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Invited Paper

Imaging nearby, habitable-zone planets with the Large Binocular Telescope Interferometer

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ABSTRACT

One of the main design considerations of the Large Binocular Telescope (LBT) was the goal to resolve the habitable zones (HZs) of the nearest stars at mid-infrared wavelengths around 10 μm. The LBT Interferometer (LBTI) makes use of the telescope's two 8.4 m mirrors on a common mount and their 22.7 m edge-to-edge separation for sensitive, high-angular resolution observations at thermal-infrared wavelengths. In addition to adaptive optics imaging using the two mirrors separately, the instrument enables nulling and Fizeau imaging interferometry exploiting the full resolving power of the LBT. The LBTI team has successfully completed the Hunt for Observable Signatures of Terrestrial planetary Systems (HOSTS), for which we used nulling-interferometry to search for exozodiacal dust, and we are continuing the characterization of the detected systems. Here, we describe a new program to exploit the LBTI's Fizeau imaging interferometric capabilities for a deep imaging search for low-mass, HZ planets around a small sample of particularly suitable, nearby stars. We also review the LBTI's current status relevant to the proposed project to demonstrate the instrument is ready for such a large project.

Keywords: Infrared, adaptive optics, interferometry, high contrast, habitable zones, exoplanets imaging

1. INTRODUCTION

One of the defining goals of astronomy in the coming decades is the detection and characterization of rocky, potentially habitable planets around stars other than our Sun (exo-Earths) and to search for biosignatures in their atmospheres. This goal can only be achieved by coordinating the development and integrating the results from powerful resources within the whole astronomy community across funding agencies and across the world.

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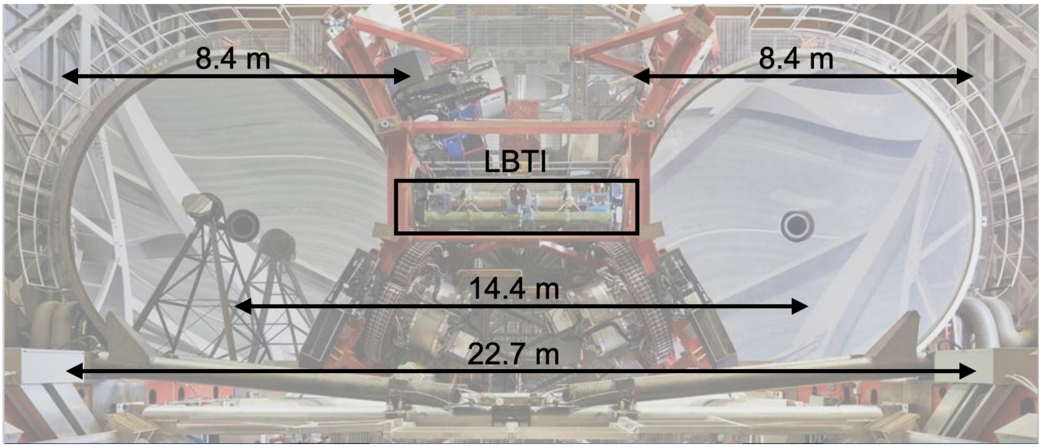

Figure 1. Illustration of the LBT's scales when used in conjunction with the LBTI. The LBTI structure is highlighted by the central box. The LBT is in this image not configured for sending light to the LBTI. Background image credit: LBTO – Enrico Sacchetti.

The community-wide focus is particularly evident from the recent National Academy of Sciences' report on the Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)*, which recommended that the design of NASA's next flagship mission be driven substantially by the goal to image the habitable zones (HZs) around a significant number of nearby stars and to detect rocky, potentially Earth-like planets there. The amount of resources that need to be expended to reach this goal can be significantly reduced by better understanding the technical and astronomical requirements for such a mission. Hence, while a large exo-Earth imaging mission is a few decades away, preparatory research at the present time can critically enable such a mission while at the same time reducing its burden on the rest of the astronomy community. This preparatory research includes, for example, the determination of the frequency of rocky, HZ planets around nearby stars, the understanding of the effects of the host stars on planet habitability, the identification of candidates to image, and the exploration of nearby HZs to characterize their dust content. If a future, large mission costs of the order of \$10 B and will study ~ 20 targets (possibly optimistic), then the cost per target will be \$500 M and target selection is critical to maximize the scientific output. In addition, we could potentially already image the first planets around a small sample of particularly suitable stars in the coming years or decades and at a cost per target that could be two orders of magnitude lower! Even eliminating possible targets of a future, large mission, e.g., because they have detected giant planets in their habitable zone making the presence of a low-mass planet less likely will be important. Finally, contextual information on planetary systems and planet that cannot be obtained from a scattered-light imaging mission alone will be critical to reliably assess planetary habitability[1].

This preparatory research is a major science driver for the Large Binocular Telescope Interferometer (LBTI[2–4]). The LBTI is designed for sensitive, high-angular resolution, thermal-infrared observations. The N band (wavelengths $\sim$8-13 μm) is particularly suitable to study nearby HZs with ground-based observations because the Earth's atmosphere is sufficiently transparent, the thermal emission of dust and planets at temperatures around 300 K is close to its maximum, and thus the contrast between that emission and the host star's light is manageable. The long wavelength, however, requires the use of very large telescopes to achieve sufficient angular resolution to resolve HZs even around the closest stars. The high thermal background at those wavelengths requires a large collecting area and special mitigation efforts such as the use of adaptive secondary mirrors when performing adaptive optics observations. The Large Binocular Telescope, when used in conjunction with the LBTI, possesses many of the features of future 30-m-class telescopes and is thus particularly well-suited to carry out the first such observations now, almost a decade before the first of these telescopes comes online. Fig. 1 illustrates the scales of the LBT when used in conjunction with the LBTI.

The LBTI combines the two 8.4 m apertures of the LBT interferometrically in addition to modes using the individual apertures. Using nulling interferometry in N band to detect and study exozodiacal dust[5–13],

*Pathways to Discovery in Astronomy and Astrophysics for the 2020s, https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s

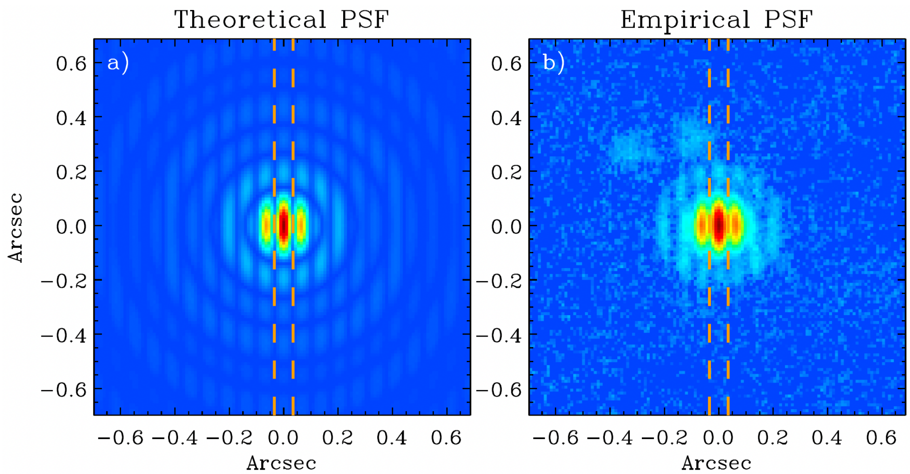

Figure 2. Theoretical (a) and observed (b) Fizeau PSF obtained with LBTI/LMIRCam[21] at 4.8 μm. The vertical, dashed lines indicate the theoretical location of the first dark fringes. The two faint sources in the upper-left of the observed PSF are optical due to internal reflections in the instrument that have been mitigated since these data were taken.

specifically HZ dust around stars other than our Sun, was the goal of the now-completed Hunt for Observable Signatures of Terrestrial planetary Systems (HOSTS) and the original core science driver for the LBTI[10, 11, 14, 15]. Fizeau imaging interferometry is a different interferometric mode of the LBTI that can provide sensitive, high-fidelity, and high-contrast images at the angular resolution of a single, 23 m telescope and over a relatively large field-of-view (up to ∼20 arcsec with the current LBTI).

In this paper we outline a program to use the Fizeau imaging mode of the LBTI to perform a deep search for low-mass planets in the HZs of the nearest, most suitable stars. We first summarize the status of interferometry at the LBTI (Sect. 2) before we outline the proposed project in Sect. 3. We discuss the technical requirements and upgrades to the LBTI needed to complete the program (Sect. 3.1), present our predictions of the sensitivity of LBTI's Fizeau mode after these upgrades (Sect. 3.2), and introduce the targets and estimate the required observing time (Sect. 3.3). In Sect. 4 we provide a brief summary of our proposal.

2. CURRENT STATUS OF INTERFEROMETRY AT THE LBTI

Originally, the LBTI's interferometric efforts were focused on nulling interferometry in the context of the HOSTS survey. Observations for HOSTS were completed in spring 2018. The HOSTS results and their impact on the design of a future exo-Earth imaging mission were prominently featured in the Astro2020 decadal survey and earned the LBTI team two NASA Honor Awards. The results have also informed all recent designs and yield studies of large space missions to detect and characterize exo-Earths through direct methods[16–20]. We have obtained new NASA/XRP funding (PI: S. Ertel) to further characterize the detected dust systems through detailed follow-up observations and this project is currently ongoing.

In summer 2018, the LBT started its Single-conjugated adaptive Optics Upgrade for the LBT (SOUL)[22, 23], for which the basic technical work was completed on LBTI's hardware in the spring of 2019, so that adaptive optics observations with the LBTI could resume while additional software work and commissioning are still ongoing. In spring 2019, we have demonstrated that the SOUL upgrade does not impair interferometric observations. In early 2020, the right (DX) adaptive secondary mirror had to be taken offline for necessary preventive and corrective maintenance. This work was delayed due to COVID and the mirror was only re-installed at the telescope in spring 2022. At that point, double-sided interferometry at the LBTI had not been done in three years (Non-redundant Aperture Masking, NRM, on the left aperture of the LBT was still possible and has been used). Over that period, we focused on single-aperture observations. In May and June 2022 we used a small amount of sky time (equivalent to an approximate total of two nights distributed over approx. two weeks of queue observing) to successfully re-commission double-sided observations (including new, cold field stops to image the fields from the two LBT apertures next to each other on the science camera instead of overlapping their backgrounds[4]) and nulling interferometry. We expect to resume nulling-interferometric observations for our NASA-funded program to characterize the detections from the HOSTS survey and other interferometric observations in fall 2022.

In addition to nulling interferometry, which is available with NOMIC in N band only, the LBTI has two more interferometric modes combining LBT's two apertures interferometrically; Fizeau imaging interferometry and NRM (the latter can also be done using the two apertures individually or only one aperture). Both modes combine LBT's two apertures in the focal plane on the detector. In Fizeau mode, the full apertures are used. This mode is available for use with both LBTI's LMIRCam (J to M bands) and NOMIC (N band) detectors. For NRM, a pupil plane mask with holes covering both pupils of the LBTI is inserted and the resulting fringes are imaged on the detector, analogous to single-telescope aperture masking[24,25]. This mode is, in principle, available for both LMIRCam and NOMIC, however, in practice only the masks in LMIRCam have been commissioned and used. This is because of the high thermal background in N band that limits the sensitivity and thus usefulness of NRM with NOMIC. In turn, NRM is more robust against phase errors which are more pronounced at shorter wavelengths, so that this mode is more suited for LMIRCam high-contrast observations unless the sensitivity of the two full apertures is required. All modes of the LBTI are available with and without fringe tracking, however, fringe tracking is critical to reach useful precision in nulling mode while routines to minimize non-common path and chromatic effects (i.e., optimizing differential tip-tilt and phase on the science camera relative to the fringe tracker) in the Fizeau imaging and NRM modes are not yet fully commissioned. Nonetheless, open-loop and fringe-tracked Fizeau imaging and NRM observations have been obtained and have produced ground-breaking science results[26–31].

Combining the light from the two LBT apertures in the focal plane in Fizeau mode creates an 'instantaneous Fizeau PSF'[21] with the angular resolution of the 22.7 m edge-to-edge baseline of the LBTI in one direction and the resolution of an 8.4 m telescope in the perpendicular direction (Fig. 2). Field rotation can be exploited to reconstruct a more circular 'reconstructed Fizeau PSF' with the 22.7 m resolution in all directions[21,28] (Fig. 3). In addition to the improved angular resolution compared to a single 8.4 m telescope, the background-limited sensitivity is improved because of the doubled collecting area, the more compact PSF into which the light is projected (higher peak source brightness), and/or the more compact photometric region that can be used (lower background photon noise for source detection and photometry).

When imaging point sources such as exoplanets, Fizeau interferometry has several advantages over nulling interferometry. The former produces a more compact PSF and the data can be analyzed using standard high-contrast imaging methods that are particularly sensitive to point sources such as angular differential imaging. Fizeau interferometry also uses all the light from both of LBT's apertures, while nulling interferometry uses a beam splitter for beam combination, rejecting 50% of the light. Moreover, nulling combines the two beams in the pupil plane and re-images them on the detector with the angular resolution of a single 8.4 m telescope (after suppressing the star light interferometrically with a 14.4 m baseline[32]). Hence, nulling interferometry is particularly suitable for detecting exozodiacal dust which produces extended emission that cannot be easily detected with ADI. This advantage of Fizeau interferometry is a result of LBT's small ratio between interferometric baseline and primary mirror diameter. Other implementations will prefer nulling interferometry for planet detection[20,33,34].

Since the completion of HOSTS, we have pursued a range of improvements to the system. We have carried out a range of Fizeau observations and tested approaches to minimize non-common path aberrations between the science camera and the fringe tracker[35,36]. An algorithm for closed-loop, real-time control of these aberrations is under development. Fizeau observations of Altair have produced the strongest direct-imaging constraints on circumstellar companions available so far down to a mass of $1.3\,M_\odot$ at close separations down to 0.15 arcsec[31]. We have also further developed dual-wavelength fringe tracking in the H and K bands to mitigate $n\lambda$ phase jumps[37,38] and to predict and correct chromatic atmospheric effects from precipitatble water vapor[39]. We have also obtained the first fringe-tracked dual-aperture NRM science observation, imaging the disk and companion candidate around the Herbig Be star MWC 297[27] (Fig. 4).

One of the main limitations of fringe-tracked interferometry is currently the bright limiting magnitude of $K \sim 4.5$ of our fringe-tracker, PhaseCam. This is due to LBTI's fringe tracking method[40] which tracks phase delay, tip, and tilt simultaneously, and due to the relatively high noise of the PICNIC detector used. The limiting magnitude is acceptable for nulling interferometry targeting bright, nearby stars, and for the new

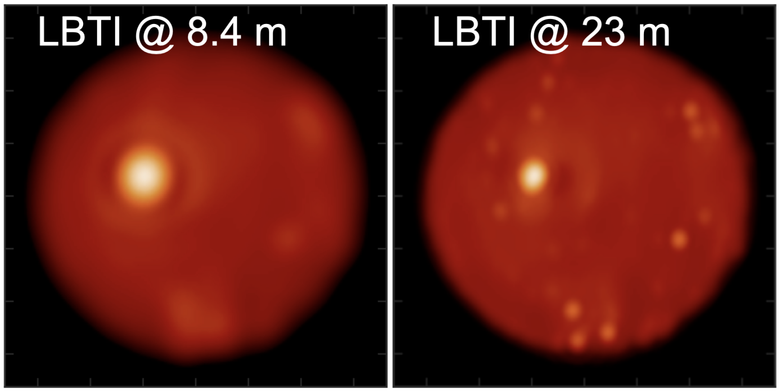

Figure 3. LBTI images of Jupiter's moon Io in M band with a single 8.4 m aperture and a reconstructed image from 22.7 m Fizeau interferometry. Io's disk has a diameter of ~1.2 arcsec in these images. Both the improvement in angular resolution and background-limited sensitivity (where the background here is dominated by Io's surface emission) are visible.

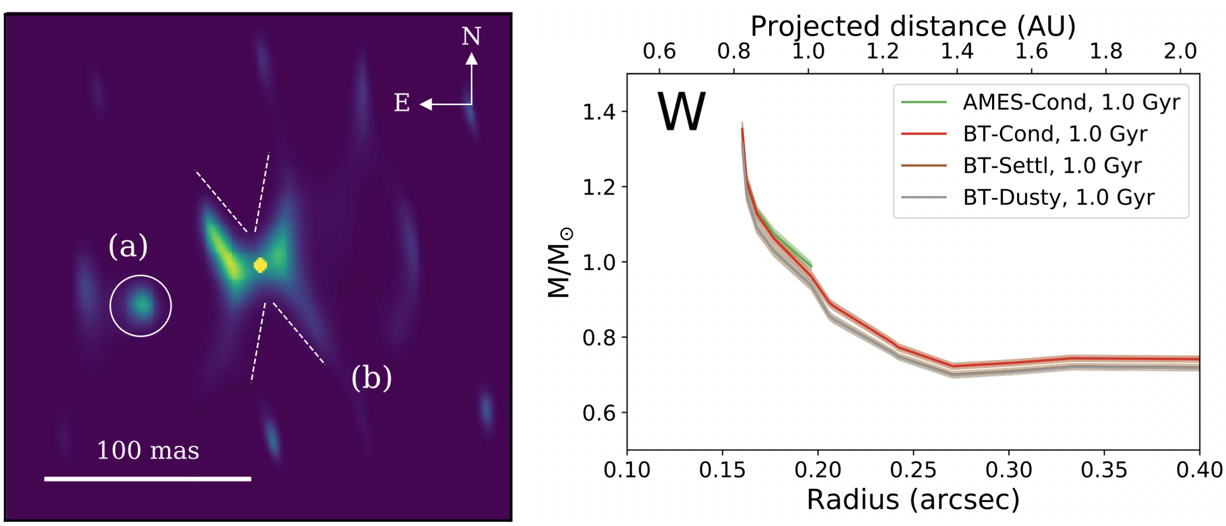

Figure 4. Recent LBTI interferometry results. *Left:* Model-independent image of the MWC 297 disk at 3.7 μm and companion candidate using fringe-tracked NRM observations[27]. Only ~10 min of science data were obtained to derive this image demonstrating the LBTI's snapshot capabilities. *Right:* Contrast curves from Fizeau observations of Altair[31] obtained with LMIRCam at 4.05 μm reaching down to a separation of ~0.15 arcsec from the star, the strongest direct-imaging constraints on companions around that star available today at such small separations.

project to search for HZ exoplanets around the nearest stars we are describing here. However, it is not suitable for many other interferometric observations that could otherwise be executed with the LBTI such as the imaging of protoplanetary disks, young planets, and potential Solar System and extragalactic observations requiring fringe tracking. We are in the process of developing a new fringe tracking camera using a low-noise SAPHIRA array which will help us overcome this limitation by reaching an expected limiting magnitude of $K \sim 9$ (lead: J. Stone).

Another challenge for interferometric observations at thermal-infrared wavelengths is the strong telescope and sky background. Classically, frequent nodding of the telescope (together with chopping to suppress low frequency detector noise where necessary) is used to correct for this. However, this is not always possible or efficient when performing interferometry because it would normally break the phase loop. We are developing new background-subtraction methods based on principal component analysis[41] to better remove the background in post-processing of the data. This can be applied to all LBTI data including Fizeau and nulling interferometry and has been shown to improve the background-limited sensitivity of NOMIC observations by a factor of up to a few over classical nod-subtraction methods.

3. USING FIZEAU IMAGING INTERFEROMETRY TO IMAGE EXO-EARTHS

In principle, the thermal infrared is a powerful wavelength range for imaging extrasolar planets. The contrast between the thermal emission of the cool planet and the light from the hot star is lower compared to the near-infrared. In particular, the emission of planets at temperatures around 300 K peaks near the N band. On the other hand, the angular resolution of telescopes decreases with wavelength and the thermal infrared background increases toward longer wavelengths, thus limiting the sensitivity of the observations. As a consequence, the N band imaging of planets in and near a star's HZ is generally considered the domain of future 30-m-class telescopes and limited to the nearest systems. As a proof of concept, the New Earths in the Alpha Centauri Region (NEAR) campaign on the Very Large Telescope reached sub-Neptune sensitivity in the HZs of the α Cen binary star in 100 hours of cumulative observations[42].

The LBT is in many respects the largest optical/infrared telescope in the world, and the LBTI the most sensitive ground-based mid-infrared instrument for this kind of observations. It also shares many properties with NEAR, in particular the use of adaptive secondary mirrors for adaptive optics correction and a sensitive N band camera (NOMIC[43]). We are currently executing the LBT Exploratory Survey for Super-Earths/Sub-Neptunes Orbiting Nearby Stars (LESSONS[4], lead: Wagner) in the northern hemisphere. The use of both apertures of the LBT simultaneously (but not combining them interferometrically), chopping with both positions on the science detector, and the cold winter temperatures of Mt. Graham's inland peak result in a significant sensitivity advantage over NEAR that helps compensating for the fact that potential target stars in the North are by a factor $\gtrsim 2.5$ further away than α Cen. To suppress the Excess Low Frequency Noise (ELFN) of NOMIC's Aquarius detector, we chop using the LBTI's pathlength correctors which are designed for fast tip-tilt control in addition to piston control and provide a chop throw of up to $\sim$8 arcsec. We can thus reach Saturn to Jupiter mass sensitivity in/near the habitable zones of $\sim$10 northern stars such as Sirius or Vega in a night of integration and expect to reach sub-Neptune size with a deep integration of 5-10 nights.

Over the next decade, the ultimate tool to enable the imaging of low-mass planets in the habitable zones of the nearest, most interesting Northern stars, however, is Fizeau interferometry! Combining the LBT's two apertures interferometrically in this mode can improve both the inner working angle and the background-limited sensitivity over individual-aperture observations. As a consequence, we can reach sensitivities to planet sizes similar to that reached by NEAR for α Cen around a small sample of particularly promising northern stars. In the following sections, we outline the technical challenges of this observing mode and discuss a detector upgrade as the one critical upgrade needed to achieve the predicted sensitivity, estimate the sensitivity we will reach after fully implementing the Fizeau mode for these observations, briefly introduce the primary targets, and compute the required observing time to execute these observations.

3.1 Technical requirements and limitations

Fizeau imaging of exoplanets is limited by the same requirements as sensitive AO imaging: high contrast and high sensitivity. High contrast is achieved by LBT's high-performance AO system and LBTI's phase-delay

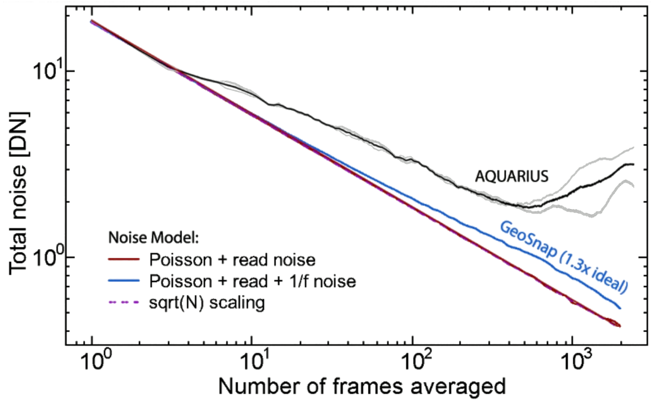

Figure 5. Noise performance of the GeoSnap detector in the lab compared to NOMIC's current the Aquarius and the ideal Poisson noise behavior. A single-frame integration time of 100 ms is used in all cases which results in 60% to 80% full wells in NOMIC for both the Aquarius and GeoSnap detector. Standard data reduction methods are applied (e.g., nod subtraction of the thermal background). The noise in the on-source image sequence after a nod offset is assumed to be entirely de-correlated spatially (in detector coordinates) from that in the previous nod position due to use of a different detector region and temporally from that in the last and next image sequence in the same nod position, so that the $\sqrt{t}$ behavior is expected to continue beyond the sequences of 2000 frames shown here.

fringe tracking and internal tip-tilt correction. Both closing the AO loop and the phase and tip tilt loop on bright, nearby stars has been done routinely during the HOSTS survey and the ability to control the loops for high-contrast observations has been demonstrated throughout the survey. The performance metrics from those observations can be used to quantify the performance for Fizeau interferometry. The system has a residual differential tip-tilt jitter of 10 mas RMS between the two telescope beams, equivalent to $\sim$1/30 of the single-aperture telescope PSF and $\sim$1/10 of the Fizeau PSF. In addition to tip-tilt jitter, the stability of the Fizeau PSF is also limited by the stability of the phase between the two wavefronts, as phase variations will shift the fringes of the PSF and thus skew its shape. A phase shift between the two apertures of one wavelength would move the fringe pattern by one full cycle, i.e., by λ/B where λ is the wavelength of 11 μm and B is the baseline of 22.7 m, i.e., $\lambda/B = 100$mas. LBTI's phase variations in closed-loop are limited by phase jitter at high frequencies (periods shorter than the typical integration time of the science camera of $\sim$50 ms). The typical amplitude of this jitter during the HOSTS survey was 650 nm RMS or 0.06 λ at 11 μm, resulting in a shift of the fringe pattern by $\sim$ 6 mas, lower than the residual differential tip-tilt jitter of the system. The amplitude of the phase jitter at lower frequencies is $\sim$4 times lower than that of the high-frequency phase jitter and thus negligible. Given the very short integration times of the science camera and the available telemetry from the fringe tracker at a frequency of 1 kHz, these quantities turn into well-known statistical properties that can be controlled during the data reduction, thus further mitigating their impact on the contrast of the observations. Ongoing vibration mitigation efforts at the LBT are expected to further reduce the amplitudes of all of these parameters in the near future.

The second limitation to our observations is the background-limited sensitivity. This is constrained by the background photon noise and, more so, by the ELFN of NOMIC's current Aquarius detector. This noise is known to be of the order of 5$\times$ the background noise after a few minutes of integration and usually suppressed by fast ($\sim$ 10 Hz) chopping. Chopping, however, creates significant residuals for high-contrast observations (see, e.g., the persistence stripe described for NEAR[4,42]). Furthermore, the current method of chopping with the LBTI uses the pathlength correctors and thus moves both telescope beams on both the science camera and the fringe tracker. This breaks the phase loop, which is not compatible with fringe-tracked Fizeau interferometry. An instrument upgrade with a chopper downstream of the fringe tracker would be technically challenging and likely result in poorly controlled non-common path aberrations between the fringe tracker and the science camera. Instead, we have explored the use of two alternative detectors; a HAWAII detector with a 13 μm cut-off wavelength and a GeoSnap detector with a similar cut-off. Both detectors are produced by Teledyne Imaging Sensors (TIS).

While both detectors have been found to be free of ELFN, the HAWAII detector has the disadvantage of a very low well depth which makes it challenging to use in the high-background environment of ground-based, broad N band observations. We find that the detector would need to be operated in NOMIC with integration times <7 ms, which requires sub-framing to very small readout regions (effectively a 2.5×10 arcsec stripe), thus severely limiting the field-of-view. The resulting limitation to NOMIC's versatility as a general-use science instrument is not acceptable, so that we reject this detector for a possible upgrade.

The GeoSnap detector we used for characterization is destined for the MIRAC instrument[44]. Its high well depth allows for integration times of the order of 100 ms in NOMIC without saturating on the background. This is comfortably within the full-frame operation regime of this detector. On the other hand, the GeoSnap detector is known to exhibit red $1/f$ noise. We find from our laboratory testing that under realistic sky conditions the $1/f$ noise is small compared to the background photon noise and the total noise of the observation, solely suppressed by nodding at a frequency of ∼0.01 Hz and common data reduction methods, is only a factor ∼1.3 worse than the ideal, background-photon noise limited case (Fig. 5). It is important to note that this result specifically applies to NOMIC with its specific thermal background and in particular the heavily over-sampled PSF. NOMIC's pixel scale is 17.9 arcsec (and with the GeoSnap would be 10.7 arcsec), designed to sample the Fizeau PSF from the 23 m baseline, but only collecting background from two 8.4 m apertures. As a consequence, the background per pixel is lower compared to the Nyquist-sampled PSF of a filled-aperture telescope. This allows for longer single-frame integrations, which we found to effectively reduce the $1/f$ noise.

The fact that the GeoSnap detector operates at near-ideal, background-limited noise performance in NOMIC makes it the best available replacement for NOMIC's current Aquarius detector. This detector upgrade is a critical prerequisite for our proposed program as it increases the sensitivity of our observations by a factor ∼ 4 over the current system when not chopping, and thus the required integration time per target by a factor ∼16. We are currently actively seeking funding to perform this upgrade (total hardware and labor cost ∼$2.5M).

3.2 Sensitivity

The great success of NEAR has established it as a sensitivity benchmark for the N band imaging of exoplanets. LBTI's NOMIC camera is comparable to NEAR in all its main properties. In particular, it is located behind an adaptive secondary mirror (one for each of the LBT's apertures) and currently has a similar Aquarius detector. During the LESSONS commissioning we have demonstrated that the two cameras show comparable performance under the same conditions. We thus use the sensitivity achieved by NEAR as a baseline for our sensitivity estimates for NOMIC. We have also shown that the sensitivity of LESSONS observations with NOMIC is ∼2.5 times better than NEAR when taking advantage of the peculiarities of the LBT and LBTI:

- Using both apertures of the LBT with the fields-of-view placed next to each other on the detector without overlapping the PSFs or background provides a factor $\sqrt{2}$ in sensitivity.
- Chopping with LBTI's pupil mirrors with both positions on the detector while NEAR chopped on/off the coronagraph provides another factor $\sqrt{2}$.
- The colder average temperatures on Mt. Graham's inland peak compared to Paranal reduce the thermal background, providing another 25% improvement.

In addition, when using Fizeau interferometry, we expect an improvement from the improved angular resolution. The instantaneous Fizeau PSF has an FWHM of $\sim \lambda/B$ (where B is the maximum baseline of 22.7 m) along the minor axis and of $\sim \lambda/D$ (where D is the primary mirror size of 8.4 m) along the major axis. This means that a non-circular photometric aperture with ∼1/3 of the area of the single-telescope aperture can be used to detect point sources in science images. This reduces the background photon noise in the aperture by a factor of $\sqrt{3}$, increasing the sensitivity by the same amount. This is an approximation, because ultimately we will use image reconstruction exploiting field rotation to obtain a near-circular reconstructed Fizeau PSF and a different, circular photometric aperture, but more detailed simulations are generally consistent with this factor $\sqrt{3}$ in sensitivity improvement.

The GeoSnap detector shows $1/f$ noise reducing its sensitivity by about a factor 1.3 compared to the ideal photon noise regime when not chopping. This is well compensated for by a ∼ 50% improved quantum efficiency over the Aquarius detector. In addition, our estimates comparing the GeoSnap's sensitivity without chopping

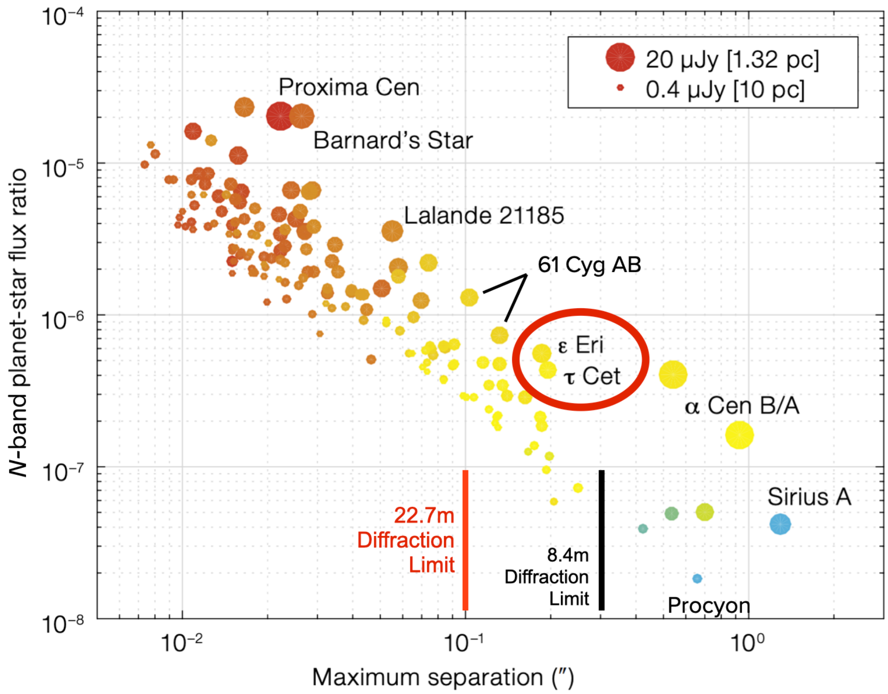

Figure 6. Separation, brightness, and N band contrast of Earth in N band when placed around the nearest stars[45], at a separation scaled from 1 au multiplied by the square-root of the star's luminosity with respect to the Sun (Earth-equivalent insolation distance).

with that of NEAR's Aquarius detector with chopping are conservative, as we are assuming that chopping fully removes NEAR's ELFN noise, does not leave other residuals, and apart from ELFN the Aquarius's behavior is otherwise ideal. Those assumptions are not true, as strong persistence effects limit NEAR's sensitivity to only $\sim$50% of the azimuthal field-of-view and other effects such as detector cosmetics further limit the sensitivity[42]. We here conservatively assume a factor $\sqrt{2}$ for these effects, while the real factor can be considered at least that large due to NEAR's field-of-view limitation which would have required double its integration time to cover its full field-of-view.

To conclude, we expect the following improvement factors in sensitivity from using the LBTI in Fizeau imaging mode:

- 2.5 as demonstrated by LESSONS,
- $\sqrt{3}$ from Fizeau interferometry,
- $\geq \sqrt{2}$ from other noise sources in NEAR that we do not expect to be present.

Therefore, in total we expect a factor of 6.1 improvement with respect to NEAR. In the following section, we discuss the scientific opportunities this improved sensitivity presents.

3.3 Targets and required observing time

Since the LBT is located in the northern hemisphere, the closest Sun-like star, α Cen, is not reachable by our proposed program. However, the improved sensitivity and inner working angle enable observations of a range of other targets, most notably ϵ Eri, τ Cet, and 61 Cyg A and B. Compared to α Cen, those systems are 2.3-2.6 times farther away, so the angular size of their HZs is smaller by that same factor. This is, however, well compensated by the 3× better angular resolution of LBTI compared to the VLT which observed α Cen. Comparable planets are also five to seven times fainter around those stars then around α Cen, which is well compensated by the $\sim$6.1× better sensitivity of the LBTI in Fizeau mode. In turn, the contrast of comparable planets around our target

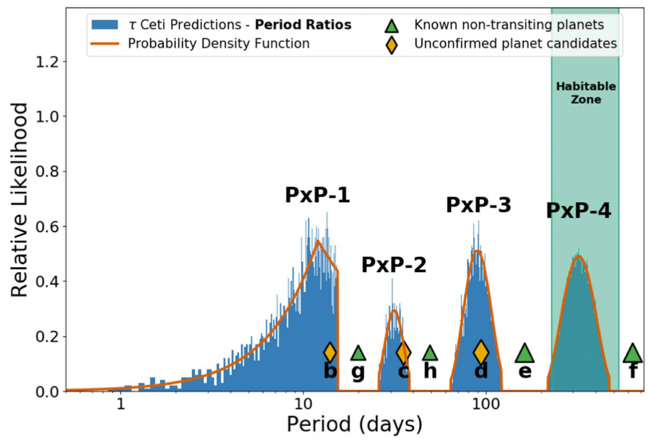

Figure 7. Probabilistic analysis of the architecture of the τ Cet system with confirmed radial velocity planets, suggesting the presence of a super-Earth or mini-Neptune planet in the HZ[48].

stars is more favorable (Fig. 6) and both ϵ Eri and τ Cet have well-characterized systems with planets known from radial velocities, with strong indication that planets around those stars could also be imaged directly. Moreover, the binarity of the α Cen system reduces the probability that this system hosts planets[46], making ϵ Eri and τ Cet more promising targets for an exo-Earth imaging search. The closest approach of the 61 Cyg binary on its orbit is several times farther from the stars' HZs than in the α Cen system, making it more likely to host HZ planets[46] so that it is still a promising target. ϵ Eri and τ Cet were observed by NEAR, providing detection limits to giant planets outside their respective HZs[47], but not providing the sensitivity and inner working angles we expect to reach with the LBTI. In the following, we briefly discuss the relevant aspects of each of those systems. In Table 1 we list the relevant observational properties and the integration time required to reach a similar sensitivity to planet mass as NEAR did around α Cen. In addition to these prime targets, more stars could be observed, e.g., early-type stars such as Sirius, Vega, etc. or slightly more distant stars for which Neptune- or Saturn-mass planets slightly outside the HZ could be detected, still putting critical constraints on the architectures and dynamics of their planetary systems in general and their likelihood of hosting HZ planets in particular.

ϵ Eri: This is the closest broadly Sun-like star (spectral type early K2 V) after α Cen and the closest such star that is not in a binary system. The star hosts a prominent debris disk that includes warm emission from a proposed asteroid belt[49,50]. Most noteworthy, the star is orbited by a $0.66\,M_J$ planet at 3.5 au[51,52] which has not been imaged previously, but will be easily detectable by our observations in about one night of observations. ϵ Eri also hosts a massive zodiacal cloud[11] that is expected to contain structures from the gravitational interaction with any planet present, likely allowing for the indirect detection of lower-mass planets than we could image directly, and for the better characterization of detected planets through the structures they create in the dust. The star is relatively young compared to the Sun (~600 Myr). Our limited knowledge of the emergence of life in the universe or even on Earth is limited, but there is evidence that it emerged on Earth before or around that age[53]. Thus, discovering a potentially life-bearing planet around a young, very nearby start that could potentially be studied via probes in the not-too-distant future would be particularly interesting. The formation of biosignatures observable from Earth with current or planned instrumentation may take much longer, so that studying planets at different ages is important to test evolutionary trends in broadly Earth-like planets potentially developing life[54,55].

τ Cet: This is the closest G-type star (G8 V) after α Cen and closest such star that is not a binary, making it the closest single Sun-like star. At an age of 5.8 Gyr, it also has a similar age to our Sun and thus circumstellar planets had a similar amount of time to develop life and for it to alter its atmosphere to create detectable biosignatures. The star is known to host a number of low-mass radial velocity planets in or near the habitable zone and a probabilistic analysis of the system strongly suggests the presence of a super-Earth or mini-Neptune planet in the HZ[48] (Fig. 7). The system contains a cold debris disk[56], but no signs of warm dust have been detected[11], so

Table 1. Integration time estimates per target.

	α Cen	ϵ Eri	τ Cet	61 Cyg AB
distance [pc][58]	1.35	3.23	3.56	3.50
brightness factor[a]	1.0	0.17	0.14	0.15
integration time[b] [h]	100	93	137	119

Notes: [a] The brightness factor $\xi_\star$ is computed as $\xi_\star = (d_{\alpha\,\mathrm{Cen}}/d_\star)^2$ and describes how much fainter a planet around the target star would be compared to the same planet with the same temperature around α Cen, simply due to the different distance d. [b] The integration time $t_\star$ required to detect this planet around the target, taking into account the estimated sensitivity improvement factor f of LBTI in Fizeau mode compared to NEAR is computed as $t_\star = t_{\alpha\,\mathrm{Cen}}/\left(6.1\xi_\star\right)^2$, where the factor 6.1 is the expected sensitivity improvement from using LBTI. We use 100 h for the NEAR integration time instead of the 75-80% best data ultimately used[4], because we can expect a similar amount of poor quality data when executing the observations with the LBTI in an efficient queue mode compared to the classically scheduled NEAR time, but with the higher fraction of poor weather on Mt. Graham.

that such dust is unlikely to strongly obscure any HZ planets detectable by our proposed observations.

61 Cyg A and B: 61 Cyg is a binary star similar to α Cen but of later spectral types (K5 V and K7 V). At an orbital semi-major axis of the binary of 85 au and an eccentricity of 0.5, the habitable zones around both stars are stable. The late spectral types of both stars make the contrast between a rocky, HZ planet and the host star particularly favorable. On the other hand, the HZs around both stars are more compact than around ϵ Eri and τ Cet, making them more challenging to reach. No planet or dust detections have been reported in this system. However, its binarity makes the system a likely target for the Toliman project[57], so that any detected planet could be more precisely characterized by precisely measuring its mass, orbit, temperature, and density. The binary also has a similar age to the Sun giving planets a similar amount of time to develop life.

4. SUMMARY

We described a new program to use the LBTI/NOMIC in Fizeau imaging interferometry mode to perform a direct imaging search for planets in the HZs around the most promising, Sun-like, northern stars. While more distant than α Cen, these stars may be considered as interesting and promising for hosting detectable planets as α Cen, and two of our targets, ϵ Eri and τ Cet are in many respects more likely to do so with already known and inferred planets. We expect to reach a sensitivity to planet diameters around these stars comparable to that of the NEAR experiment around α Cen in a similar integration time. The resolution and sensitivity improvements from the LBTI in Fizeau mode compensate for the larger distance and thus more compact angular size of the stars' HZs and the lower flux from similar planets compared to α Cen. These observations require replacement of NOMIC's Aquarius detector with a detector that is free of ELFN to alleviate the need for fast chopping and thereby enable sensitive, fringe-tracked Fizeau interferometry. We have identified the GeoSnap detector from Teledyne Imaging Systems as the most suitable detector and are actively searching for funding to implement this upgrade, after which the observations can start almost immediately.

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