TOLIMAN JNEXT

Jet Propulsion Laboratory
California Institute of Technology

Searching for earth analogs around the nearest star system

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NASA Ames/SETI Institute/JPL-Caltech

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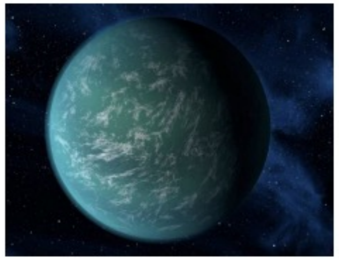
Exoplanet Exploration Strategy

MOTIVATED BY NASA ASTROPHYSICS ROADMAPS

Priority Area: Pathways to Habitable Worlds

We are on a path to exploring worlds resembling Earth and answering the question: "Are we alone?" The task for the next decades will be finding the easiest of such planets to characterize, and then studying them in detail, searching for signatures of life.



Astrophysics Decadal Survey (2020)

Specific tasks:
1) Finding the easiest targets to characterize and study Earth analogs in detail.

How?
List of best stars to study Earth analogs
- *Distance*
- *Stellar type*

Then, search for planets around those stars

Specific tasks:
2) Then study them in detail searching for signatures of life.

Key parameter harder to measure by UV/O/IR mission:
- *Mass determination*

Why measure masses?
- Distinguish terrestrial rocky planets from giant planets
- Determine system inclination, confirm RV.
- Facilitate retrieval of atmospheres' chemical species
- Need to complete the "extrapolation region"
- HabEx, LUVOIR, and Starshade have limited ability to infer masses

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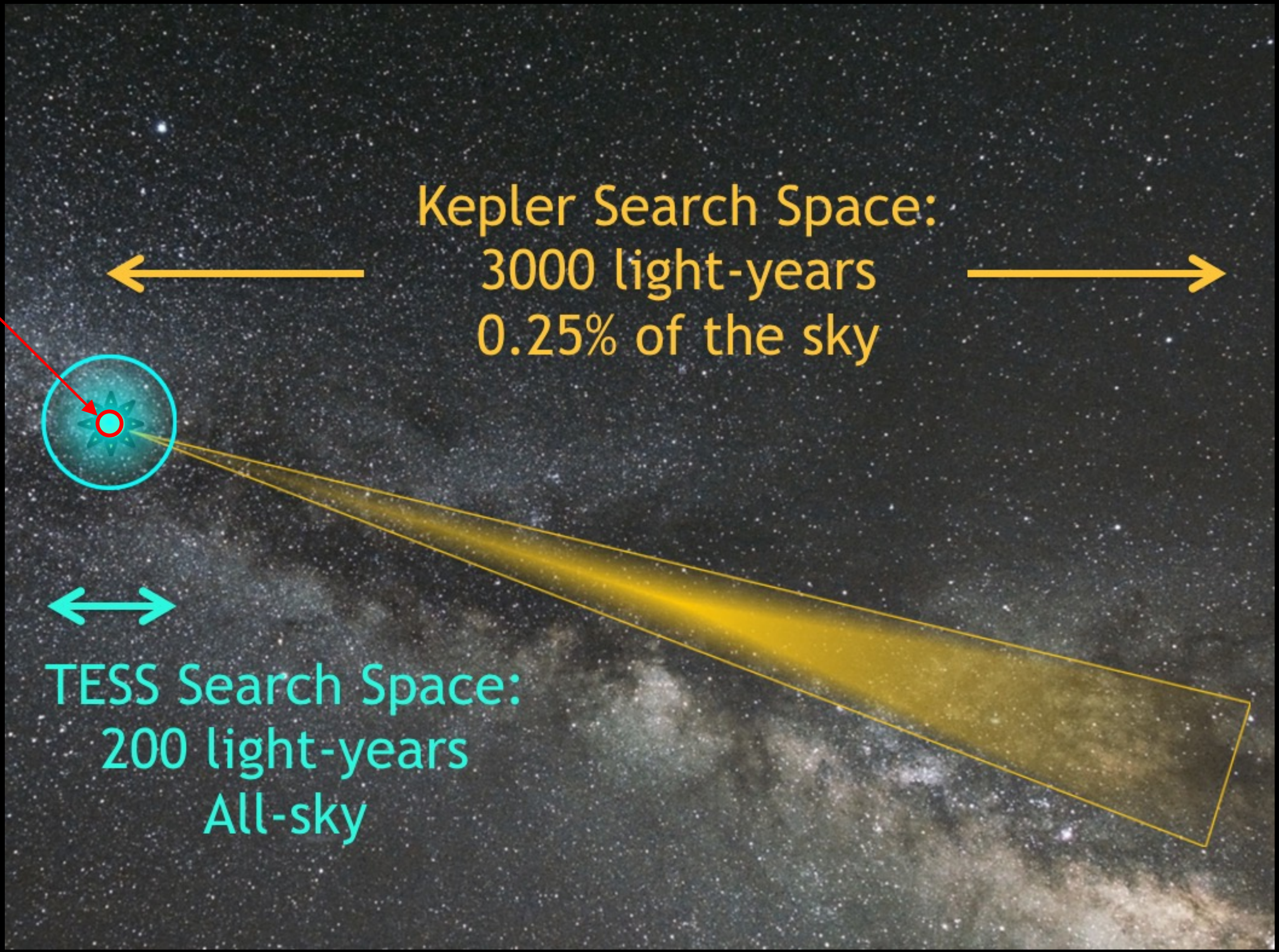
From demographics to habitability studies

10 pc Sphere



The TESS search space compared to that of the Kepler Mission. Image Credit: Zach Berta-Thompson

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1) Finding the easiest targets

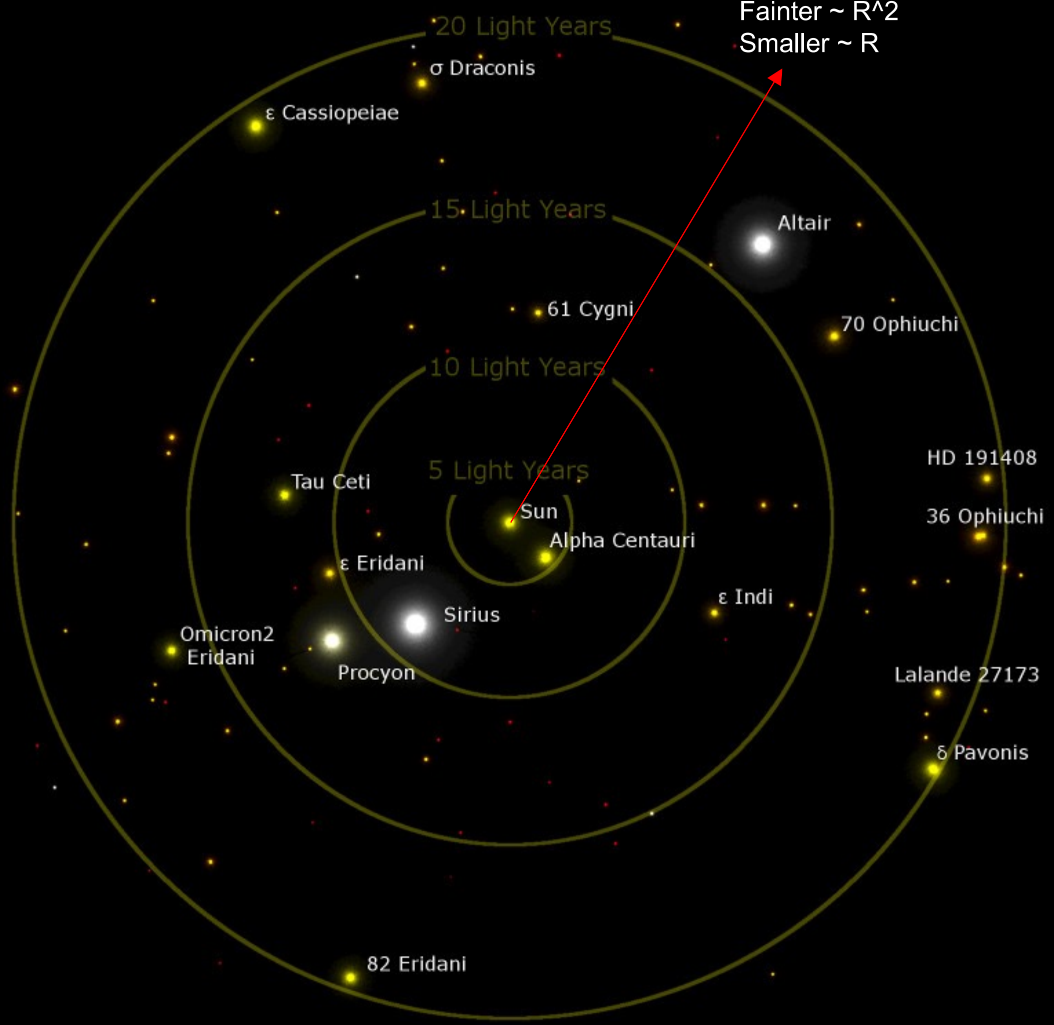
Our stellar neighborhood, few targets, each one is valuable

- Only 67 sun-like stars are within 10 pc radius, 41 of those are binary systems => We cannot ignore binaries

- *Alpha Centauri A & B* is three times closer than the next sun analog *Tau Ceti.* Planets around αCen A&B are:
  ~9x brighter
  ~3x greater resolution
  than around next Sun analog, Tau Ceti

Observing an earth analog at 10 pc with a 6 m UV/O/IR is equivalent to observe aCen A&B with a 0.6 m aperture small sat

- Time critical because informs the design of an exoplanet flagship (Kepler, GAIA, TESS, cannot observe aCen A&B)



"Alpha Centauri system, if not for the fact that it is a binary, would easily be the best target for direct imaging searches for planets"
--HabEx Final report

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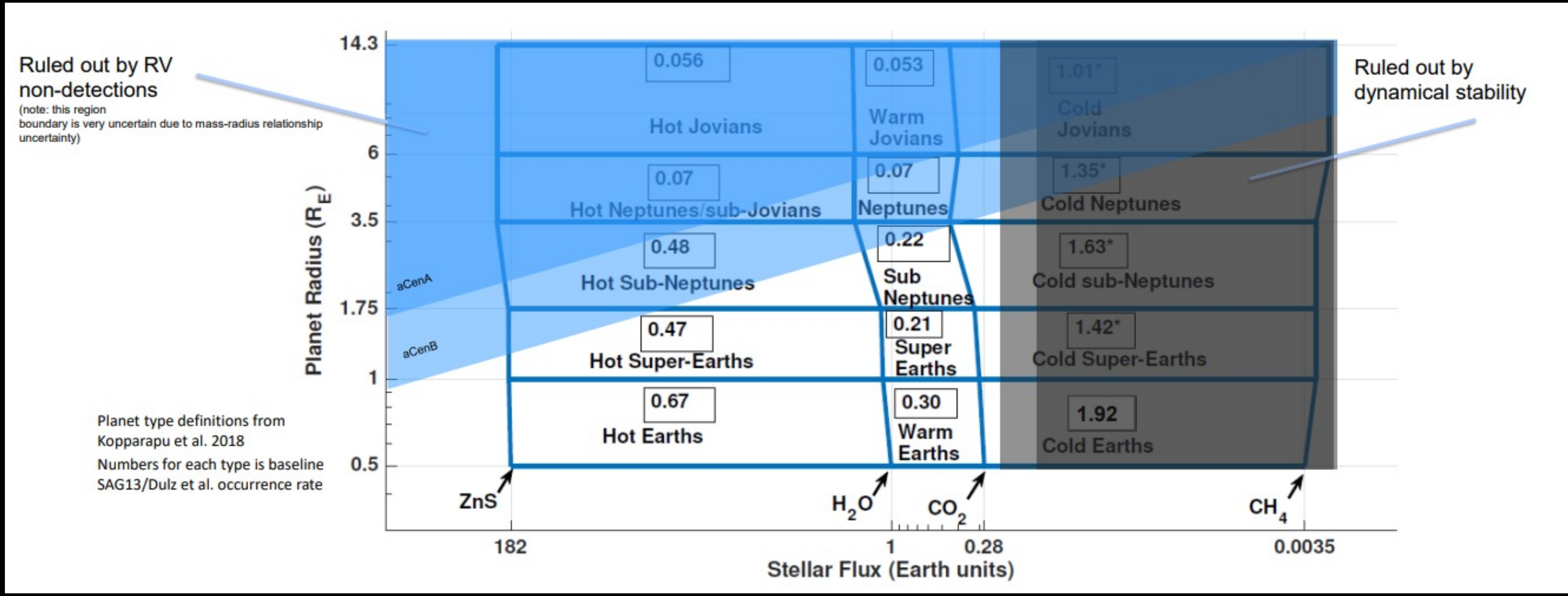
aCen A&B state-of-the-art

Binarity and stellar noise limits instrumentation sensitivity to detect earth-analogs around the best target!

- Stability limits allows planets beyond the H.Z.
- *R.V. limits have ruled out Neptunes or larger planets*
- *Earth analogs remain possible (and likely) around both stars*

There is a knowledge gap of the entire H.Z. of aCen A&B because instrumental limitations



Belikov et. al, 2022 SAG13 update at (Exoplanets IV)

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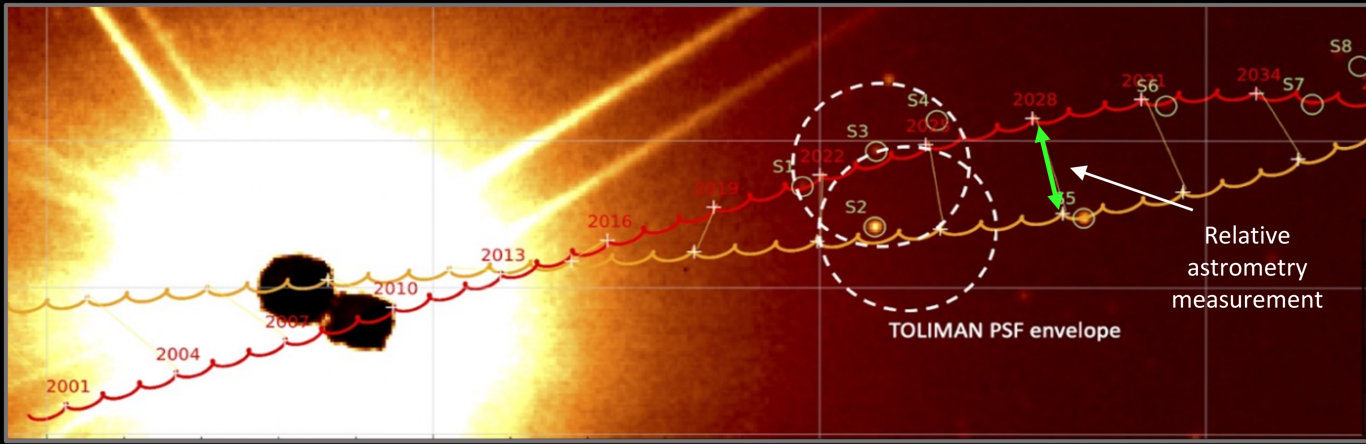
Using the binarity as a solution

This concept uses relative astrometry between binaries to detect planets and measure their masses

Challenge: The signal is ~ 1 uas, optical distortion term dominates. State-of-the-art is about 25 times less accurate (Hubble, GAIA, Gravity ~ 25 uas)



Star	V
S1	20.0
S2	15.7
S3	19.7
S4	16.2

Image of the αCen A&B field taken from the ESO's NTT 4.0m
Courtesy: P. Kervella.

Opportunity that αCen A&B offers:

- ***Proximity:** An Earth analog around aCen A&B will exhibit the **highest astrometric signal possible** of ~3μas*
- ***Brightness:** A 9cm aperture collects enough photons from αCen A&B to reach 1μas photon noise in 6hrs!*

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What limits the astrometric detection of earth analogs?

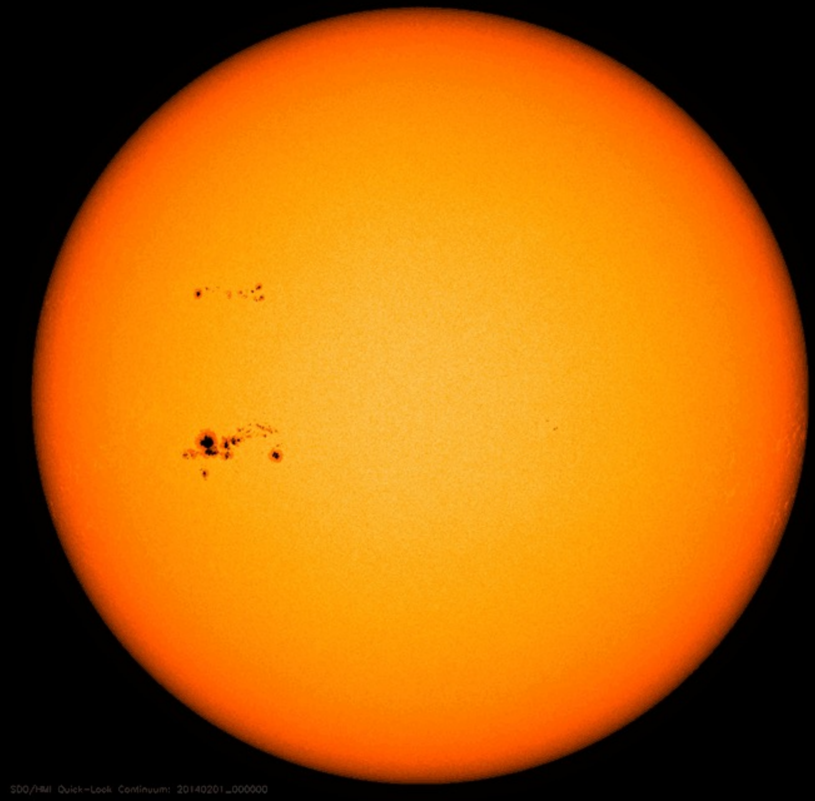
Photon noise

A 9cm aperture collects enough photons from αCen A&B to reach 1μas photon noise in 6hrs!

Astrophysical noise is benign (in contrast to EPRV)

- Sun-like stars at 10pc viewed from equator = 0.087μas jitter Marakov et al 2009 (ApJ 707, L73)
- Similar study in 2011 is consistent = 0.07μas RMS, 0.2μas PV Lagrange et al 2011 (A&A 528, L9)
- Absolute astrometric Jitter from solar data = 0.52μAU (0.11mR) jitter Marakov et al 2010 (ApJ 717, 1202)
- Signal earth-like planet around the sun: 0.46mR = 2.17μAU = 0.3μas @ 10pc
- Peer reviewed literature agrees on a stellar astrometry jitter ~ <0.1uas

Several studies shows that stellar jitter is NOT a showstopper for astrometric detection of earth-analogs.



Sun spot AR1967. *Animation: SDO/NASA.*

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What limits the astrometric detection of earth analogs?

Instrument

Optical distortion

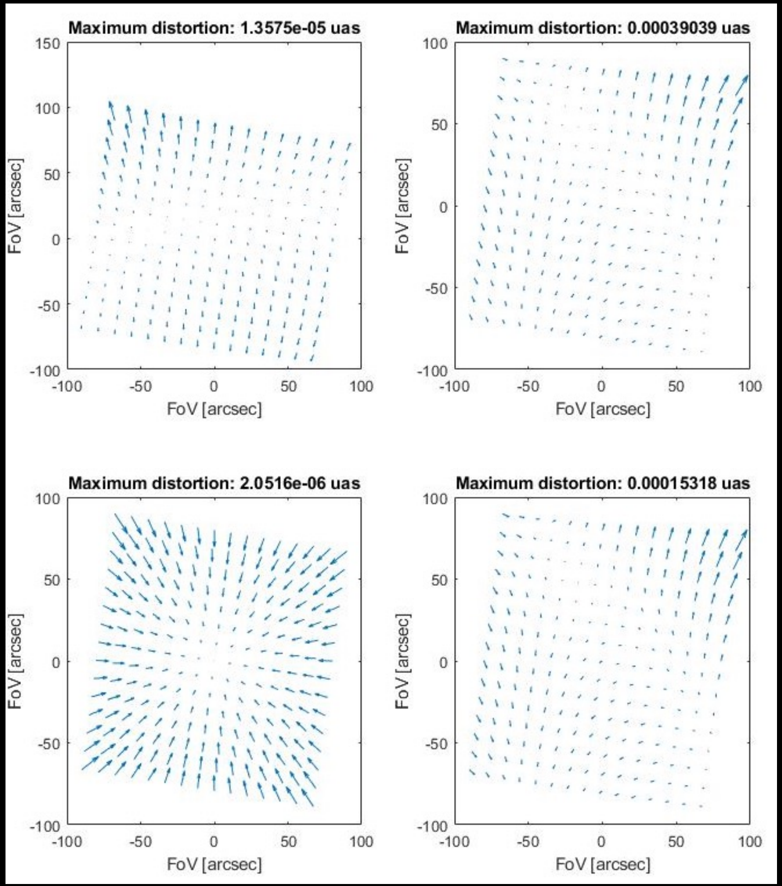
- The image or magnification changes in the entire or part of the field of view.
- Static distortion is OK
- Dynamic distortion changes the scale of every epoch

Detector errors

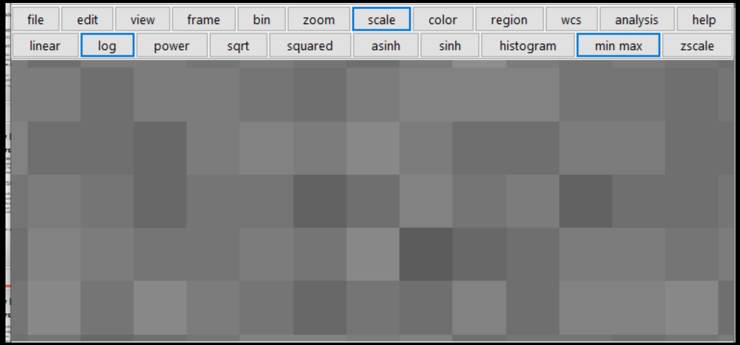
=>If the PSF moves to a differ pixel the response is different.

- Pseudo static: Inter and intra pixel QE changes, pixels position, pixel gaps, circuitry for front illuminated CMOS. => "Flat field"
- Dynamic: Thermal expansion, brighter-fatter effect, detector bending, etc

This also applies to photometric observations, Kepler, Tess, Plato, etc



Sample of modal of distortion of the Habex Work Horse camera (4 modes of 121 shown)
Astrometry exoplanet detection using the Habex Work Horse Camera Bendek et al. Proc SPIE 11823



Typical flat field error under uniform illumination. This is 3.76 um pixel BSI CMOS

See **Catalina Flores Quintana poster** to learn how to reduce the diffraction spikes data

See Matt Noyes **poster** about our picometer controller active light source

The diffractive pupil approach

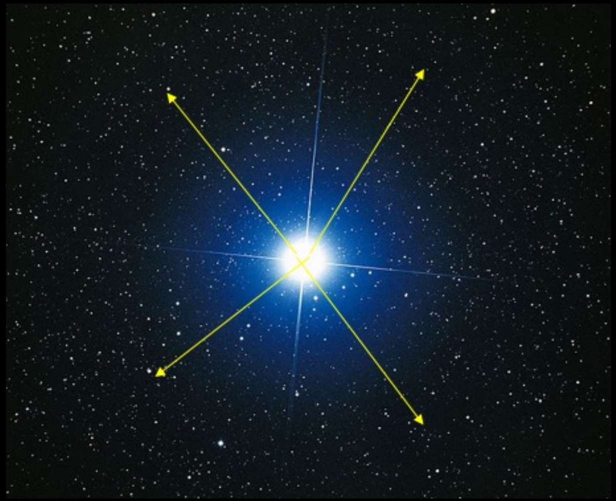
Single and binary stars optimizations: Solve distortion and camera pixel errors

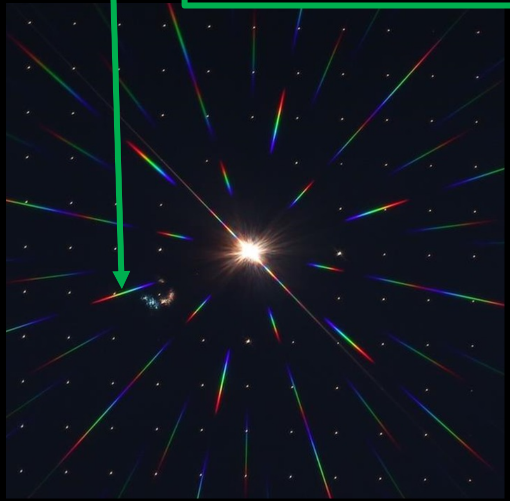
Absolute stellar astrometry

Astrometry reference are the background stars with enough SNR resulting in:

- Larger telescope
- Wide FoV
- Solve target v/s bkg dynamic range problem

- Guyon, O., and Coauthors, 2012: High-precision Astrometry with a Diffractive Pupil Telescope. *The Astrophysical Journal Supplement Series*, **200,** 11.]
- Bendek, E., et al., 2013: Laboratory demonstration of astrometric compensation using a diffractive pupil," *PASP*, Vol. 125, No. 932, pp. 1212-1225.
- Bendek, E., et al, 2017: Results of the astrometry and direct imaging testbed for exoplanet detection," Proc. SPIE, 10400.





Narrow field relative astrometry

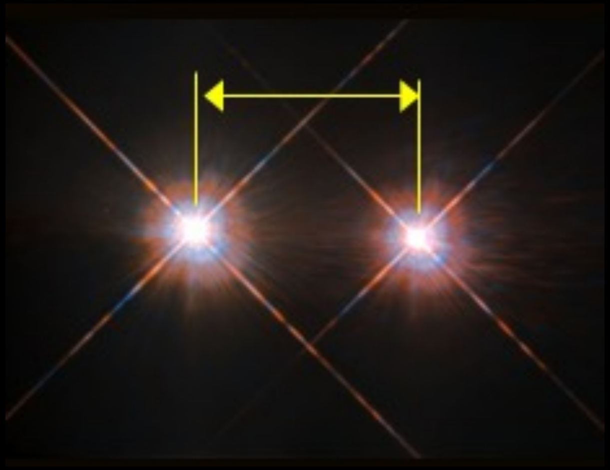
Astrometry reference is binary companion:

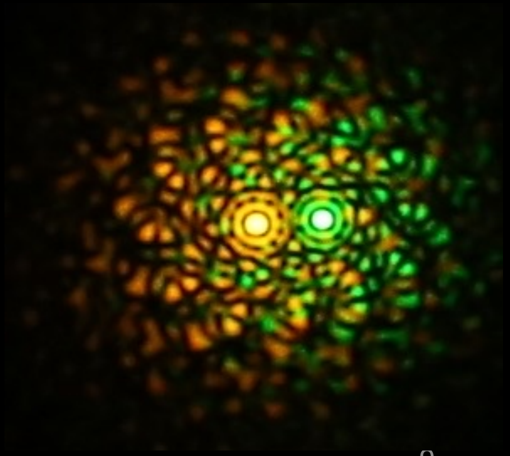
-> **Smaller telescope**

Narrow field of view to capture the binary

-> **Simple telescope**

- Bendek, E., and Coauthors, 2018: Precision astrometry mission for exoplanet detection around binary stars, Proc. SPIE, 10698.
- Tuthill, P., and Coauthors, 2018: The TOLIMAN space telescope. 107011J.





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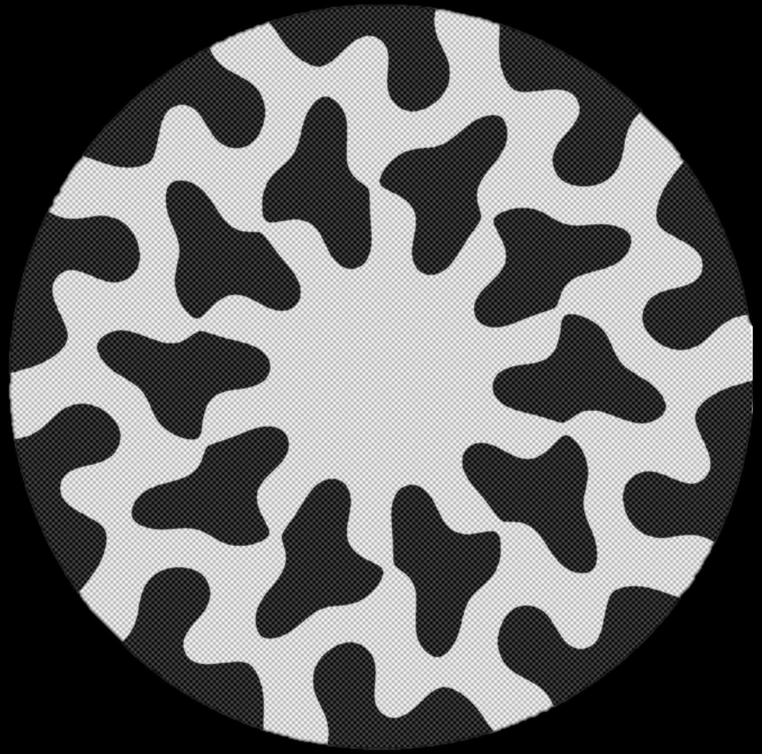
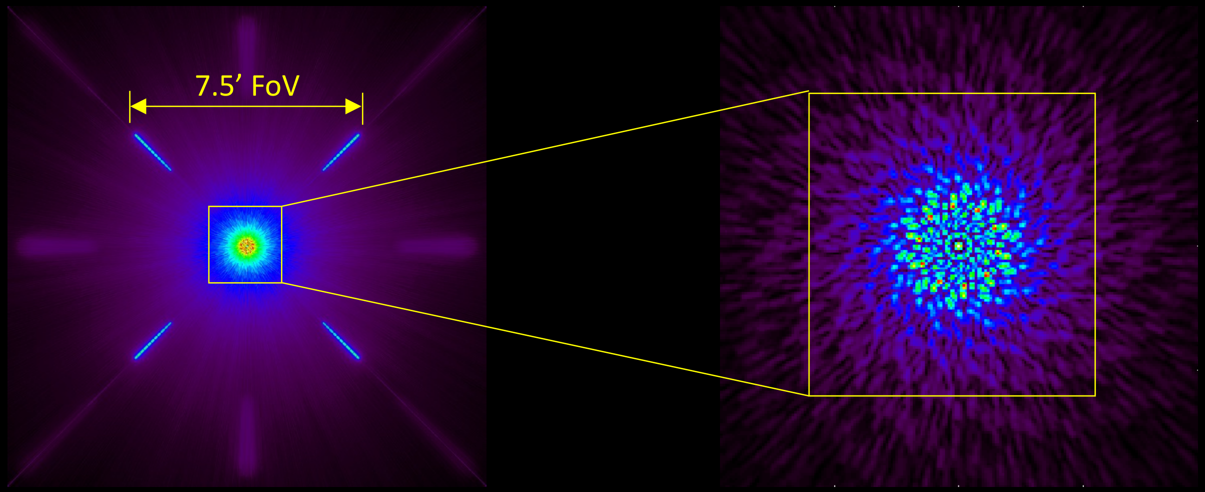
Diffractive Pupil for binaries

Pupil plane (Primary mirror)



Diffractive pupil topography
λ/4 height difference between black and white

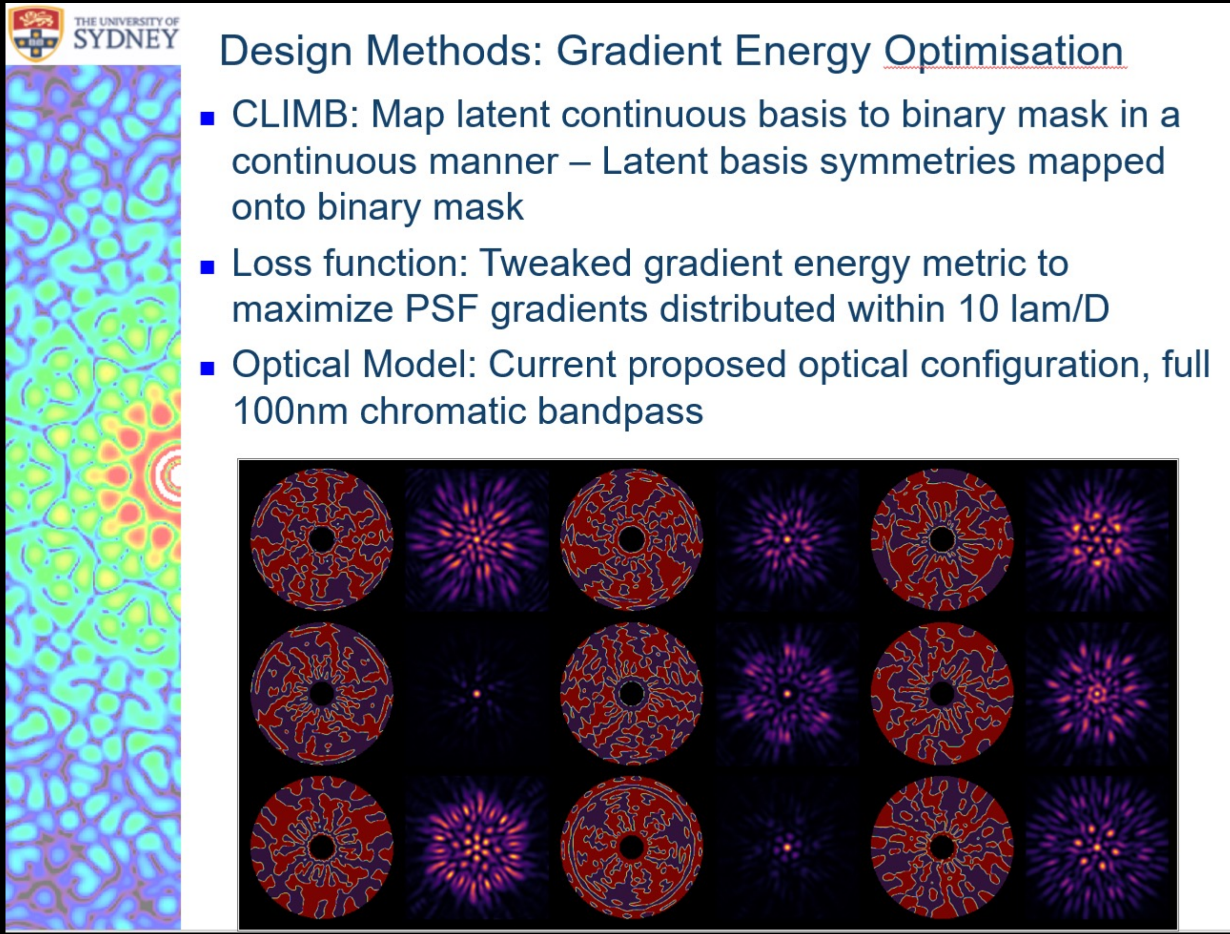
Focal plane Point Spread Function(PSF)



Diffractive Pupil for binaries optimization

- Univ. of Sydney has developed advance code to explore the DP shape optimization
- See Louis Desdoigts Poster #45: Optical Design, Analysis & Calibration using δLux

- TOLIMAN development at **Univ. of Sydney led by Prof. Peter Tuthill** funded by breakthrough initiatives.



Louis Desdoigts Poster #45: Optical Design, Analysis & Calibration using δLux

JNEXT TOLIMAN Project goals:

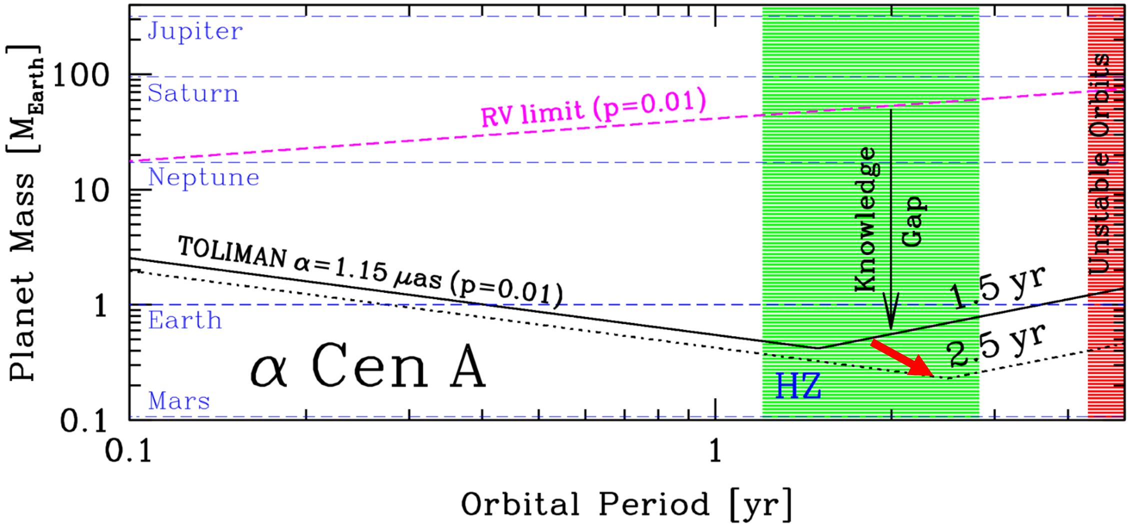
Technology: Demonstrate the diffractive pupil technology in preparation for larger NASA missions that can survey the nearest binaries.

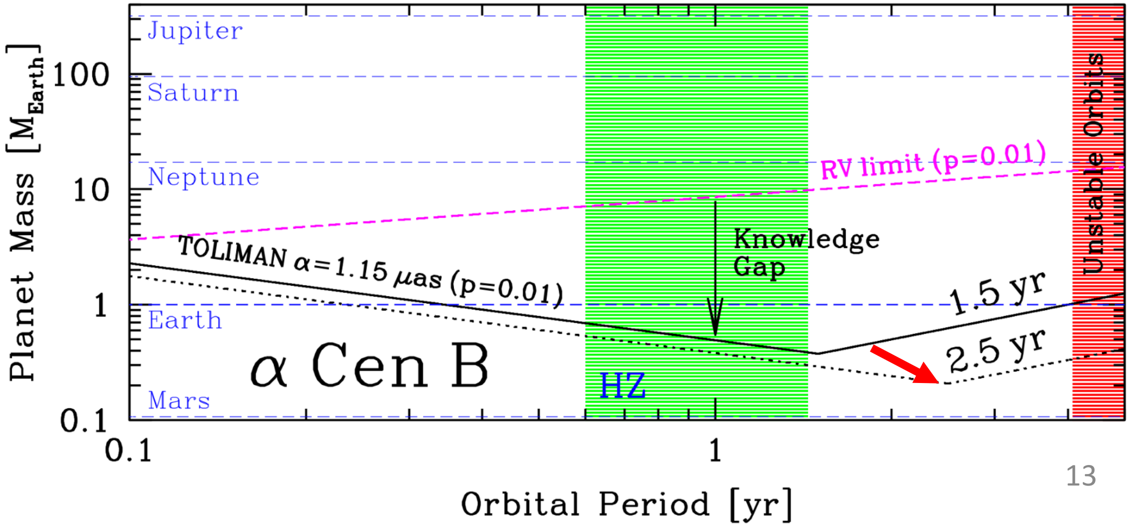
Science: Survey the entire habitable zones of Alpha Centauri A and B with enough sensitivity to detect and measure masses or earth analogs

Discovering an earth analog around Alpha Centauri, our closest star system, would be a major scientific breakthrough and will herald the search for life and biosignatures.

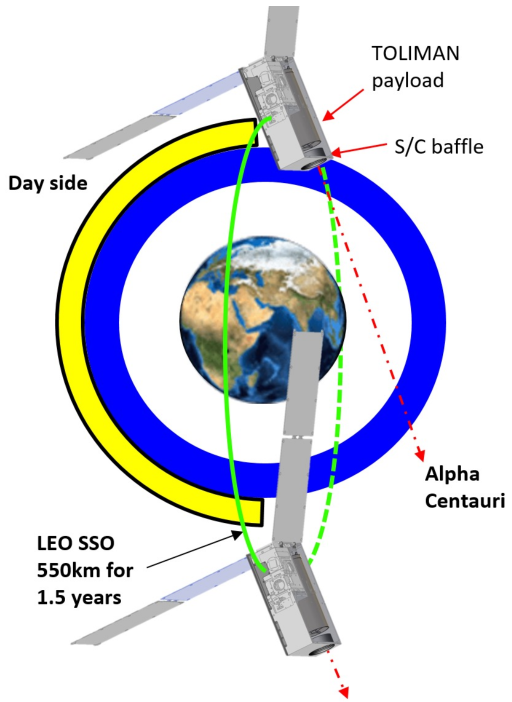
System Trades: Mission Duration

- **Mission duration** drives sensitivity, not number of targets
- Minimum duration: 1.5 years, ideal 2.5 years
- **Options:** gradual increase in mission duration. S/C is designed for 5 yrs in LEO SSO.
- **Trade:** Higher cost, more planets, longer period, and enables detection of Mars analogs

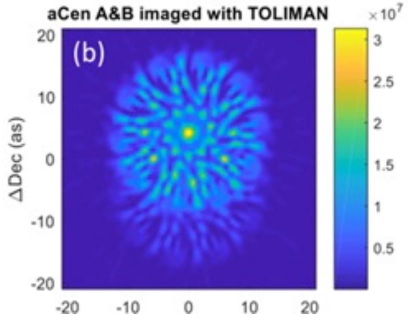


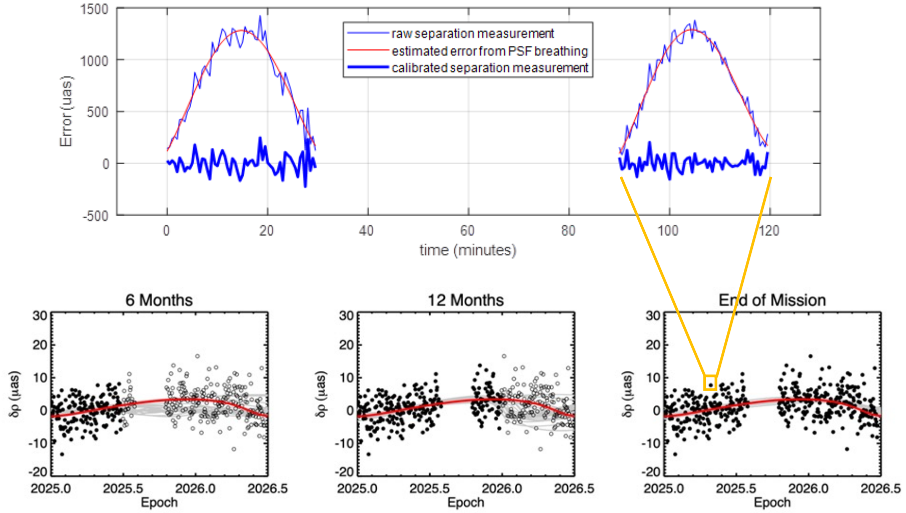


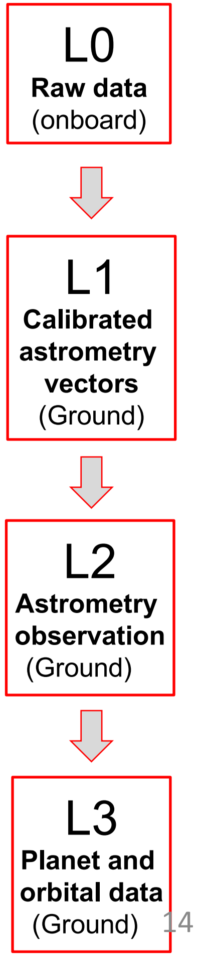
The TOLIMAN mission in a nutshell



TOLIMAN Data:
- 1 observation/orbit
- 9,000 frames, 0.2 s each
- PSF contains plate scale calibration



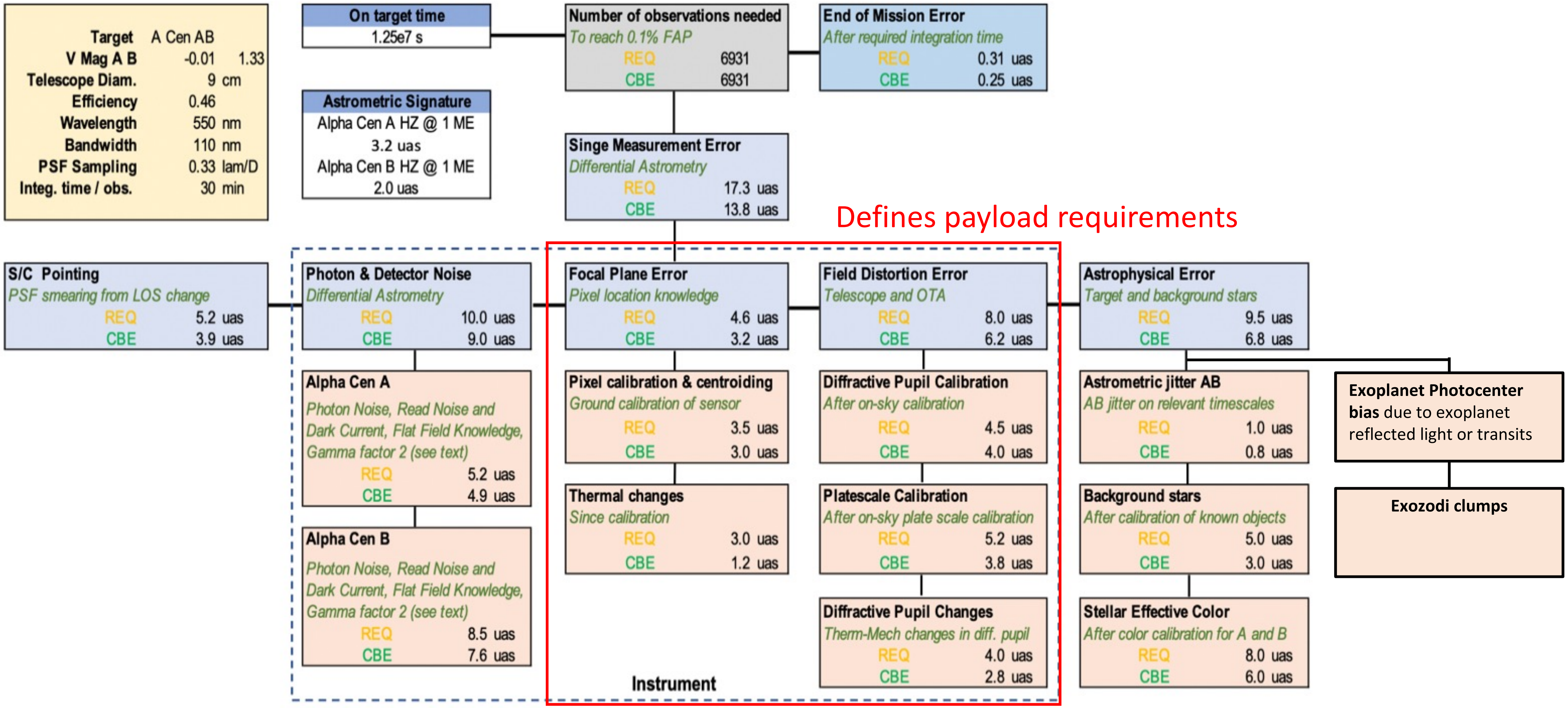




- TOLIMAN uses a BCT 6U CubeSat.
- The instrument is a 9cm aperture Cassegrain telescope equipped with the DP
- The Mission duration is 1.5 years

Orbital fit provides planets, masses, orbit

Mission Error Budget



End-to-end simulation

We are simulating the entire process from observations to planet retrieval

UNIVERSE SIMULATOR
Generate data "as it will be seen" from orbit for the mission duration
OUTPUT: Astrometry vector time series *A(t)* between the two stars

Optional noise sources
- Star spots
- Stellar temporal spectral changes
- Planet signal
- Earth orbit parallaxes
- Orbital relativistic effects

INSTRUMENT
Create images as will be seen by the instrument detector. Input is *A(t)*
OUTPUT: images readout by the detector *Im (t)*

Optional noise sources:
- Telescope plate scale
- Detector errors
- DP changes
- Filter bandwidth changes
- Jitter and pointing image smear

ASTROMETRY MEASUREMENT
Calculate calibrated astrometry vectors from images. Input is *Im(t)*
OUTPUT: Measured astrometry vectors *Am(t)*

Optional noise sources:
- Telescope magnification calibration errors
- Image shift and co-add errors
- Cosmic rays

PLANETS DETECTION
Recover planets and orbital fitting tool

Assess performance comparing raw data with recovered data

Laboratory demonstration to demonstrate that the telescope can be calibrated using the DP

End-to-end simulation

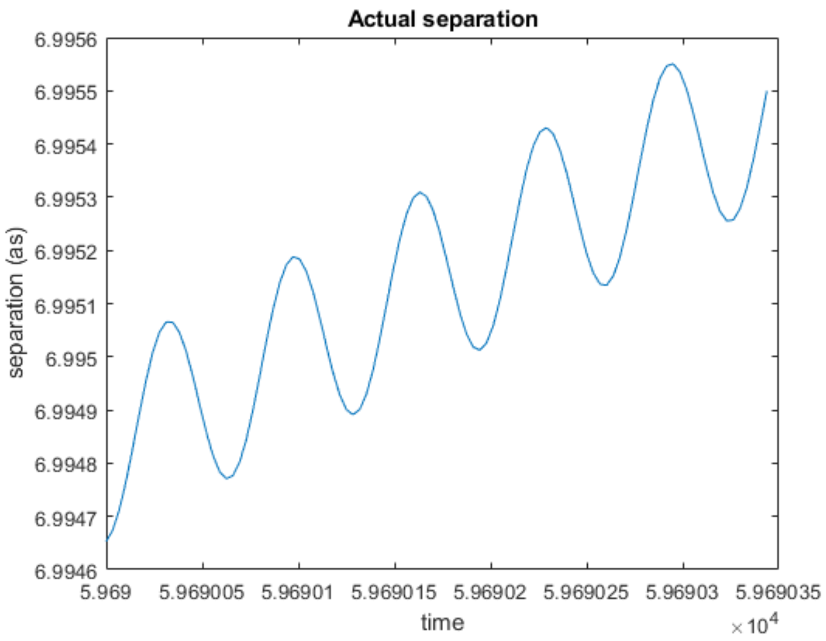
Part of the simulator is already working

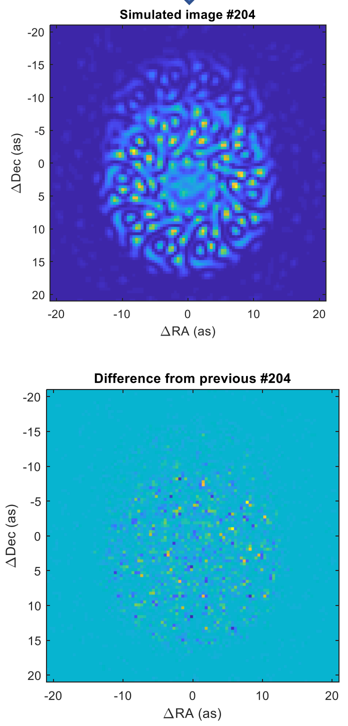
UNIVERSE SIMULATOR
Complete, no noises.

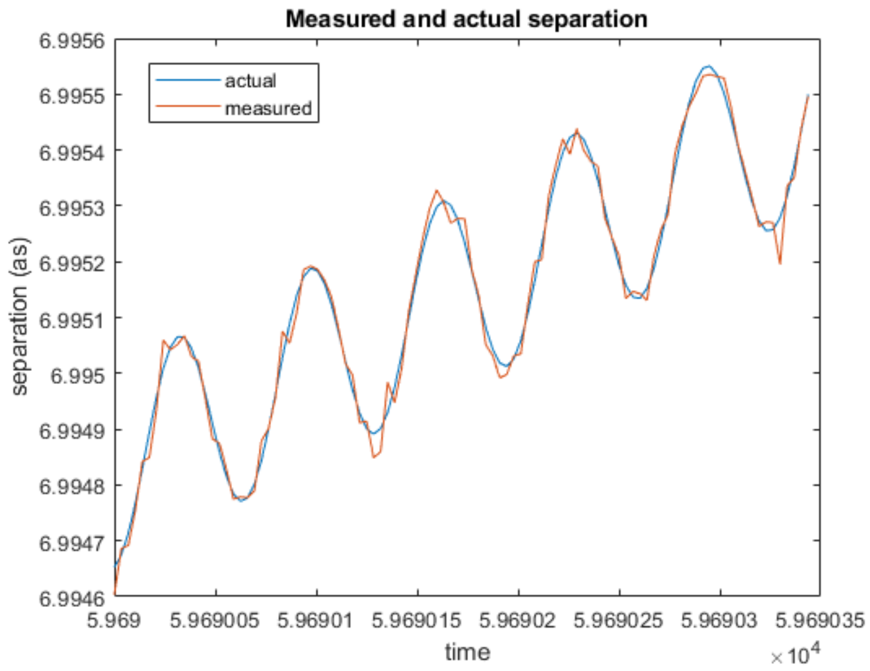
INSTRUMENT SIMULATOR
Complete, only detector noise

ASTROMETRY MEASUREMENT
Complete, no noise

PLANETS DETECTION
Orbital fitting Under implementation

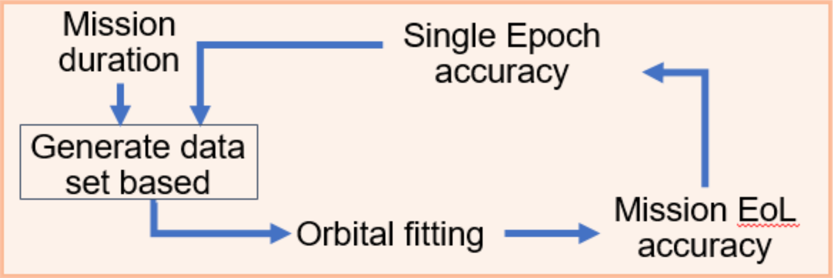






Orbital Fitting

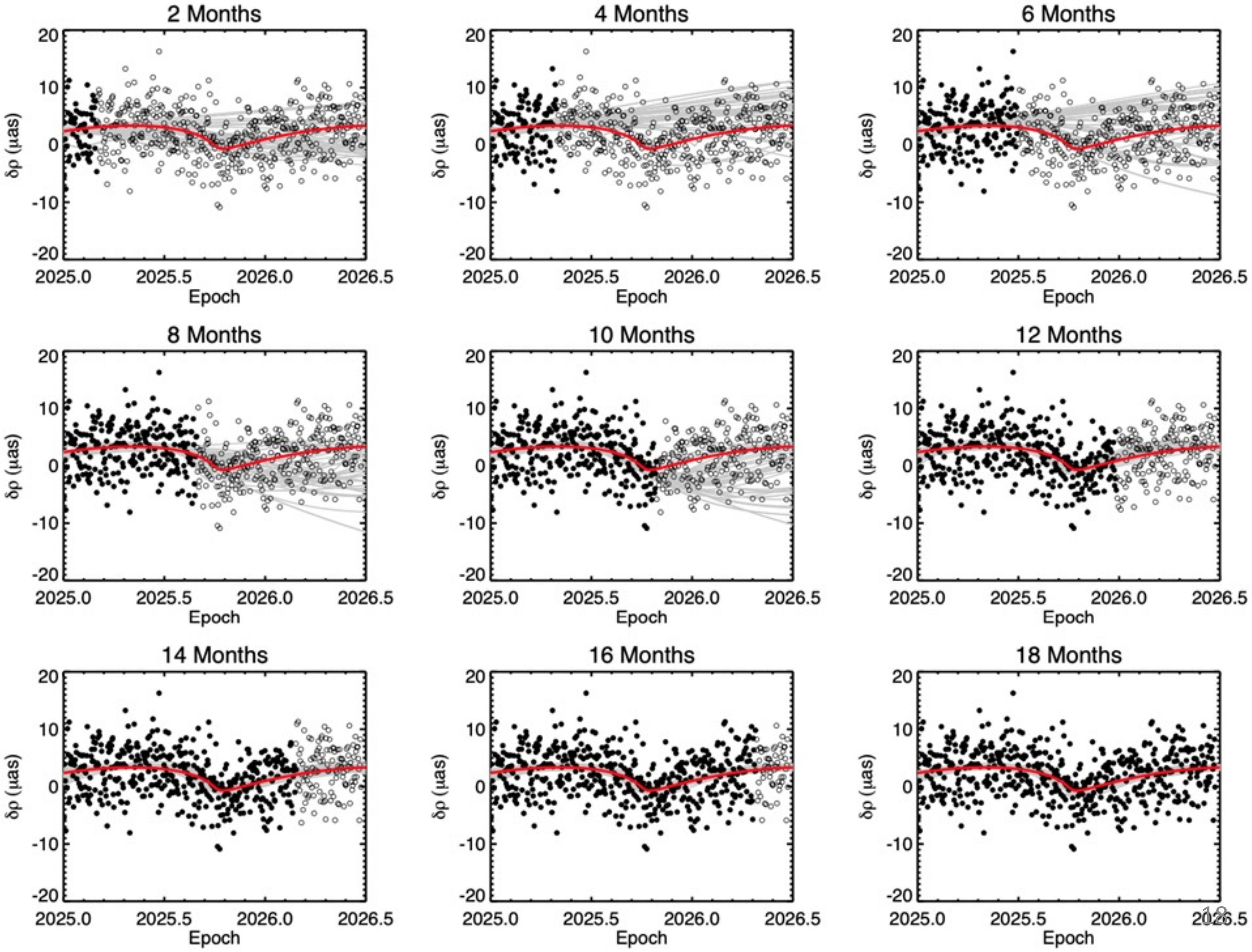
Requirements derivation



E. Nielsen
University of New Mexico

Anyone interested in doing a postdoc at NASA/JPL or thesis to work on these models?
- Adding RV
- Resolving host star degeneracy
- Blind spots

Talk to me, or email me at eduardo.Bendek@jpl.nasa.gov

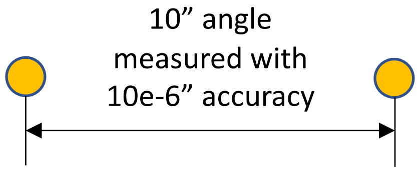


Technology demo roadmap

Goals

1. **Demonstrate end-to-end exoplanet injection and recovery**
2. **Demonstrate single-epoch relative astrometry accuracy that enables the mission**:

- 10 µas for a 9.0 cm aperture for sources separated by 10” (7 λ/D) => 1 ppm signal (7e-6 λ/D)
- Demonstrate manufacturability of the DP



Roadmap

2015 — Completed

TRL 2
Concept proposal
- Simulation validation

2017 — Completed

TRL 3
Laboratory proof of concept.
- DP manufactured in transmissive glass
- Validate PSF model with reality
- Astrometry measurements validated down to lab limitations

2022 — In execution

TRL 4
Medium fidelity demo in air
- Build and verify calibrated active light source
- Manufacture DP on reflective curved substrate
- Detector calibration
- Build scaled aperture instrument
- Design for high-fidelity (10 µas) demo resolution
- Demonstrate 100 µas
- Develop end-to-end simulator

2023 — Proposed

TRL 5
High fidelity in vacuum
- Build protoflight payload
- Build actual DP on primary
- Upgrade light source to deliver collimated beam

Exit criteria:
- Demonstrate 10 µas single epoch measurement

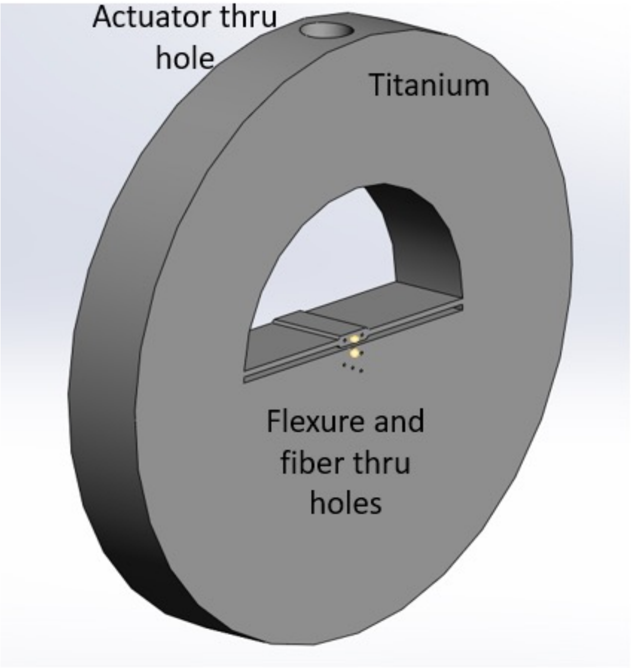
2024

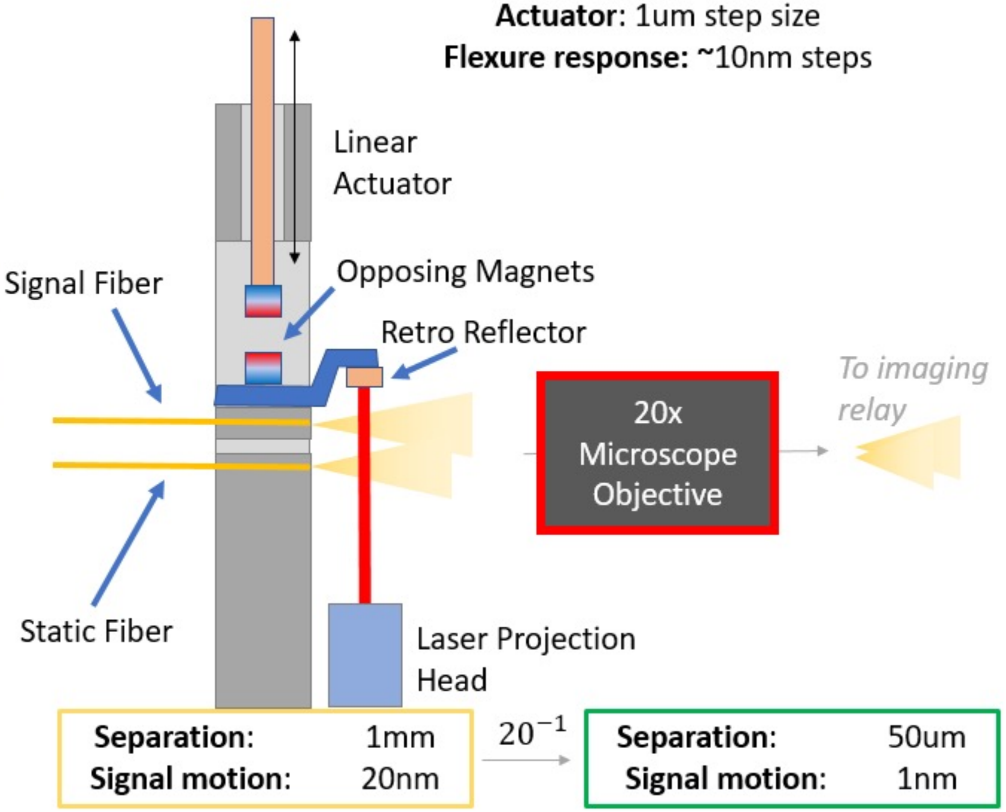
Ready for flight mission implementation

Laboratory demonstration

The universe simulator: An active star simulator

- Simulate Alpha Cen A and B and inject a 10 μas signal (70 pm signal)
- Temporal modulation mitigate system drifts
- 50 μm source separation to match the 7 λ/D angle on sky

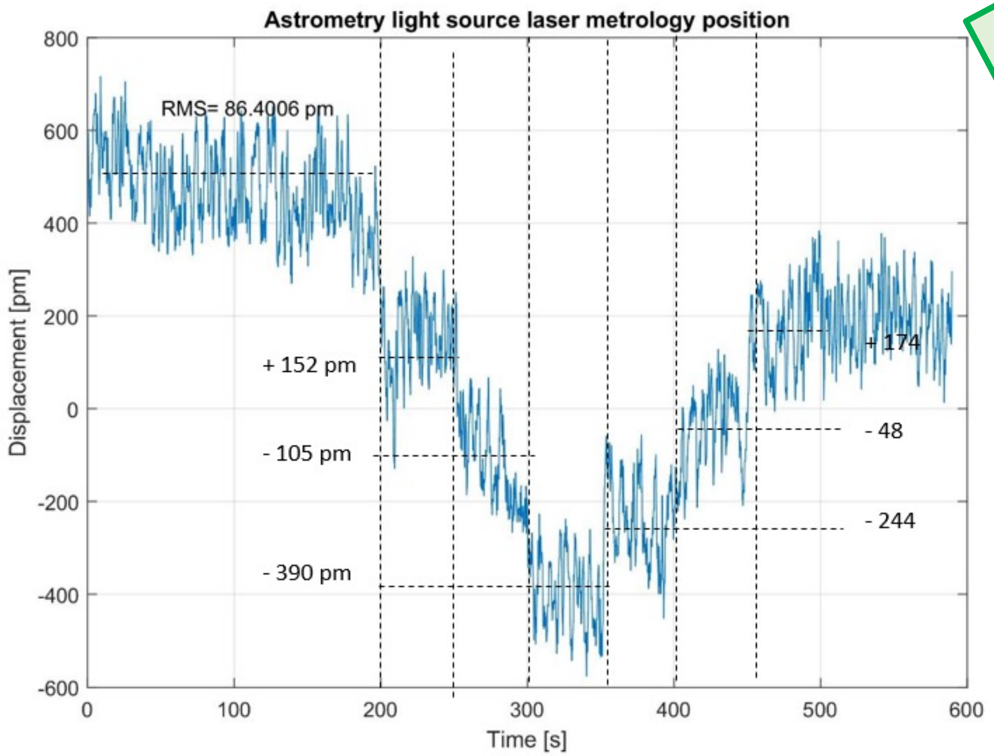




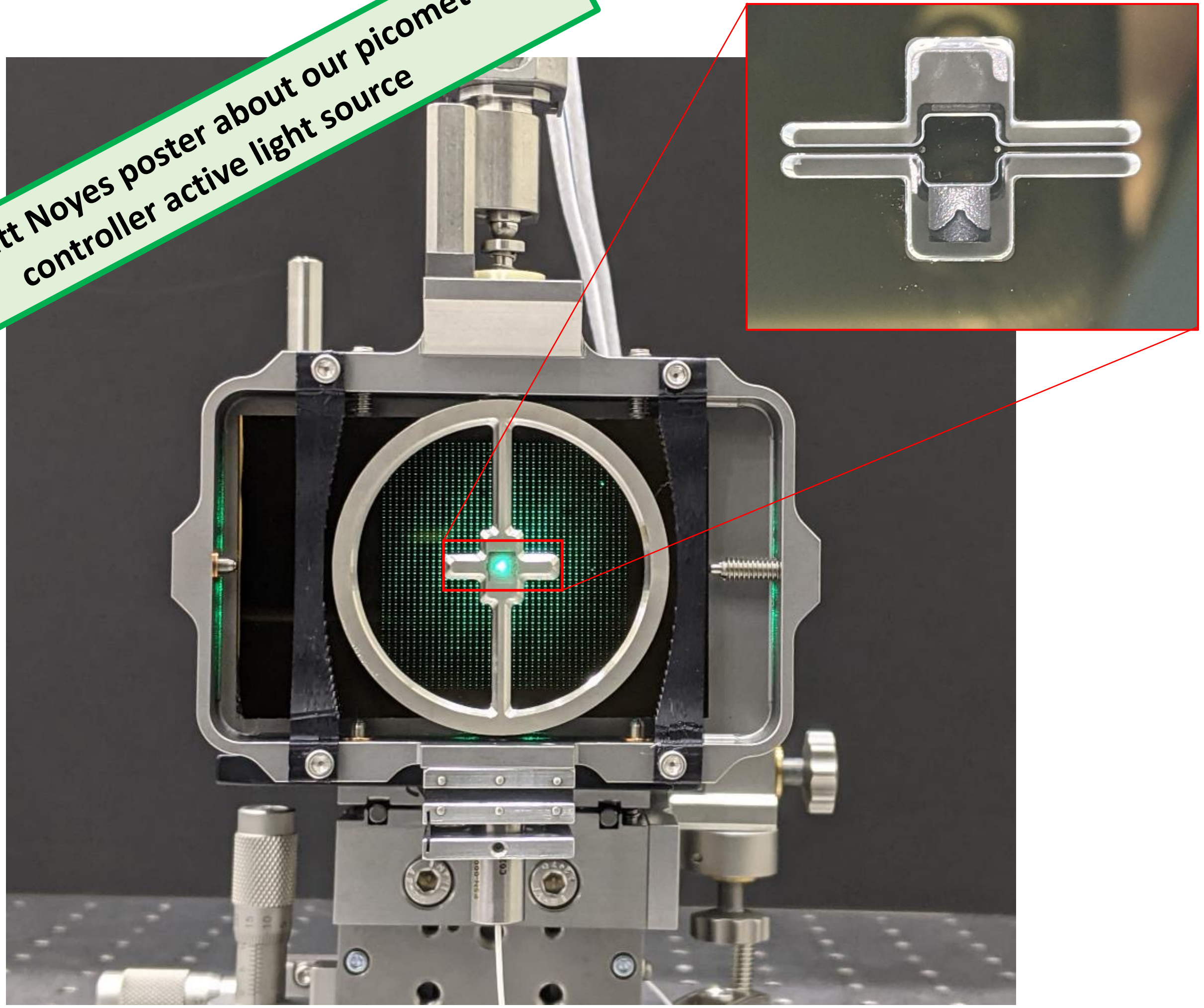
Laboratory demonstration

Heritage of APRA light source

- Measurable 200 pm step control using laser metrology
- 5x higher resolution than needed for TOLIMAN



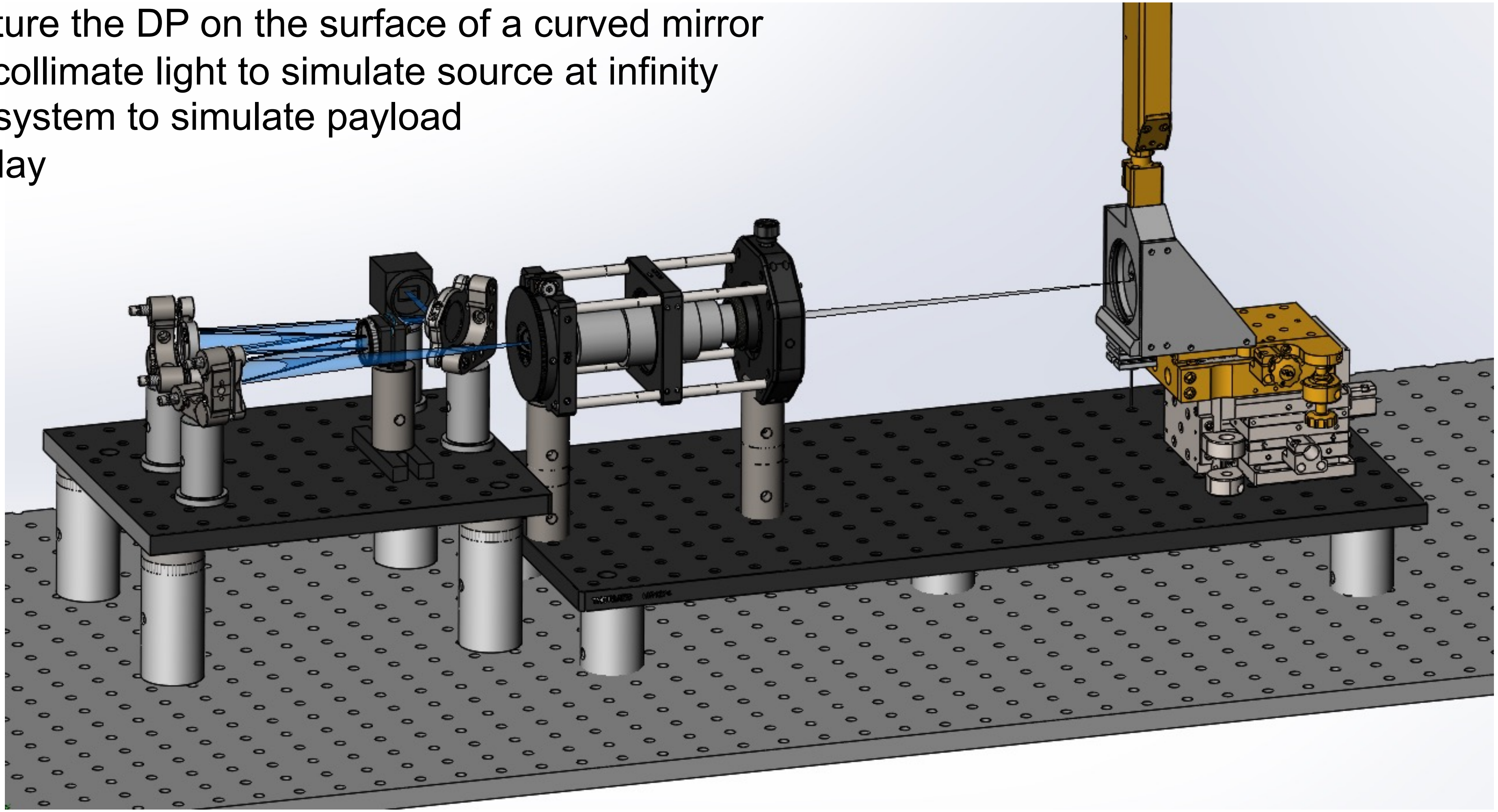
See Matt Noyes poster about our picometer controller active light source



Laboratory demonstration

The imaging system: Collimator and instrument payload

- Manufacture the DP on the surface of a curved mirror
- Need to collimate light to simulate source at infinity
- Imaging system to simulate payload
- Offner relay

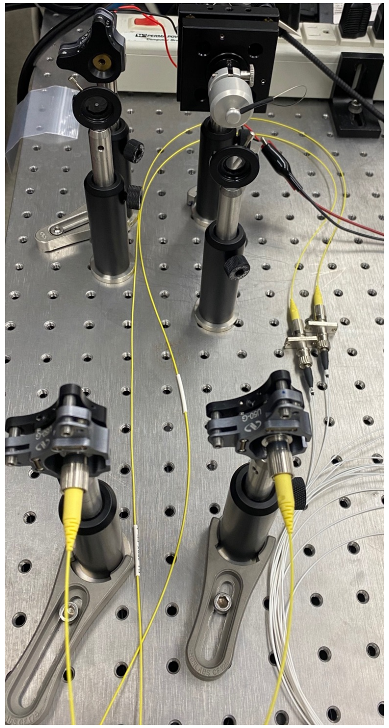


Laboratory demonstration is in preparation

Combination of current and previous investments

Source: JNEXT
Achievements:

1. Secured **lab space and optical bench**
2. Secured two white broadband **lasers** for source
3. Acquired and evaluated **CAMERA** candidate for flight
4. **Optical and mechanical** layout is almost finished.
5. Work with MDL ongoing for **DP manufacturing**

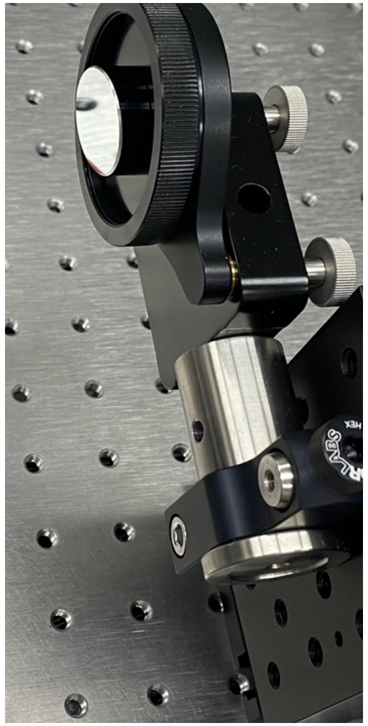


Binary Target Simulation

Injection of Finaium supercontinuum laser in one of the sources and narrow band laser of the other source to simulate a binary target

FLIR Camera intended for flight
(Board level for flight)

Same electronics as the Mars2020 EDL camera



Off-axis reflective optics

Next steps and conclusions

Science

- Finding the easiest targets to study exoplanets focuses us on nearby FGK
- Alpha Centauri is a unique target for its proximity and brightness

Technology

- Narrow angle relative astrometry is one of the most effective approaches to detect planets and measure masses around binaries
- Astrometry accuracy is limited by optical distortions that can be calibrated using a diffractive pupil

Implementation

- A cube sat with a 9 cm aperture is capable of collecting enough photons to perform the detection

Simulations: We are looking for people to help with modeling.