The TOLIMAN mission:
precision astrometry for exoplanetary discovery in the solar neighborhood

Abstract

We propose an innovative low-cost mission that will be the first capable of revealing potentially habitable planets around a handful of the nearest solar-type stars to the sun. The finding of rocky planets in temperate orbits among our immediate stellar neighbors will be a signature discovery, widening humanity's horizons by revealing worlds sufficiently close as to enable detailed characterisation of atmospheres and surfaces, and prospecting for potential bio-signatures. On long timescales, these may furnish targets for futuristic robotic probes. Our mission is founded on leading-edge concepts in optical physics, and will deliver measurements of stellar position and motion at unprecedented precision. These data, in turn, will reveal the presence, orbit and mass of all orbiting exoplanets: for the case of our primary targets Alpha Centauri A & B, objects down to one Earth mass will be accessible. This focussed mission aims for rapid deployment and results, while the innovative detection strategy will pave the way for future large instruments.

Executive Summary: mission goals and basic architecture.

Astrometry is the only technology capable of detecting all Earth-mass planets in the Habitable Zones of very nearby sun-like stars such as Alpha Cen (see Appendix 3 for further discussion). The technique will directly reveal not only the presence of the planet, but deliver fundamental data such as masses and 3-D orbital parameters including eccentricity and inclination. These data form a critical bridge to audacious future instruments in which these new worlds will be characterized and studied with a range of technologies on the ground and in space, and ultimately by space probes which span the interstellar voids. For such missions, TOLIMAN will provide the foundational charts: where to aim future generation missions and probes and what may be found there.

TOLIMAN will perform high precision astrometric measurements of a sample of nearby, bright, close binary stars, with specific emphasis on the Alpha Centauri system. The mission has the following core science deliverables (minimum required performance in blue / goal in green):

- End-of-Mission astrometric precision (micro-arcseconds) - 0.4 / 0.2

- Alpha Cen A, final HZ Planet 5-sigma detection threshold (Earth Masses): 0.8 / 0.4
- Alpha Cen B, final HZ Planet 5-sigma detection threshold (Earth Masses): 1.3 / 0.7
- Secondary Stellar Targets: Study 6 systems within 10pc, brighter than V=6th mag.
- Secondary Stellar Target detection threshold (Earth Masses): 5.0 / 2.5

A straw man outline of the basic architecture of the TOLIMAN mission:

- Thermally stabilized space telescope with 0.3m diameter aperture
- 2-mirror high stability optical design with a single focal plane
- Minimum complexity optical and mechanical systems
- Fast, agile, low-cost mission
- Full Science Mission duration - 3 years
- Can be designed for various orbits (GEO is baseline)
- Pointing 1 arcsecond with drift/jitter better than 1arcsec/sec
- Observing Wavelength Band: 510-570nm
- Detector: CMOS (rapid readout mode)
- Raw Data Rate: 10GB/Hour
- Estimated downlink requirement < 1GB/day (after on-board processing)
- On-board instrument flight metrology: thermal and optical monitoring

1. Introduction. First Light onto our planetary neighborhood

The astonishing current rate of planetary discovery (approximately one new exoplanet per day at present) in contemporary astrophysics masks a remarkably wide and pervasive observational blind spot. If we wish to know whether any particular star hosts a rocky planet in the Habitable zone, we have only a remote chance of being able to find out. Most of the announced detections are systems where astronomers got a lucky break, most often in the form of the orbital alignment (odds of order 1%) resulting in a transit across the face of the star with a corresponding measurable dip in the stellar light.

As a consequence, astronomers have very patchy knowledge of the planetary census of stars in our own galactic backyard within 10 parsecs (32 light-years) or so. While missions like Kepler have given information on the statistical incidence of planets in various stellar environments, we still have no data on whether the nearest handful of sun-like stars such as Alpha Centauri, Tau Ceti and Epsilon Eridani actually host a potentially-habitable rocky world. Even worse, with present technologies we have no way of finding out. Although the technique of spectroscopic detection of Radial Velocities requires no particularly lucky alignment (as for Transits), it has proved very difficult to push the precision to the levels required for Earth-mass objects orbiting at temperate-zone AU scales. The limiting noise floor is usually intrinsic to the star, so that simply improving the instrumentation does not provide an immediate way forward.

Finding Earth-analogs in the immediate solar neighborhood is, however, a critical goal at the top rung of science priority for every national astronomy roadmap. As catalogs climb into the thousands of confirmed entries, the era of detection has already given way to the new science of exoplanetary characterisation. The critical questions are now to reveal the diverse planetary chemistry, atmospheric composition and physics, surface abundances and potential for a temperate environment that may support life. In this task, our plentiful sample of exoplanets is confronted with a problem: most are at kiloparsec scale distances and quite beyond the reach of follow-up observations such as adaptive optics imaging that has the potential to isolate the faint planetary light from the glare of the host star. On the other hand, planets (if they could be found) around nearby stars would be at ideal scales for this purpose, potentially yielding spectra in which the fingerprints for potential habitability (Water) or even an active biosphere (Oxygen) might be found.

Quite apart from this immediate scientific utility, discovery of nearby temperate-zone planets would mark a signature accomplishment, and sets an inspiring challenge for future generations. These are the places to prospect for the signatures of a biosphere with alien life, and further into the future, provide targets for interstellar probes (e.g. the Breakthrough Starshot initiative).

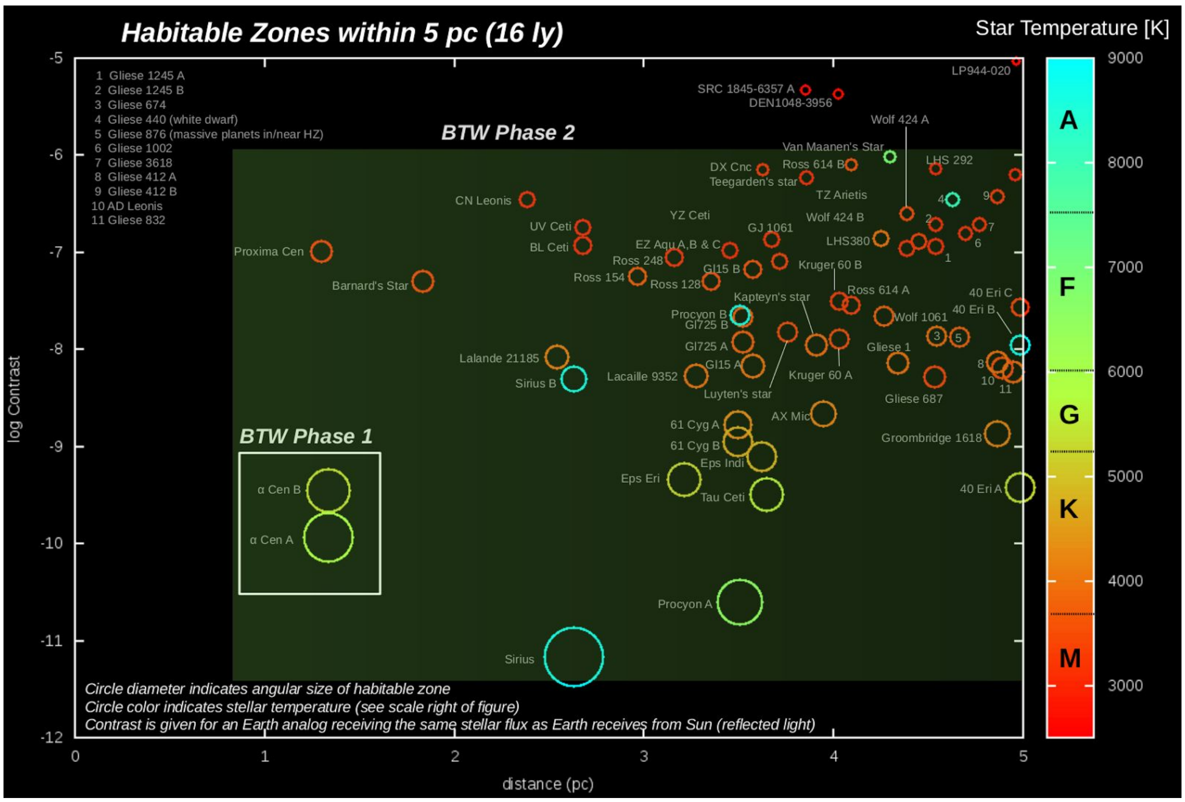


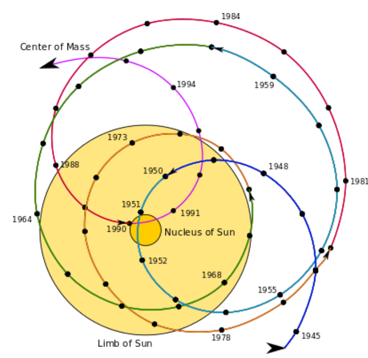
Figure 1: Habitable zones of all stars within 5pc. This mission targets the critical solar-like FGK stars (habitability around M-dwarfs is a topic of intense current debate). Distance increases from left to right, and vertical axis encodes planet-to-star reflected light contrast. As a BTW Phase 1 effort, TOLIMAN will specifically target Alpha Cen A & B.

2. TOLIMAN: a precision astrometric satellite mission

The TOLIMAN[1] (Telescope for Orbital Locus Interferometric Monitoring of our Astronomical Neighborhood) mission is a modest astrometric space telescope designed to discover and perform dynamical characterization of rocky planets around nearby stars. It is a narrow-field 30cm diameter imaging space telescope based on innovative optical principles with a fast (~18 month build time, followed by a 3yr observation period), inexpensive envelope and a focussed science goal. The first priority science for TOLIMAN will be the detection of all planets of Earth mass in the habitable zone of either Alpha Cen A or B. The mission will yield immediate constraints on the orbit and mass of any detected planets from the habitable zone out to the dynamical stability limit imposed by the binary (see below). If such a planet is found in the nearest solar-type star system, it will be a game-changing discovery which will trigger intensive characterization efforts. TOLIMAN will also observe a handful of F/G/K spectrum stellar targets within the immediate solar neighborhood, variously probing down to Earth or Super-Earth mass (with limiting sensitivity depending on the specifics of each system).

2.1 Astrometric Exoplanetary Detection

Astrometric detection involves precise measurement of stellar positions, and is overwhelmingly regarded as the only technology presently ready to find all earth-mass planets orbiting nearby FGK stars. As a planet orbits a star, the star is tugged in a small circular motion which can be detected. Tracking the very small angular displacements imposed on the host star by the gravity of orbiting exoplanets, a full solution of the planet mass and orbit can be recovered. Unlike competing methods, there are few blind spots, and the signal generated by companions increases with planet-star separation (converse to RV and Transit methods) making it ideal to probe habitable zones at larger orbital radii. To an external observer, the gravitational influence of the planets in our solar system (the principal player being Jupiter) tugs the Sun about with a complicated locus given in the figure to the right. However, angular excursions induced by habitable-zone Earth-analog planets are small – in the range of micro-arcseconds for Alpha Cen. Instrumentation to measure such signals has proved challenging to construct, so that the promise held out by astrometric detection has gone largely unrealized.



Ground based astrometry campaigns at high precision must fight the considerable additional noise process injected by the starlight path through the Earth's turbulent atmosphere. Long-baseline optical interferometers have historically delivered precisions better than 100

[1] TOLIMAN is also the Arabic name for the Alpha Cen star system from antiquity.

micro-arcseconds, with a recent resurgence of interest prompted by ESO's GRAVITY instrument which aims at 10 μas astrometric accuracy (not sufficient for Earth mass planets). However the nearest stars to Earth present a large apparent angular diameter and are correspondingly difficult to observe on long baselines (over-resolved objects have low interferometer fringe contrast). These intrinsic challenges for ground-based astrometric observation have motivated enduring interest in space.

Conventional astrometry measures the position of a star using bright field stars in the neighboring regions of sky as references. This requires a wide field of view, as the distance between the science target and sufficiently bright reference stars is typically on the order of a degree. Maintaining a stable image scale over such large angles is notoriously challenging, requiring high accuracy metrology (see for example the >$1B Space Interferometry Mission, which was studied by NASA but ultimately canceled). Space astrometry over wider angles has proved to be extremely productive delivering basic stellar positions, distances and kinematics with the HIPPARCOS mission, and its ambitious successor GAIA which is measuring a billion stars with precision up to the ten(s) of micro-arcseconds. Although this mission is expected to deliver a rich harvest of gas giant planets, pushing detection thresholds down to rocky planets in temperate orbits (signals of order 1 micro-arcsecond or less) will require dedicated new technology. Several such missions have been proposed by groups in Europe, the US and China, however solving the general problem of precision astrometric detection is challenging and viable architectures typically have been priced in the hundreds of millions of dollars (even the lowest-cost concepts usually exceed $50M).

3. Alpha Centauri: an ideal astrometric target

Earth does have several (extremely unlikely) pieces of luck in our favor when confronting the daunting challenge imposed by attempting to find Earth-analog planets around nearby stars. Our very nearest celestial neighbor, Alpha Cen, contains solar-analog stars which means that habitable-zone exoplanets will be true Earth-twins in year orbits: wide enough to yield good signals, yet not so wide as to require a very long mission lifetime for detection. The astrometric detection technique relies on referencing the position of the star against separate fiducials, usually fainter background stars that are at considerable distance on the sky. However, the presence of a very nearby (4 arcsecond) bright binary companion makes the task overwhelmingly more favorable for this system.

Fundamentally, high precision astrometry yields a relative measurement, so that narrow-angle astrometry (where the reference star is very close) is proportionately more precise than wide-angle astrometry. With the fortuitous presence of a bright phase reference only arcseconds away, measurements are immediately 2 - 3 orders of magnitude more precise than for a randomly chosen bright field star were many-arcminute fields (or larger) are required to find background stars for this task. Maintaining the instrument imaging distortions stable over a few arcseconds is considerably easier than requiring similar stability over arcminutes or degrees.

Alpha Cen's proximity to Earth means that the angular deviations on the sky are proportionately larger (typically a factor of ~10-100 compared to a population of comparably bright stars). The astrometric signal from an Earth mass planet orbiting in the habitable zone of Alpha Cen A is about 2.5 micro-arcseconds, while for Alpha Cen B it is half that. Since the centroid shift of the star due to its solar-like activity is expected to be at the microarcsecond level (Marakov 2009 (ApJ 707, L73), Lagrange et al.), the TOLIMAN mission will include a ground-based effort to understand and calibrate stellar activity noise that could degrade the HZ exoplanet sensitivity.

4. The TOLIMAN space telescope: concept and performance

The TOLIMAN mission is empowered by a novel optical architecture that can be implemented on a relatively modest 30cm space telescope that promises to deliver the required micro-arcsecond astrometric precision. This employs the concept of a Diffractive Pupil Telescope in which features embedded in the pupil cause starlight to diffract in the image. This innovation offers a cunning solution to the key problem that overwhelmingly dominates astrometric error budgets: stability. When trying to reference stellar positions at micro-arcsecond scales, a host of small imperfections and minute mechanical drifts, warps and creep of optical surfaces create instabilities that can be orders of magnitude larger than the true signal. Rather than trying to directly contain all these errors, the Diffractive Pupil approach sidesteps them by creating a new astrometric ruler to register the star's position: one formed from the starlight itself. The diffraction pattern from the pupil broadcasts a reference grid onto the detector plane against which stellar locations are registered. The genius of this approach is that the diffractive grid of starlight suffers identical distortions and aberrations to the signal being measured (the binary separation). Drifts in the optical system therefore cause identical displacements of both the object and the ruler being used to measure it, and so the data are immune to a large class of errors that beset other precision astrometric experiments. The principle is illustrated in the figure below.

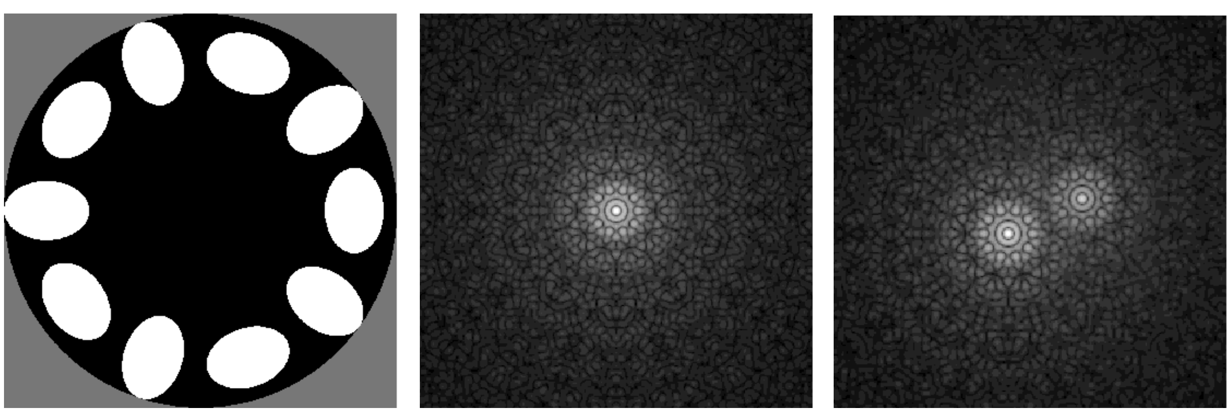


Figure 3 Left: pupil plane for TOLIMAN diffractive-aperture telescope. Light is only collected in the 10 elliptical patches (the remainder of the pupil is opaque in this conceptual illustration, although our flight design will employ phase steps which do not waste starlight). Middle: The simulated image observing a point-source star with this pupil.

The region surrounding the star can be seen to be filled with a complex pattern of interference fringes, comprising our diffractive astrometric grid. Right: A simulated image of a the Alpha Cen binary star as observed by TOLIMAN.

Numerical simulations based on this proposed architecture imply a fundamental noise floor limit (photon noise) that will achieve the mission goal astrometric precision of 0.2 micro-arcseconds for observations of bright targets such as Alpha Centauri (mV = 0/1.3mag) in only 6 hours of cumulative on-source integration. Fainter targets in the secondary science campaign will require significantly longer full exposure times, with an V=6mag star requiring about 2 weeks for the same final astrometric signal-to-noise.

The TOLIMAN mission has a detailed strategy to limit the impact of various forms of systematic noise, so that fundamental (photon-noise) limits can be obtained. In addition to the immunity to many forms of optical aberration (such as drift in the focal length) conferred by the diffractive pupil concept described earlier, TOLIMAN will also control errors by employing:

- An intrinsically stable thermal and mechanical design (with low CTE materials)
- Active controlling spacecraft temperature to <0.1K
- A network of thermal sensors to monitor all structural elements
- An on-board laser metrology to continually monitor the readout array
- A calibration campaign interleaving observations of stable multiple-star systems

The optical system required for the mission is extremely simple: this is a major design advantage in ensuring stability and predictability of the instrumental response under all conditions. A ray-trace of a potential TOLIMAN optical design is given in the figure below.

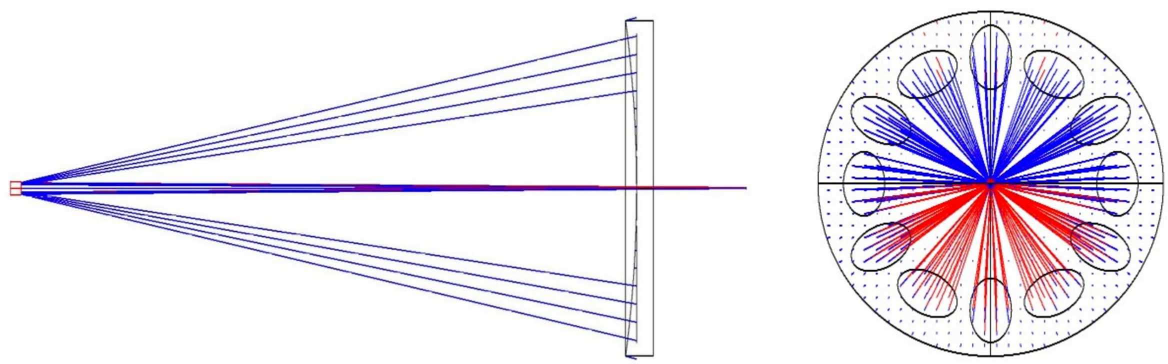


Figure 4. Left: Optical ray trace of a preliminary TOLIMAN telescope design. This is a deliberately-simple two mirror RC design with a 300mm primary and f50 beam from the secondary to the detector. Right: Rays from the primary mirror with a diffractive pupil pattern embossed on the surface are illustrated.

Appendix 1: Secondary Science Targets

TOLIMAN targets stars close to the Sun - these align with the core mission science (to deliver objects near enough for comprehensive characterization of properties with successor missions), as well as being well suited to astrometric detection. Furthermore the modest aperture requires relatively bright targets of spectral classes hotter than M-dwarfs, which also boast habitable zones in wider (months-to-years) orbits and proportionately larger astrometric signals. Fortunately, binary stars which provide an ideal phase reference to leverage the innovative TOLIMAN optical detection methodology are relatively plentiful.

Along with the primary science target Alpha Cen, a selection of the next best half-dozen multiple-star systems perfectly suited to study by the TOLIMAN astrometric mission are given in the table below. From a fundamental signal-to-noise perspective, all are bright enough to yield astrometric signals to meet the end-of-mission astrometric goal of 0.2 micro-arcseconds with a total cumulative on-source integration time of order several weeks: quite achievable (even taking overheads into account) over a 3 year mission without compromising the core science mission to Alpha Cen.

Name	Distance (PC)	Spectrum	V Mag
Alpha Cen	1.3	G2V + K1V	0.0 / 1.3
61 Cyg	3.5	K5V + K7V	5.2 / 6.0
70 Oph	5.1	K0V + K4V	4.0 / 6.0
36 Oph	6.0	K2V + K1V + K5V	5.1 / 5.1 / 6.3
Xi Boo	6.7	G8V + KvV	4.7 / 6.8
P Eri	7.8	K2V + K2V	5.9 / 5.8
Xi UMa	8.2	G8.5V + G0V	4.3 / 4.8

Appendix 2: Statistical probability for Alpha Cen hosting an Earth-like planet

At 4.3 light years away, Alpha Centauri is the closest star system to Earth. The next closest Sun-like (F, G or K type) star, Procyon, is at 11.4 ly, more than 2.5x further. Alpha Cen is a triple system: Alpha Cen A & B are Sun-like stars, while Proxima Cen is a lower mass main sequence M star, now known (by radial velocity study) to host an Earth-mass planet in a temperate-zone orbit (the only known rocky planet in the HZ for any star within 10 pc).

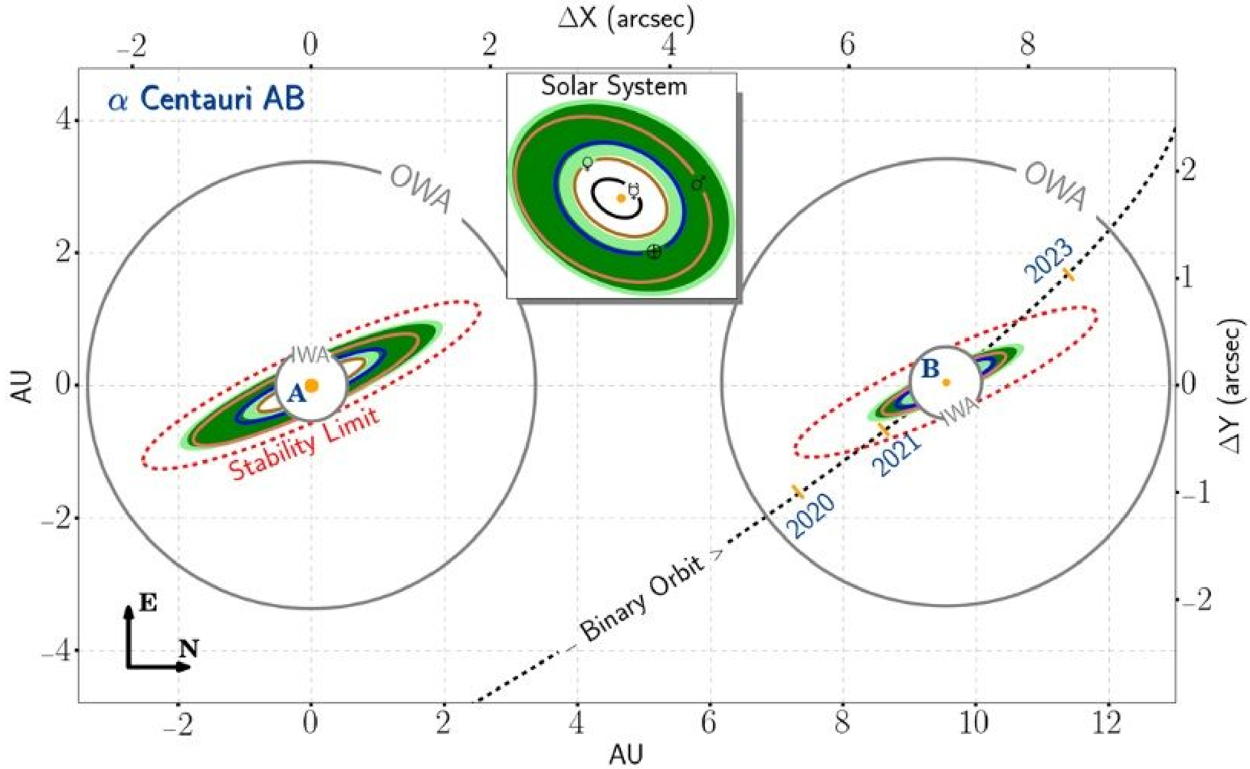


Figure 5: Habitable zones of Alpha Cen A (left) and B (right) in green, along with dynamical stability boundary (red dashed line), 0.4” and 2.5” inner and outer working angles (IWA and OWA) of a small coronagraphic mission. The inset shows the Solar System to scale. Planetary systems of Alpha Cen A & B are assumed to be in the plane of the binary (the likeliest scenario) and orbits of hypothetical Venus-like, Earth-like, and Mars-like planets are shown.

Based on existing astrophysical data, what is the likely incidence of Planets in the Alpha Cen A & B System? Dynamical studies have confirmed that habitable zone planet orbits are stable in the system (see Fig 5); indeed binary interactions dictate a stability limit well outside the temperate orbital zone for both stars. Recent studies based on statistics from the Kepler planetary dataset have found that the planetary formation process proceeds with lower efficiency in binary stars than for single stars (a factor of up to 3 suppression in expected planetary incidence was reported by Kraus and Ireland 2016).

Mitigating this to a degree, observing multiple stars with two or more components also gives proportionately greater odds for finding a planet. Careful studies taking all of these factors into account, and integrating over known exoplanetary incidence data as a function of planetary mass, orbit and host spectral type find that chances are in fact quite high (>70%) that a planet in the range 0.5 to 5 Earth masses exists in the HZ of at least one component of the Alpha Cen system.

Appendix 3: Overview: technologies for exoplanetary discovery in the solar neighborhood

A very brief summary of the technological landscape for projects targeting rocky planets around nearby stars is given. Several approaches are poised to deliver results: these are all complementary to the proposed outcomes of the TOLIMAN mission.

Radial Velocity. Recent discoveries of temperate-orbit exoplanets by the radial velocity (RV) method have been announced; most famously Earth's nearest neighbor Proxima Cen. This technique is now able to get down to Earth mass for cases where the primary star is extremely low mass (and therefore the planetary signal proportionately larger). This occurs for M-dwarf stars for which temperate orbits lie very close to the host. The potential habitability of such systems, so different in configuration from the Earth-Sun, is an area of active debate. Pushing RV down to sensitivity levels required for true Earth analogs around FGK stars is difficult due to intrinsic stellar noise processes, although many groups are working to improve the precision. RV is nicely complementary to the astrometric approach of TOLIMAN, which works well with solar-type stars, but loses efficiency for M-dwarfs.

Imaging. High resolution imaging assisted by advanced technologies such as coronagraphs is also a promising emerging technology for planetary characterization. Ambitious large space coronagraph missions should begin to make inroads on a timescale of a decade or two. In the near term, the most promising avenue is ground based imaging in the thermal infrared (around 10 microns) for which the planetary contrast against the host star is maximized. For Alpha Cen itself, projects currently sponsored by the Breakthrough Watch initiative on the present generation of 10m class telescopes have the potential of discovering rocky exoplanets. Although less sensitive than TOLIMAN and not able to reach stars beyond Alpha Cen until implemented on the coming generation of extremely large telescopes, information from imaging (yielding temperatures and radii) is highly complementary (TOLIMAN yields masses, orbits, and better mass detection thresholds). Both are supported by Breakthrough.

Astrometry. Existing astrometric missions, both from space (GAIA) and ground (ESO's GRAVITY instrument) are capable of astrometric precisions in the 10's of micro-arcseconds (typically planets at this detection threshold would be expected to be gas giants). Astrometric missions targeting rocky planets have been proposed, however almost all have a far larger envelope than our TOLIMAN proposal (telescopes of order meter class, budgets in excess of $50M). Size is driven by the requirement to collect sufficient photons while observing wider-field reference stars (such objects require more collecting area, and far more demanding specifications on optical and mechanical systems).

Transits. Transits are unlikely to contribute significantly to near-field (<10 pc) planetary science. Event probabilities are too low for such a narrow, volume-limited sample. If we restrict interest to only Sun-like FGK stars, probabilities are extremely remote.