Searching for Earth analogs around the nearest star system

TOLIMAN JNEXT
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Exoplanet Exploration Strategy
MOTIVATED BY NASA ASTROPHYSICS ROADMAPS

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

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
From demographics to habitability studies

The TESS search space compared to that of the Kepler Mission. Image Credit: Zach Berta-Thompson
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 αCen 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
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)
Using the binarity as a solution

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

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

**Opportunity that αCen A&B offers:**

- **Proximity:** An Earth analog around αCen A&B will exhibit the **highest astrometric signal possible** of $\sim 3\mu$as
- **Brightness:** A 9cm aperture collects enough photons from αCen A&B to reach $1\mu$as photon noise in 6hrs!
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: 0.46μR = 2.17μAU = 0.3μas @ 10pc
- Peer reviewed literature agrees on a stellar astrometry jitter ~ <0.1μas

Several studies shows that stellar jitter is NOT a showstopper for astrometric detection of earth-analogs.
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
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 vs bkg dynamic range problem

Narrow field relative astrometry
Astrometry reference is binary companion:
- Smaller telescope
  Narrow field of view to capture the binary
  - Simple telescope

- Tuthill, P., and Coauthors, 2018: The TOLIMAN space telescope. 107011J.

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
Diffractive Pupil for binaries

Pupil plane (Primary mirror)

Diffractive pupil topography
$\lambda/4$ height difference between black and white

Focal plane Point Spread Function (PSF)

7.5' FoV
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.

Design Methods: Gradient Energy Optimisation
- CLIMB: Map latent continuous basis to binary mask in a continuous manner – Latent basis symmetries mapped onto binary mask
- Loss function: Tweaked gradient energy metric to maximize PSF gradients distributed within 10 lam/D
- Optical Model: Current proposed optical configuration, full 100nm chromatic bandpass
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.*
• **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

Defines payload requirements

- **Target**: A Cen AB
  - V Mag A B: -0.01, 1.33
- **Telescope Diam.**: 9 cm
- **Efficiency**: 0.46
- **Wavelength**: 550 nm
- **Bandwidth**: 110 nm
- **PSF Sampling**: 0.33 lanVD
- **Integ. time / obs.**: 30 min

**On target time**: 1.25e7 s

**Number of observations needed**
- To reach 0.1% FAP
  - REQ: 6931
  - CBE: 6931
- End of Mission Error After required integration time
  - REQ: 0.31 uas
  - CBE: 0.26 uas

**Astrometric Signature**
- Alpha Cen A, HZ @ 1 ME: 3.2 uas
- Alpha Cen B, HZ @ 1 ME: 2.0 uas

**Single Measurement Error**
- Differential Astrometry
  - REQ: 17.3 uas
  - CBE: 13.8 uas

**Phenom & Detector Noise**
- Differential Astrometry
  - REQ: 10.0 uas
  - CBE: 9.0 uas

**Focal Plane Error**
- Pixel location knowledge
  - REQ: 4.6 uas
  - CBE: 3.2 uas

**Field Distortion Error**
- Telescope and OTA
  - REQ: 8.0 uas
  - CBE: 6.2 uas

**Alpha Cen A**
- Photon Noise, Read Noise and Dark Current, Flat Field Knowledge, Gamma factor 2
  - Ground calibration of sensor
    - REQ: 5.2 uas
    - CBE: 4.9 uas

**Alpha Cen B**
- Photon Noise, Read Noise and Dark Current, Flat Field Knowledge, Gamma factor 2
  - Since calibration
    - REQ: 8.5 uas
    - CBE: 7.6 uas

**Pixel calibration & centroiding**
- After on-sky calibration
  - REQ: 3.5 uas
  - CBE: 3.0 uas

**Thermal changes**
- After calibration
  -REQ: 5.2 uas
  - CBE: 3.8 uas

**Platescale Calibration**
- After on-sky plate scale calibration
  - REQ: 4.0 uas
  - CBE: 2.8 uas

**Stellar Effective Color**
- After calibration for A and B
  - REQ: 8.0 uas
  - CBE: 6.0 uas

**Astrophysical Error**
- Target and background stars
  - REQ: 9.5 uas
  - CBE: 6.8 uas

**Exoplanet Photocenter bias due to exoplanet reflected light or transits**

**Exozodi clumps**
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.

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

Assess performance comparing raw data with recovered data.
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

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**Actual separation**

![Graph showing actual separation over time](image)

**Simulated image 0004**

![Simulated image](image)

**Difference from previous 0004**

![Image showing difference](image)

**Measured and actual separation**

![Graph comparing measured and actual separation](image)
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
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

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<thead>
<tr>
<th>TRL 2</th>
<th>2015</th>
<th>Completed</th>
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<tbody>
<tr>
<td>Concept proposal</td>
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<td>Simulation validation</td>
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<tr>
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<tr>
<td>Laboratory proof of concept</td>
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<tr>
<td>DP manufactured in transmissive glass</td>
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<tr>
<td>Validate PSF model with reality</td>
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<tr>
<td>Astrometry measurements validated down to lab limitations</td>
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<tr>
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<td>Medium fidelity demo in air</td>
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<tr>
<td>Build and verify calibrated active light source</td>
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<tr>
<td>Manufacture DP on reflective curved substrate</td>
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<td>Detector calibration</td>
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<td>Build scaled aperture instrument</td>
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<td>Design for high-fidelity (10 μas) demo resolution</td>
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<td>Demonstrate 100 μas</td>
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<tr>
<td>Develop end-to-end simulator</td>
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<td>High fidelity in vacuum</td>
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<td>Build protoflight payload</td>
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<td>Build actual DP on primary</td>
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<td>Upgrade light source to deliver collimated beam</td>
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<td>Exit criteria:</td>
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<td>Demonstrate 10 μas single epoch measurement</td>
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<td>Ready for flight mission implementation</td>
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10" angle measured with 10e-6" accuracy
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**
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.