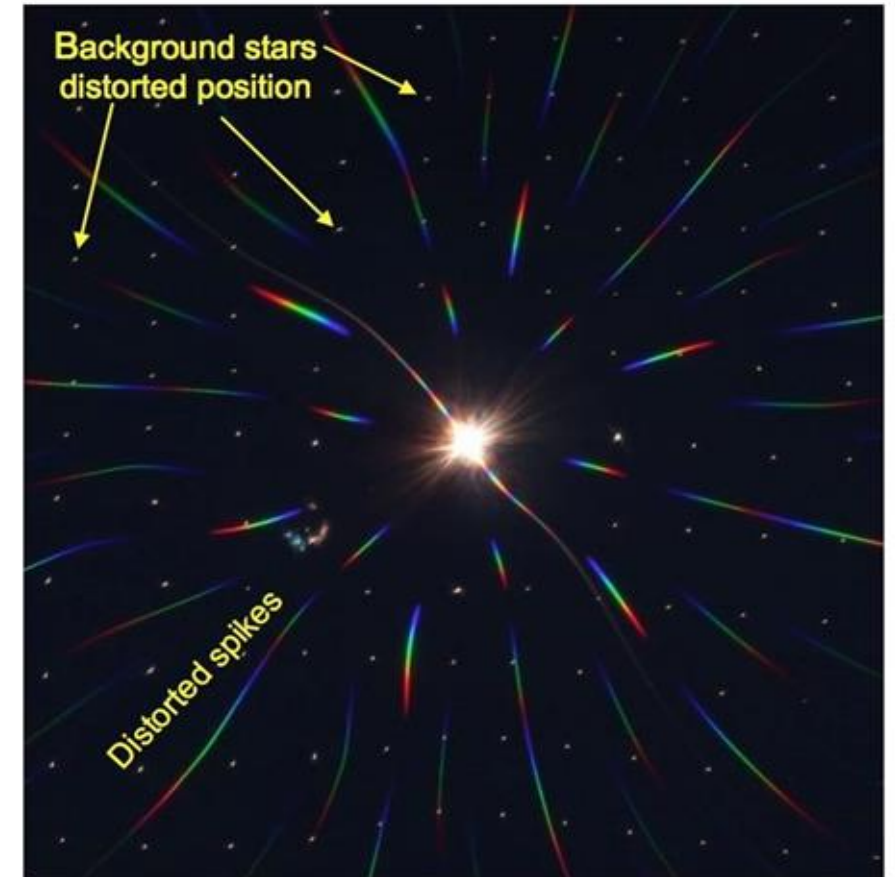
Opportunity delivered by NASA investments

- NASA has funded the maturation of technology from TRL-2 to TRL-5
- (APRA09, NPP12, SAT13, APRA17)
- Now it is ready to deliver results.

Demonstrated laboratory performance:

- **$1.58e-5 \lambda/D$ (equivalent $0.3 \mu\text{as}$ single-epoch on HWO)**
- In vacuum without performing detector calibration
- Over very large FoV >1 deg

(Bendek et al. SPIE Proc. 2023)



Distortion and the use of a diffractive pupil to calibrate it.

Mission implementation and trades

- **Aperture vs FoV:** only if the FoV is constant.
Engineering limitations forces to reduce FoV as D increases.
- **Stellar magnitude bin vs FoV:**
To get more photons from background stars from larger FoV or deeper magnitude.
- **Mission duration:**
Increases target epochs, reduce the end-of-mission error, better orbital sampling.
- **Multiple incoherent apertures vs one large aperture:**
In era of constellations incoherent proliferation might be interesting.
Strongly dependent on telescope and S/C cost scaling
Systematics are critical

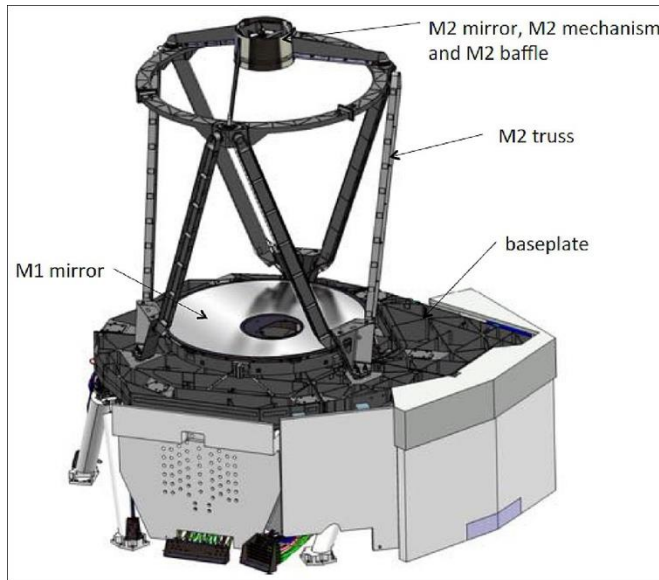
$$N = \left(\frac{D}{d}\right)^4$$

$$\frac{C_{\text{fleet}}}{C_{\text{mono}}} = \left(\frac{D}{d}\right)^{4-\alpha}$$

Mission implementation and trades

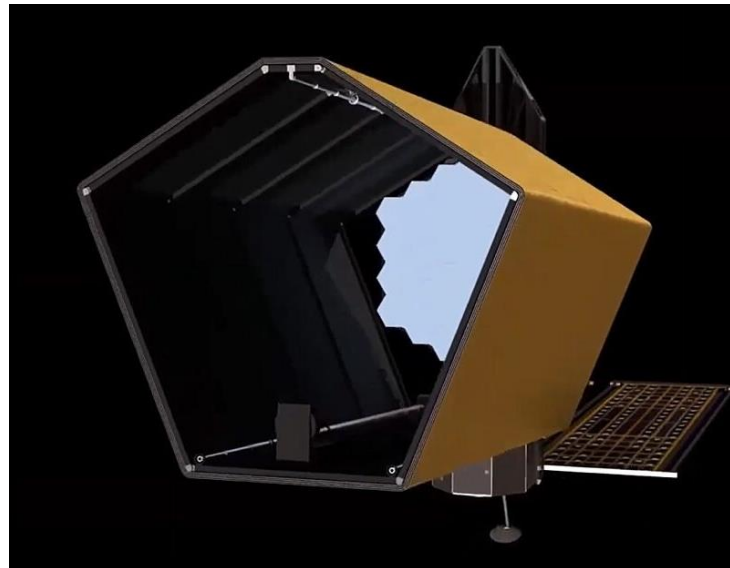
Why a **single aperture stand-alone probe**? Instead of an **Astrometry instrument on HWO** or **flight formation interferometer (SIM-lite like)**

Dedicated Probe Mission



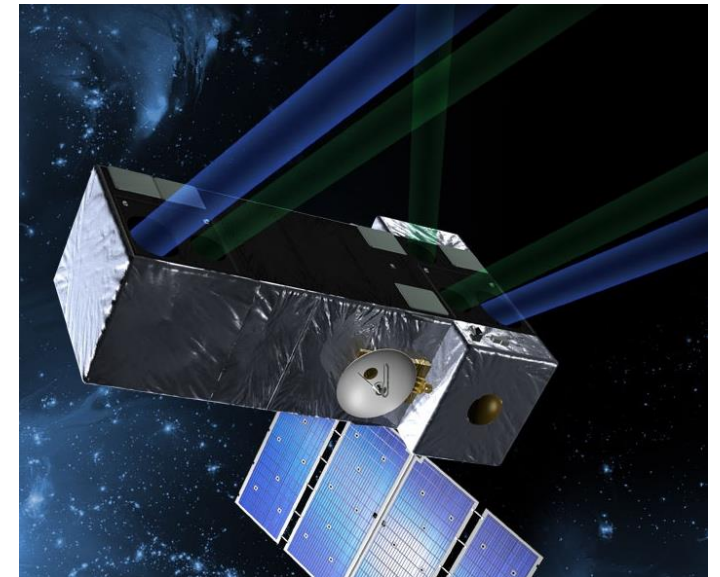
Euclid Mission Space Telescope.
Photo: ©ESA

HWO Astrometry HRI



Artistic concept of HWO Courtesy: NASA

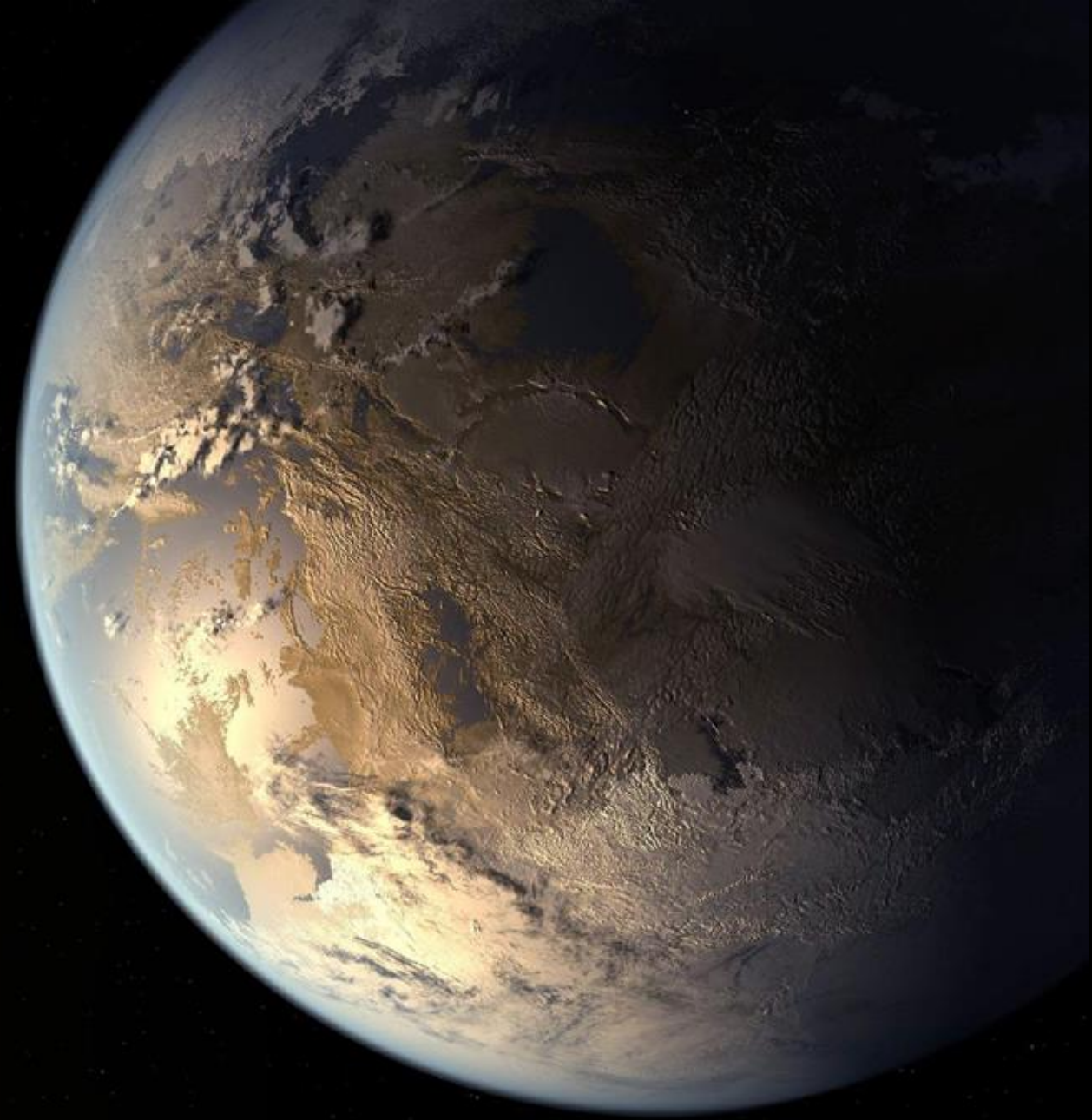
Interferometric Astrometry



Artistic concept of SIM-Lite. Adapted from:
PlanetQuest. NASA/ Jet Propulsion
Laboratory

Conclusion

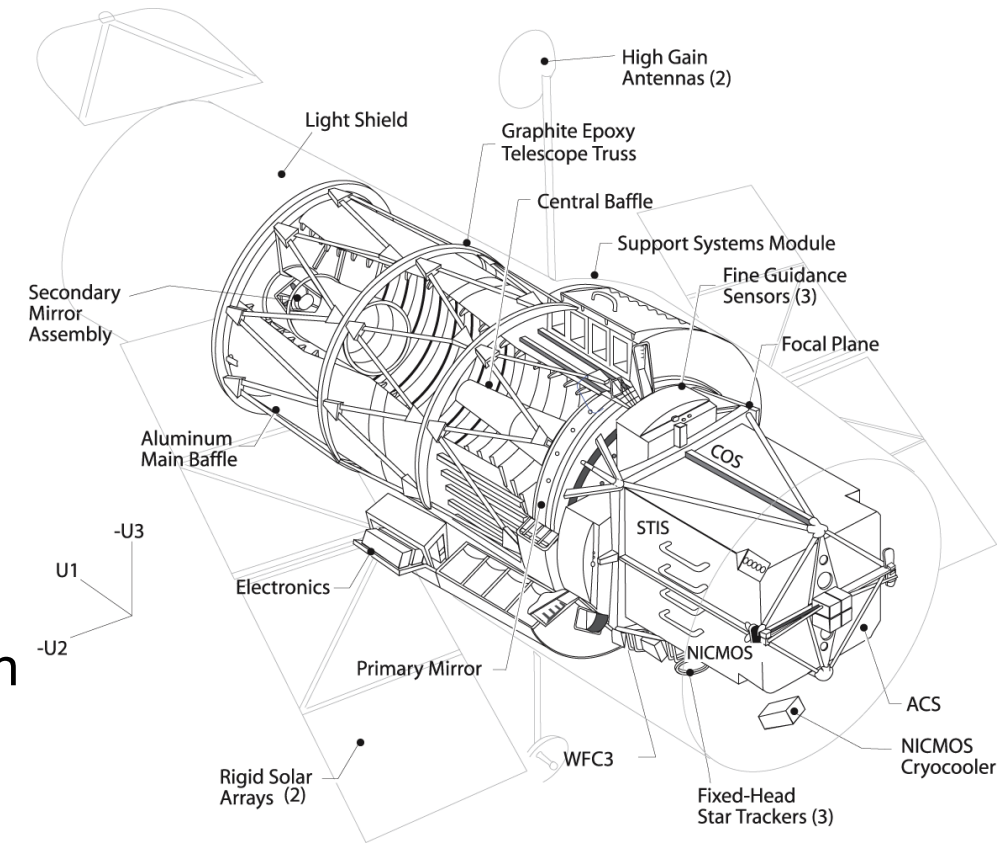
- **ASPECT delivers** inclination-free true masses, complete Keplerian orbits, and the cold-planet demographic regime — the astrometric foundation for HWO and LIFE.
- **Heritage & enabling tech:** builds on NEAT, Theia and MAP; enabled by diffractive-pupil calibration maturing to TRL 4–6.
- **Open mission concept.** Calibration architecture, target sample, cadence and detector choices are live community trades; new team members are welcome (ExoPAG / CoPAG).
- **Path:** Continue advancing mission fidelity, explore trades add collaborate closely with HWO to explore the parameter space to find the best solution for NASA. Constantly adding community members interested in helping.



Point design

We envision a single-aperture probe telescope, trades will be carried out

- **Primary mirror:** 2.0 m aperture
- **Architecture:** Off-axis TMA (on-axis trade)
- **Field of view:** $0.3^\circ \times 0.3^\circ$ (square)
- **Focal ratio:** f/15 (FL=30 m)
- **Plate scale:** 25.8 mas/px (Nyquist at 500 nm)
- **Focal-plane** ~42,000 pix/side (1.75 Gpix)
- **Detector:** Similar to IMX411 sCMOS (3.76 μm)
- **Calibration:** Diffractive Pupil + optional metrology
- **Precision:** 0.21 μas (2.0 m, 0.3deg), single-epoch
- **Orbit:** Sun–Earth L2 halo
- **Mission duration:** 5 yr nominal + 2 yr extension
- **Target sample:** ~100–200 FGK dwarfs within 20 pc



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Notional Expected Science Yield for 2-meter Point Design

Sample: 100 to 200 FGK dwarfs within 20 pc. 0.2 μ as per epoch, about 50 epochs, 5-year nominal plus 2-year extension.

Science output	Expected yield	Basis
Habitable-zone terrestrial candidates	10 to 30	Earth-analog occurrence 15 percent for FGK hosts
Total Earth-to-Neptune detections	50 to 100	Occurrence tens of percent at wider separations
Complete Keplerian orbits	Most detections with period under 7 years	Five elements per system; mutual inclinations in multiples
True masses of known radial-velocity and transit planets	Most planets on the target list	Sine-of-inclination ambiguity removed
Wide companions beyond 3.6 AU	Accelerations, no closed orbit	20-year proper-motion arc against Gaia
Cepheid parallaxes for the Hubble constant	0.2 μ as or better, visual magnitude 4 to 12	Bright regime where Gaia is saturation-limited

NOTES:
Order-of-magnitude forecast. A completeness simulation is planned for the next phase
Occurrence rates: Bergsten et al. 2022. Single-epoch accuracy: Guyon et al. 2012. Prior-knowledge yield gain: Morgan et al. 2021.