Invited Paper

Overview and prospects of the LBTI beyond the completed HOSTS survey

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ABSTRACT

The Large Binocular Telescope Interferometer (LBTI) combines the light from the two 8.4 m primary mirrors of the LBT for interferometry and adaptive optics (AO) imaging. With two high performance, state-of-the-art AO systems and adaptive secondary mirrors, a cryogenic instrument, and an edge-to-edge baseline of 23 m, the LBTI is a unique instrument for sensitive, high-angular resolution and high-contrast thermal infrared observations. After the successful completion of the NASA-funded HOSTS nulling interferometry survey for exozodiacal dust, our team is now completing the commissioning and extending the capabilities of other observing modes, namely Fizeau imaging interferometry, spectro-interferometry, integral field spectroscopy, non-redundant aperture masking, and coronagraphy for general astronomical observations. In this paper we briefly review the design of the LBTI, summarize the results and performance of HOSTS, and describe the LBTI's wider current and future capabilities.

Keywords: Interferometry, Adaptive optics, Astronomical optics, Infrared astronomy, Exozodiacal dust, Exoplanets, Spectroscopy

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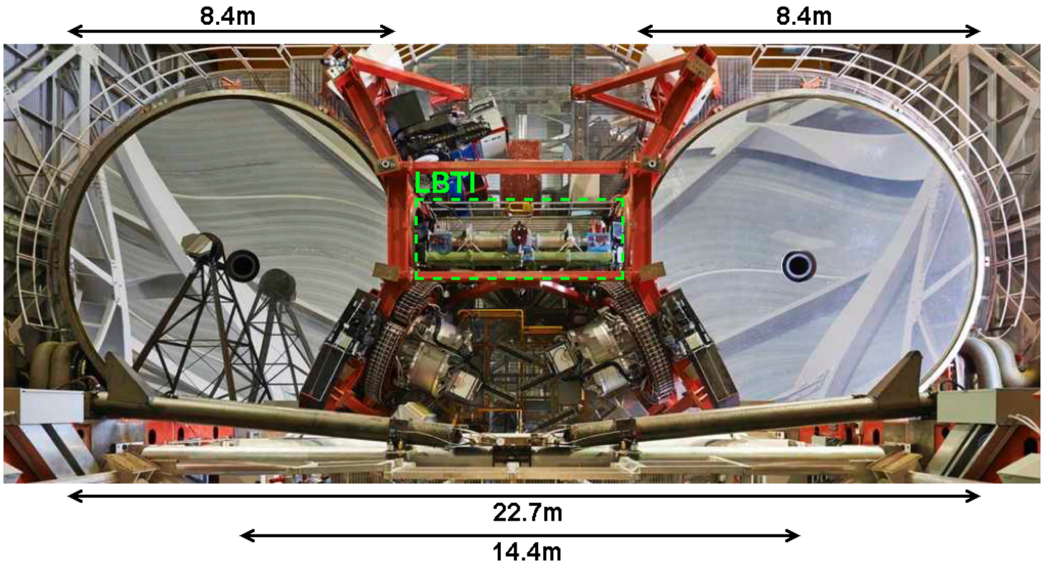

Figure 1. Front view of the LBT's primary apertures. The LBTI structure is highlighted by the green, dashed box. The relevant scales of the telescope for LBTI observations are indicated. The LBT is in this image not configured for LBTI observations.

1. INTRODUCTION

The Large Binocular Telescope Interferometer (LBTI[1]) is a sensitive thermal infrared interferometer and adaptive optics (AO) imager at the Large Binocular Telescope (LBT). It is located at the bent Gregorian foci between the telescope's two 8.4 m primary mirrors. The light is wavefront-corrected using the telescope's two adaptive secondary mirrors before it enters a fully cryogenic beam combiner. This results in a minimum number of only three warm reflections and the location on the common mount together with the primary mirrors allows for a unique instrument design without instrument rotator or long interferometric delay lines.

The development of the LBTI was funded by NASA's Exoplanet Exploration Program (ExEP) to carry out the Hunt for Observable Signatures of Terrestrial planetary Systems (HOSTS) survey for exozodiacal dust, i.e., dust in the inner regions of mature planetary systems. While such dust has also been observed very close to stars,[2–7] the LBTI has been designed to detect warm dust in and near the habitable zones (HZ) of nearby main-sequence stars. It uses nulling interferometry[8–10] in the N band to spatially resolve the dust and suppress the bright star light, so that the faint circumstellar emission can be revealed. In addition, the instrument is capable to observe in a variety of observing modes, in particular AO-assisted high-contrast and high-angular resolution imaging in the J to N bands using one or both LBT apertures, integral field spectroscopy across the L and M bands, aperture masking interferometry in the H to M bands using the two apertures individually or across both apertures for a baseline of up to 23 m, and Fizeau imaging interferometry and spectro-interferometry across both apertures in the L to N bands. The core HOSTS survey has been completed successfully in summer 2018. While the LBTI has always been available for use by to the whole LBT user community, the instrument team's main focus is now to evolve the instrument into a versatile and efficient general investigator instrument. The ultimate goal will be to hand over the LBTI to the LBT observatory as a facility instrument.

In this paper we present a status update of the LBTI project. We first present a brief overview of the LBTI's design (Sect. 2). We then summarize the results from the HOSTS survey with emphasis on an analysis of the instrument performance (in Sect. 3) and potential improvements. In Sect. 4, we describe the main observing modes and operation of the LBTI, discuss the status of each mode, and show exemplary science results. We conclude in Sect. 5 by outlining the path ahead for the instrument over the next couple of years, including future extension of capabilities and the development of LBTI toward being a facility instrument at the LBT observatory. A brief summary is provided in Sect. 6.

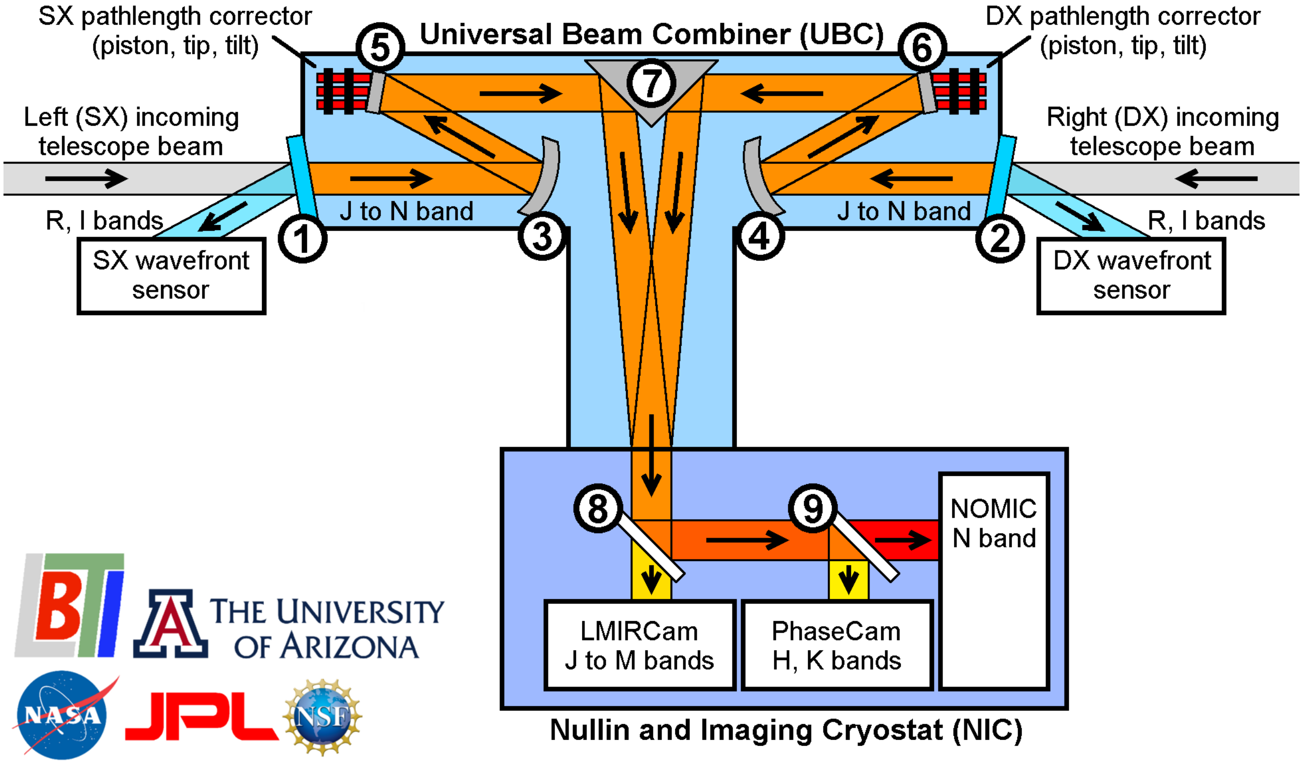

Figure 2. Sketch of the LBTI architecture. For a description, see Sect. 2.

2. DESIGN OVERVIEW OF THE LBTI AND UPDATES

Detailed descriptions of the LBTI and its components have been presented in previous papers.[1,11–15] Here, we present a brief overview and describe updates to the system since the latest comprehensive publication[1] and briefly summarize the now available observing modes.

2.1 Overview

Fig. 1 shows the location of the LBTI on the common mount of the LBT. It is located in the ∼6 m wide space between the telescope's two 8.4 m mirrors at their center bent Gregorian foci. The light from the primary mirrors is reflected into the instrument from both sides by the telescope's adaptive secondary and rigid tertiary mirrors. The Gregorian design creates a focus in front of each of the adaptive secondary mirrors where calibration sources for the AO system and science instruments can be inserted.

Fig. 2 shows a sketch of the LBTI instrument and in the following we refer to the numbered labels on this sketch. The incoming light from the tertiary mirrors first hits the Entrance window dichroics (1, 2). These dichroics serve both as the entrance windows to the cryogenic (temperature ∼80 K) Universal Beam Combiner (UBC) and as the wavefront sensor beam splitters. Red visible (predominantly R and I bands) light is reflected to the wavefront sensors.[14] Infrared light (J to N bands) is transmitted into the UBC where it is reflected by ellipse mirrors (3, 4) that create a pupil plane near the pupil mirrors (5, 6). The light is reflected from the pupil mirrors to the roof mirrors (7) and down into the Nulling and Imaging Cryostat (NIC). A selectable beam splitter (8) transmits either the L and M bands or the J to M bands to the LBT Mid-InfraRed Camera (LMIRCam[11]) and reflects the H, K, and N bands or only the N band. The reflected light is further separated in near infrared and mid-infrared light (9). The near-infrared light is sent to the fringe sensing camera (PhaseCam[13]), while the mid-infrared light is sent to the Nulling-Optimized Mid-Infrared Camera (NOMIC[12]). Phase, tip, and tilt correction are performed by the pathlength correctors on which the pupil mirrors are mounted.

2.2 Completed and ongoing upgrades

A number of upgrades have been made and are currently in process to the instrument. The wavefront sensor units have been equipped with OCAM detectors as part of the telescope-wide Single-conjugated adaptive Optics Upgrade for the LBT (SOUL[16]). This results in improved performance on bright targets and a fainter limiting magnitude around $R \sim 18$. Rotators on hydrostatic bearings have been installed that allow for the selection of different entrance windows so that a beam splitter optimized for the iLocater[*] wavelength range can be inserted.

Originally, the SX (left) pathlength corrector consisted of a Piezo stack that allowed for fast (kHz) pathlength, tip, and tilt correction, while the DX (right) pathlength corrector consisted only of a translation stage that allowed for initial pathlength minimization with long range, but not for fast pathlength correction or any tip-tilt correction. The DX side was upgraded by adding a Piezo stack on top of the translation stage, providing redundancy and additional operational flexibility and tip-tilt control capabilities on the DX side. The pathlength correctors are currently operated without the internal control loops provided by capacitive sensors on the Piezos. The calibration of the capacitive sensors for more accurate and repeatable movements is in progress. In addition, the pupil mirrors on the Piezo stacks are being replaced by new ones. The new mirrors promise improved optical quality for reduced non-common path aberrations with the AO system. Moreover, they have masks imprinted on them that block the bright infrared emission of the central obscuration of the LBT primary mirrors and from outside the telescope pupils for reduced thermal background. In an aperture wheel near the entrance windows (inside the UBC), new, cold field stops are being installed that allow for a partial obscuration of the field of view from each telescope aperture. This will in the future avoid overlapping backgrounds from the two telescope apertures across the entire field of view (FoV) when placing the images from the two sides next to each other on the science detectors for improved background-limited sensitivity. This reduces background noise and improves the background-limited sensitivity of the science cameras. A coherent, artificial light source is being mounted outside the UBC entrance window for full interferometric and independent aperture imaging simulation of the system for off sky engineering, testing, and development (lead: N. Anugu).

The original 1k×1k Hawaii H1RG LMIRCam detector has been replaced by a 2k×2k H2RG that provides a largely un-vignetted and undistorted FoV of 20 arcsec. In addition to the general FoV increase, this also provides a 2 arcsec FoV for the magnified Arizona Lenslet for Exoplanet Spectroscopy (ALES[15]) integral field unit. ALES itself has been upgraded (lead: J Stone) with a new lenslet array with improved optical quality and a range of magnifiers that will allow its combination with Fizeau imaging interferometry. LMIRcam has also been equipped with vector apodizing phase plate (vAPP) coronagraphs[19, 20] that can be combined with ALES.

3. HOSTS SURVEY RESULTS AND PERFORMANCE

The LBTI's core mission and main design driver is nulling interferometry to search for and characterize exozodiacal dust, dust close to nearby main sequence stars and specifically in their HZs. The LBTI has been funded by NASA to carry out the HOSTS survey which has been completed successfully in summer 2018 after observing 38 stars. In this section we briefly describe the results from the HOSTS survey with emphasis on the instrument performance. We also discuss the prospects of future nulling interferometric observations of exozodiacal dust.

3.1 Observing strategy and science results

The observing strategy for the HOSTS survey was described in detail by Ertel et al. (2018).[21] Nulling interferometry in N band was used to suppress the light from the central star, and to reveal faint, circumstellar emission. The optical path delay OPD between the two apertures was stabilized using PhaseCam in the K band and optimized by minimizing the total flux transmitted onto NOMIC, where the null depth (the flux ratio between destructive and constructive interference) was then measured. Nodding (offsetting the telescope pointing by a small angle of 2.3 arcsec to place the source in a different position on the detector) was used to subtract the variable telescope and sky background. Nulling observations were taken in both nod positions. A sequence of 2,000 null frames was taken (integration time 45 ms per frame) per nod position and three pairs of nods (six sequences of 2,000 frames total) were obtained per observation of a star. In addition, a photometric observation and corresponding background exposures were taken to flux calibrate the null depth. A sequence of dark frames

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[*] iLocater is an AO-assisted precision radial velocity spectrograph that uses part of the LBTI's architecture.[17, 18]

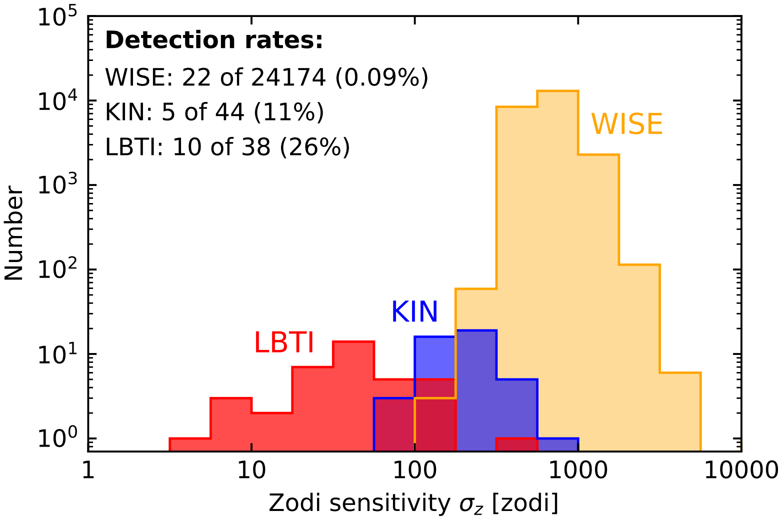

Figure 3. Distribution of sensitivity to habtable zone dust and sample sizes of LBTI,[25] KIN,[26] and WISE.[27] The unit of 1 zodi corresponds to the habitable zone dust surface density in the Solar system.

were also obtained each time a new star was targeted. Each observation of a science target (SCI) was paired with an identical observation of a reference star (CAL) to determine the instrumental null depth and to calibrate the science observations. CAL and SCI observations were typically concatenated to a CAL-SCI-SCI-CAL sequence and a nominal HOSTS observation of a science target consisted of two such sequences. Various reference stars were used to minimize the effects of imperfect knowledge about the reference stars (e.g., uncertain diameter, potential circumstellar emission, companions) and no individual reference star was paired twice with the same science target. Data reduction followed the strategy previously described by Defrère et al. (2015)[22] and Ertel et al. (2018).[21] The target selection was described by Weinberger et al. (2015)[23] and the modeling was described by Kennedy et al. (2015)[24] with updates described by Ertel et al. (2018, 2020).[21,25]

The scientific results of the HOSTS survey were published in two main survey papers.[21,25] The sensitivity reached was almost an order of magnitude higher than the LBTI's precursor, the Keck Interferometer Nuller (KIN), and about two orders of magnitude higher than space based spectro-photometry (Fig. 3). With a detection rate of 26% and a sensitivity to dust levels only a few times the Solar system level for the most suitable stars, the LBTI is now able to study common exozodiacal dust systems. The results have shown that there is a clear connection between cold debris disk dust in a system and its HZ dust, but recent work based on the detections has shown that the naive assumption of Poynting-Robertson drag from the outer dust disks to the HZ is insufficient to explain the HZ dust levels.[28] Furthermore, the LBTI has achieved the first detections of small amounts of exozodiacal dust around Sun-like stars and in particular stars without a cold debris disk. The data analysis is continuing with several detections being analyzed for detailed studies of individual systems. The HOSTS results have provided critical input for the yield estimates of future exo-Earth imaging missions.[29,30] The implications of the HOSTS results for future exo-Earth imaging missions have been discussed.[25] We found a best-fit median HZ dust level of 3 zodis from our sample, where 1 zodi is the level in the Solar system. At this level, the LUVOIR,[31] HabEx,[32] and Starshade Rendezvous[33] missions are expected to be capable of achieving the benchmark O_2 spectral detection at a wavelength of $0.76\,\mu$m with around their median sample target at a continuum signal-to-noise ratio of ten in reasonable integration times (less than 60 days). Important input has also been provided for the feasibility of the LIFE mid-infrared interferometric concept.[34] However, our measured median zodi level comes with a large uncertainty, so that the $1\,\sigma$ upper limit is 9 zodis and the 95% upper limit is 27 zodis. While at 9 zodis LUVOIR and HabEx can still achieve their O_2 measurements, WFIRST will have to relax its target signal-to-noise to $\sim$8. At 27 zodis HabEx would not reach its target signal-to-noise. A two to three times stronger median zodi constraint as achieved by the predicted sensitivity of improved LBTI observations would allow us to conclude with high confidence that exozodiacal dust is not a risk to the HabEx mission concept, and with good confidence that it has only a small impact for the Starshade Rendezvous concept.

3.2 Instrument performance

We have performed a detailed sensitivity study for HOSTS based on the science data, telemetry obtained during the science observations, and auxiliary engineering data.[35] We have used both heuristic and theoretical methods to determine the dominating sources of uncertainties in the HOSTS data and to identify realistic improvements. We have identified that telescope vibrations are the main source of statistical errors and background subtraction bias is the main source of systematic uncertainties. Vibrations dominate the error budget for bright stars and the background bias dominates for faint ones. The two contributions are equal at an N band flux of approximately 2.8 Jy and 60% of the stars observed by HOSTS are fainter than turn-over brightness.

The main source of the vibrations was determined to be a 12 Hz vibration of the swingarm holding the adaptive secondary mirror that can be excited by wind or on-telescope vibration sources. The main source of background bias was found to be excess low frequency noise (ELFN) of NOMIC's blocked-impurity band Raytheon Si:As IBC Aquarius detector.[12] Vibration mitigation is currently in progress at the LBT observatory. The ELFN noise of the current NOMIC detector cannot be mitigated easily other than by replacing the detector by one that is ELFN free. We are evaluating two detectors, a GeoSnap devise and a 13 μm H1RG detector (lead: J. Leisenring). The GeoSnap detector is showing 1/f noise that needs mitigation before it can be considered for installing in NOMIC. The H1RG detector has a limited well depth so that it needs to be operated in its fast readout mode, which is promising but feasibility remains to be confirmed. An alternative option to mitigate the ELFN of the NOMIC detector would be to implement fast chopping inside NOMIC (downstream of the PhaseCam dichroic). Enabling this possibility would require the installation of the required optics (i.e., a tip-tilt mirror and compensating optics). The main challenge would be to avoid non-common path aberrations between PhaseCam and NOMIC due to the chopping.

A detailed theoretical error budget was created and validated against the obtained survey data (Fig. 4). We then used this error budget to predict the system performance after realistic improvements (Fig. 5). In addition, Fig. 6 shows the improvements per target for the cases of only improved vibrations, only improved background bias, and both improvements.

3.3 Prospects for further nulling observations and a renewed HOSTS survey

Our sensitivity study has shown that an improvement of the instrument performance by a factor of 2-3 is realistic and the necessary technical improvements are already in progress or under study. A constraint on the typical HZ dust levels around nearby stars that is by that factor more sensitive would be critical to evaluate the feasibility of the spectroscopic characterization of exo-Earth candidates by smaller direct imaging missions than the LUVOIR concepts. Such improvements would also allow for relevant constraints on a few specific stars that are likely exo-Earth imaging targets (e.g., τ Cet). While differential piston variations between PhaseCam and NOMIC are not a significant limiting factor for the sensitivity of the HOSTS survey, correcting for them may allow for relaxing the weather constraints (precipitable water vapor, cloud coverage). This has been studied by our team and a viable approach has been proposed.[36,37]

It is important to note that new observations do not have to replace or supersede the current results, but instead can add to the constraints already achieved. Fig. 7 shows the full HOSTS sample.[23] It is visible that in particular among the Sun-like sample there is a significant number of stars for which we are the most sensitive to HZ dust that have not yet been observed. Even at the current sensitivity, observing those stars would add to the median zodi level and zodi luminosity function constraints. It would also allow us to vet a larger fraction of exo-earth imaging targets, removing the stars with the brightest exozodis as unsuitable. With an improved sensitivity, a combination of observing those stars and re-observing stars for which we are particularly sensitive and for which the strongest improvements over the available data can be achieved (e.g., the brighter ones for which the sensitivity improvement exceeds a factor of 3) can have the strongest impact and can improve the median zodi level and zodi luminosity function constraints beyond the naive improvements expected form the predicted higher sensitivity of the instrument. We have estimated the improvements based on the original HOSTS survey which include all the imperfections expected from real, ground-based observations. We conclude that a renewed survey that is optimized for complementing and improving over the existing data can likely provide a median exozodi constraint three times better than currently available. With the predicted sensitivity and using

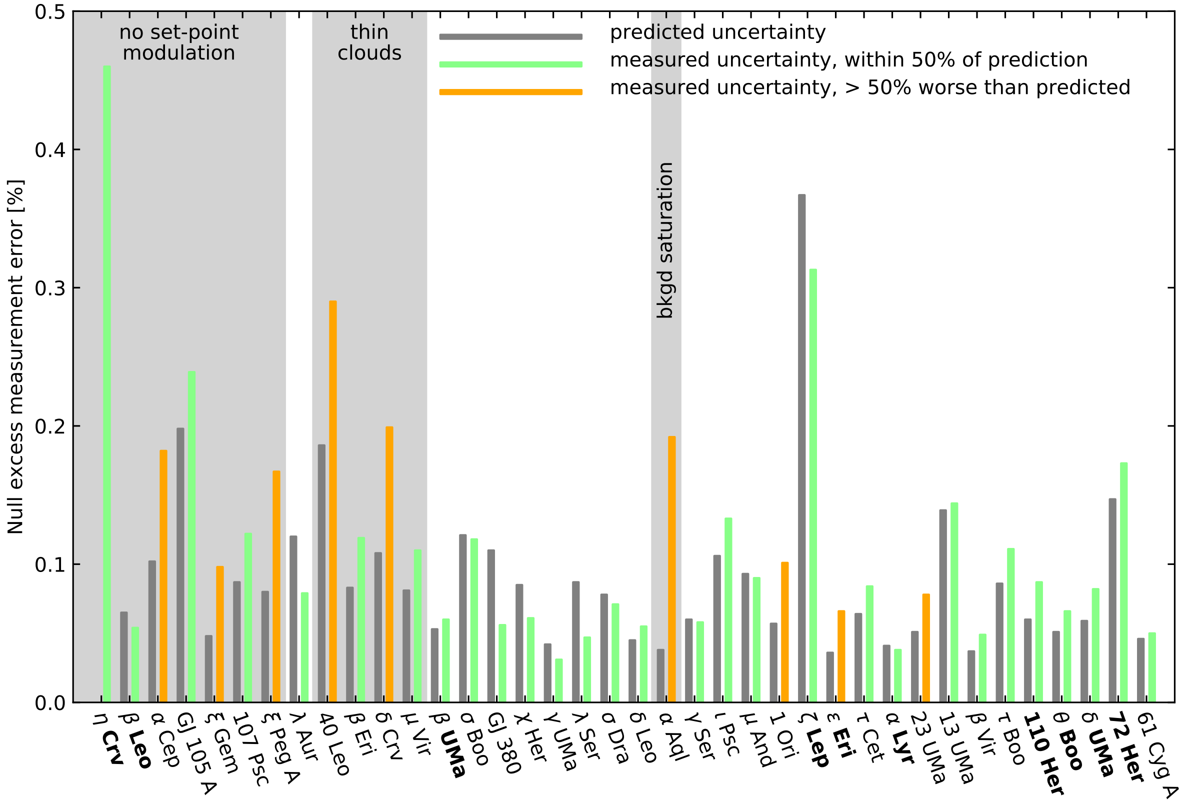

Figure 4. Comparison between predicted and measured uncertainties for the HOSTS observations. Stars are arranged by the date they have last been observed, increasing left to right. Cases where the main cause for the deviations from the predicted uncertainties is known are highlighted. Stars with detected excess are highlighted in bold face.

our best-fit luminosity function from the HOSTS survey,[25] we expect to detect bright exozodis around 10% to 30% of these stars, identifying a significant fraction of unsuitable targets for future exo-Earth imaging missions.

Another result from the HOSTS survey is that most of the detected, massive exozodiacal dust disks have been found around stars with massive cold disks detected by Spitzer and Herschel. This would suggest that the HZ of stars without known cold disks are less dusty than those in our whole sample. Better statistics and in particular a confirmation of this trend at lower HZ dust levels are needed to confirm this hypothesis. In addition, we can predict with high confidence that we will detect HZ dust around almost all stars with known cold dust, even with the current sensitivity of the LBTI. This opens up the possibility of a targeted survey of such disks with the goal to study them in detail. Such a study would produce a deep understanding of the origin of the HZ dust which will provide the means to predict the zodi levels around start that could not be observed with the LBTI.

Finally, the HOSTS results are not only *enabling* exo-Earth imaging missions. The HOSTS data have also the potential to critically *complement* the data from such missions by constraining the environment in which potentially habitable planets exist. The observations constrain the dynamics of the planetary and planetesimal systems observed, the presence and locations of asteroid belts, and the presence and influence of shepherding planets on the dynamics, and the strength of cometary activity. The latter will ultimately have a critical impact on whether a detected planet is habitable or not as cometary impacts may deliver water but also erode planetary atmospheres.[38,39] The HOSTS data can thus critically contribute to the understanding of the detected planets. An increased sensitivity and observing more stars now will ensure that more systems with potential exo-Earth detections will be characterized at the time an exo-Earth imaging mission is launched. This is already possible

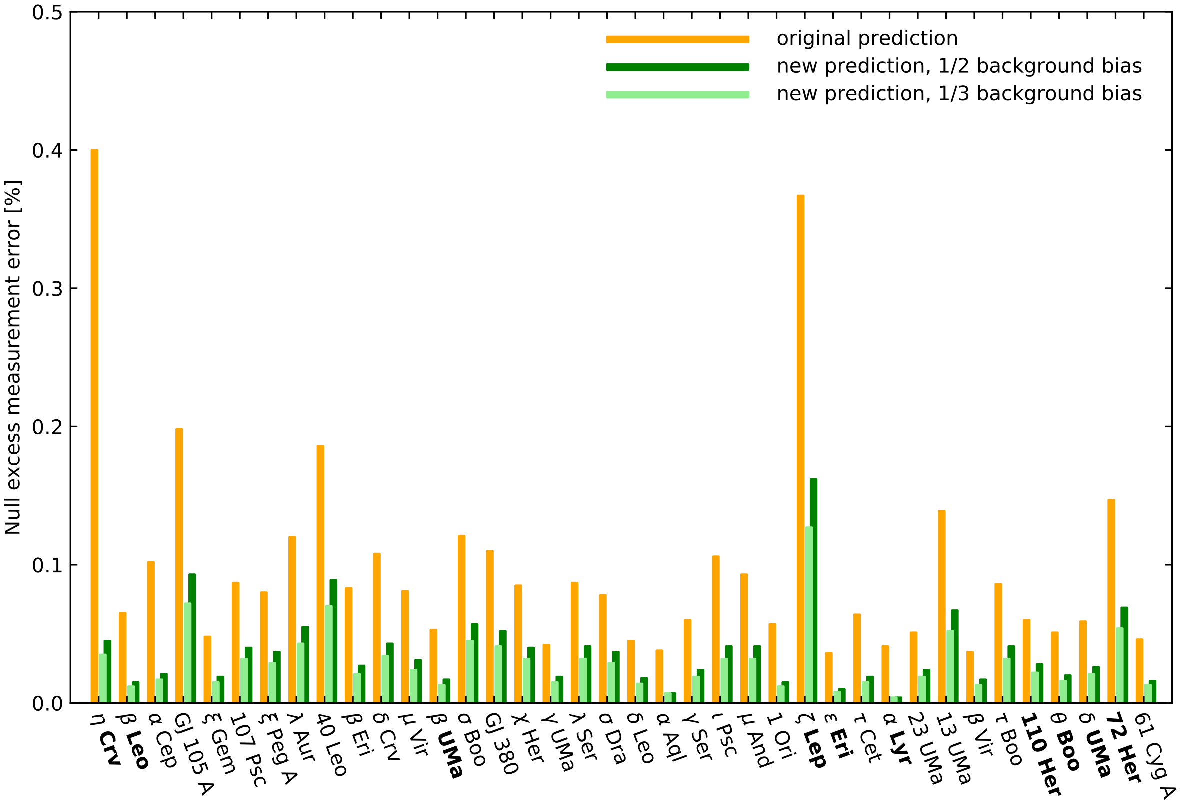

Figure 5. Predicted measurement uncertainties for new observations of the HOSTS stars after implementation of the sensitivity improvements described in Sect. 3.2. The cases of an improvement of the background error by both a factor of two and a factor of three are shown. It is clear that the former has a critical impact, while the latter only results in a small additional improvement of the overall sensitivity.

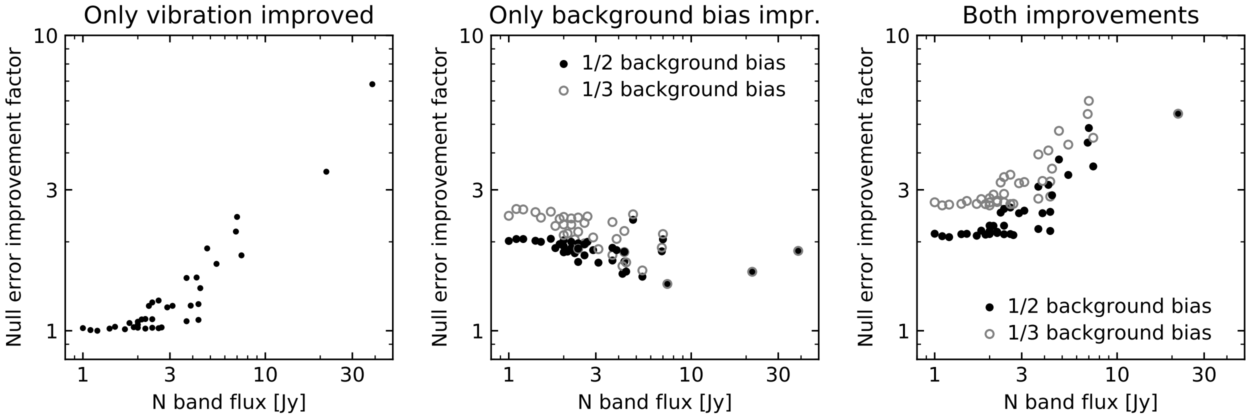

Figure 6. Improvements to the predicted uncertainty of the null depth measurements (current prediction divided by prediction after improvement) for improved vibrations (left), improved background bias (center), and both (right). Predictions have been made for the stars observed by the original HOSTS survey assuming the same amount of data for each star has been obtained again. The cases of an improvement of the background error by both a factor of two and a factor of three are shown.

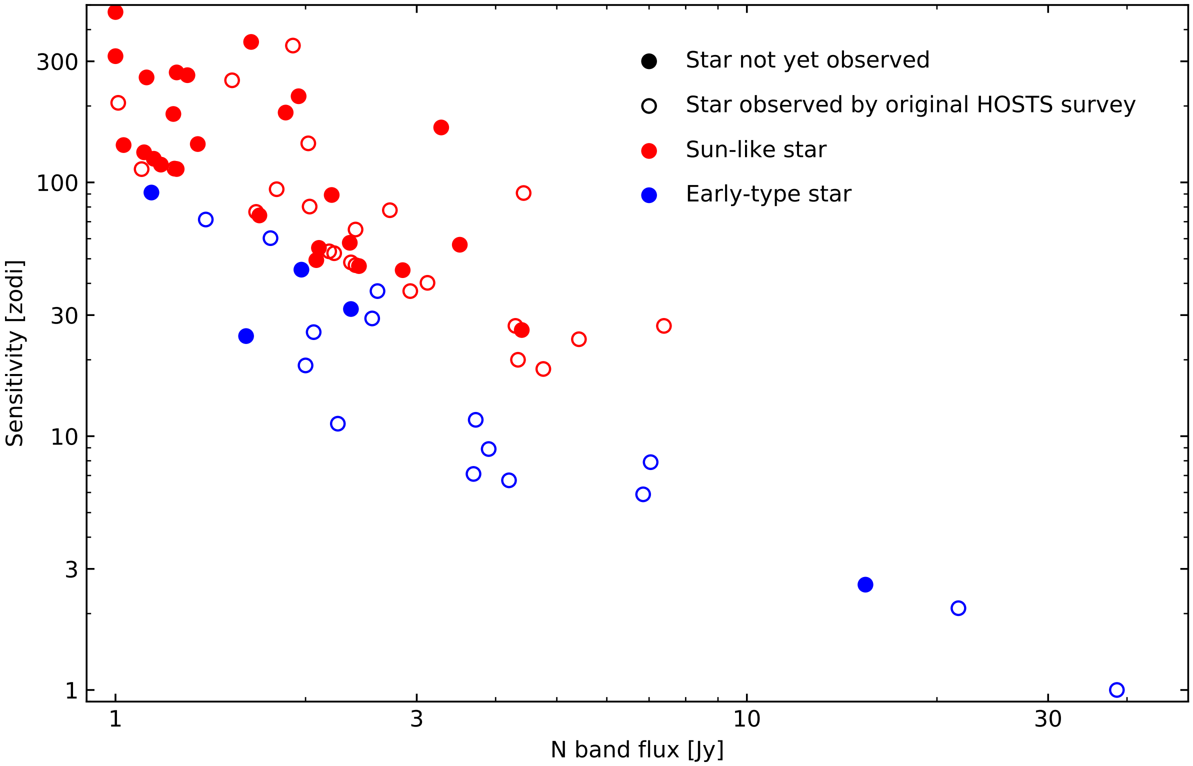

Figure 7. Full HOSTS sample.[23] The sensitivity predictions have been updated according following the results of our sensitivity study presented in this report.

with the current instrument performance for the stars with already detected exozodis. The LBTI team has been granted funding through a NASA/XRP grant (PI: S. Ertel) for the follow-up observations of all these targets following the strategy laid out in a previous paper.[40] Observations are expected to start in fall 2021. While other observations can provide complementary data to the LBTI nulling observations,[41–44] the LBTI data are by far the most sensitive, thus providing the strongest constraints for the largest sample of stars.

4. LBTI OBSERVING MODES, PROSPECTS, AND EXEMPLARY SCIENCE RESULTS

The LBTI is both a productive astronomical instrument and an instrumentation project. We offer a range of standard instrument modes to the community. In addition, a range of experimental modes are under development but not yet fully commissioned. These 'expert modes' require close collaboration and coordination with the LBTI team and are only offered in shared risk as their performance has not yet been fully characterized. In addition, the calibration and data reduction may not yet be fully understood. Even for standard modes, we strongly encourage users to closely collaborate with our team to take advantage of the available data reduction expertise. Table 1 lists the range of available LBTI observing modes and their commissioning status[†]. Several modes have been and are being developed in collaboration with outside teams. Use of these modes requires the coordination with the respective team which is typically facilitated by the LBTI team.

4.1 Adaptive Optics Imaging

AO imaging is one of the routine, standard modes of the LBTI and its most commonly used mode. It uses the two primary apertures separately as if they were two separate telescopes, but the images from the two apertures are

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[†] A continuously updated table is available at https://sites.google.com/a/lbto.org/lbti/

Table 1. Available LBTI observing modes and commissioning status.

Mode	LMIRCam	NOMIC	Status and notes
AO imaging	Yes	Yes	Routine. Single- and double-sided AO imaging. For the latter, the images from the two telescope apertures are placed in separate regions of the detector.
vAPP coronagraphy	Yes	No	Routine. Like AO imaging. Can be combined with ALES.
Separated aperture NRM	Yes	No	Routine. Single- and double-sided non-redundant aperture masking (NRM) without combining both apertures. Like AO imaging.
Nulling interferometry	No	Yes	Routine. Observing mode used for the HOSTS survey.
ALES integral field spectroscopy	Yes	No	Routine. Only single-sided due to limited detector area. Double-sided experimental.
AGPM coronagraphy	Yes	No	Experimental. Like AO imaging.
Wall-Eyed Imaging	Yes	Yes	Experimental. The two apertures point at separate, close targets for differential photometry.
Fizeau imaging interferometry	Yes	Yes	Experimental. 23 m effective aperture imaging.
Fizeau spectro-interferometry	Yes	No	Experimental. Fizeau interferometry combined with slitless spectroscopy.
Phased NRM	Yes	No	Experimental. Phase controlled NRM across both telescope apertures.

placed next to each other on the same detector. Nodding is used to subtract the sky and telescope background and the variable detector bias, where typically the source images are placed on the detector for all positions, but off-chip nodding is possible and usually preferred for sources larger than ∼7 arcsec. The mode can be used with both LMIRCam (20 arcsec FoV) and NOMIC (18 arcsec FoV). This mode was used for the LEECH high-contrast imaging survey.[45,46] Other exemplary science cases are protoplanetary disk imaging,[47,48] the imaging of circumstellar dust around evolved stars,[49] and the imaging of extragalactic sources such as lensed quasars.[50] We are currently developing a fast chopping mode with NOMIC (lead: K. Wagner) using the tip-tilt controls of the UBC's pupil mirrors to remove the ELFN and use this mode for the N band imaging of sub-Jovian planets near the HZs of nearby stars. Until now, the backgrounds from the two sides overlap on the detector, so that the sensitivity of this mode in the background limited regime is reduced compared to truly using two 8.4 m apertures. New cold field stops have been manufactured and will be installed in the near future to mitigate this limitation (lead: K. Wagner).

Two vAPP coronagraphs have been installed for each side of the telescope, one with a 180 deg suppression angle and one with a 360 deg suppression angle. In particular the 360 deg vAPP is now in routine operation and can be used together with AO imaging on LMIRCam. The vAPP's are on loan from Leiden observatory (team lead: M. Kenworthy) and using them requires coordination with this team.

LMIRCam is also equipped with two AGPM coronagraphs for each side.[51,52] Their use is experimental, in particular star-centering based on the QACITS[53] has not yet been fully commissioned. The AGPMs are on loan from the University of Liège (team lead: O. Absil) and using them requires coordination with this team.

'Wall-eyed' imaging[54,55] is also experimental, where the two apertures point at two nearby targets (but separated by more than the camera's nominal FoV) for precision relative photometry.

4.2 ALES Integral Field Spectroscopy

ALES is the world's first AO-assisted thermal infrared integral field spectrograph, operating across the L and M bands. It was designed for the high contrast detection and characterization of giant exo-planets. The magnified FoV of 2 arcsec usually limits its use to a single aperture, though there is no technical limitation to using both apertures. The standard L band mode is fully commissioned and used routinely, while other wavelength coverages are under commissioning. ALES is a PI instrument inside the LBTI and its use needs to be coordinated with the instrument team (PI: A. Skemer, UC Santa Cruz).

ALES has been used for a range of science cases, e.g., the characterization of brown dwarf and planetary mass companions around nearby stars,[56] the characterization of a benchmark binary brown dwarf,[57] and the study of volcanic activity on Jupiter's moon Io.[1] ALES observations are now also routinely combined with vAPP coronagraphy.

4.3 Separate-Aperture Non-redundant Aperture Masking

Two aperture masks, one with 12 holes and one with 24 holes (6 and 12 holes per LBT primary aperture, respectively) are available for NRM interferometry with LMIRCam. The mode can be used similarly to regular adaptive optics imaging where either a single side is used or the images from the two apertures are placed next to each other on the same detector. The mode is routinely used for high-contrast imaging of exoplanets and circumstellar disks,[58,59] but can also be used to image, e.g., the surface of Betelgeuse.

4.4 Nulling Interferometry

LBTI's raison d'être, the nulling mode is LBTI's best commissioned and most routinely used interferometry mode. It was used for the HOSTS survey for exozodiacal dust described in Sect. 3.

4.5 Fizeau Imaging Interferometry

For Fizeau imaging interferometry, the beams from the two primary apertures of the LBT are combined in the focal plane, either on LMIRCam or on NOMIC for coherent interferometric imaging with a 23 m equivalent aperture (edge-to-edge separation of the two LBT primary mirrors) and across the whole science camera FoV. Phase controlled and uncontrolled interferometry is possible. However, due to the team's scientific and programmatic focus on the HOSTS survey and nulling interferometry until recently, Fizeau interferometry is still experimental and under commissioning[37,60,61] (lead: N. Anugu and E. Spalding). The main demonstration and scientific result published so far is a study of the Jovian moon Io's volcanic activity.[62,63] Other data sets on the imaging of protoplanetary disks, disks around evolved stars, and the high contrast imaging search for giant planets around nearby stars are being analyzed. The Fizeau mode can be combined with slitless spectroscopy by spectrally dispersing the fringes in the perpendicular direction to the baseline orientation on the detector. This option is similarly experimental as the Fizeau imaging mode.

4.6 Phased, Dual-Aperture Non-Redundant Aperture Masking

This mode uses non-redundant aperture masking across the two primary apertures of the LBT with LMIRCam. The interferometric phase between the two apertures is typically stabilized with PhaseCam and as a result, fringes can be recorded across baselines up to ∼23 m. And advantage of NRM over Fizeau interferometry is that the use of closure phases minimizes the effects of phase errors, so that the impact of phase instabilities is greatly reduced. Similarly experimental as the Fizeau imaging mode, phased NRM has recently produced its first refereed science result with the imaging of the inner structure and companion candidate of the MWC 297 protoplanetary disk.[64] Observations with open phase loop are also possible.[65]

4.7 LBTI access and operations

The LBTI is a strategic (PI) instrument at the LBT. It is maintained and operated by the instrument team with support from the observatory. Access to observing time is granted through regular LBT channels, i.e., through the partner institutes' time allocation committees (TACs) or through director's time. Researchers interested in using the LBTI need to contact the instrument team (contact: S. Ertel, sertel@lbti.org) well in advance of the proposal submission to secure the team's support for their program. The instrument team then aids researcher with their proposal preparation, specifically with technical planning and justification of their program.

LBTI observing is conducted in campaign queue mode, where blocks of LBTI nights are classically scheduled and the observing programs that are allocated time are executed in queue mode according to TAC priorities, PI instructions, target observability, weather conditions, and technical readiness of the instrument and telescope. Observations are executed by the observing team which consists of instrument team members and LBT observers.

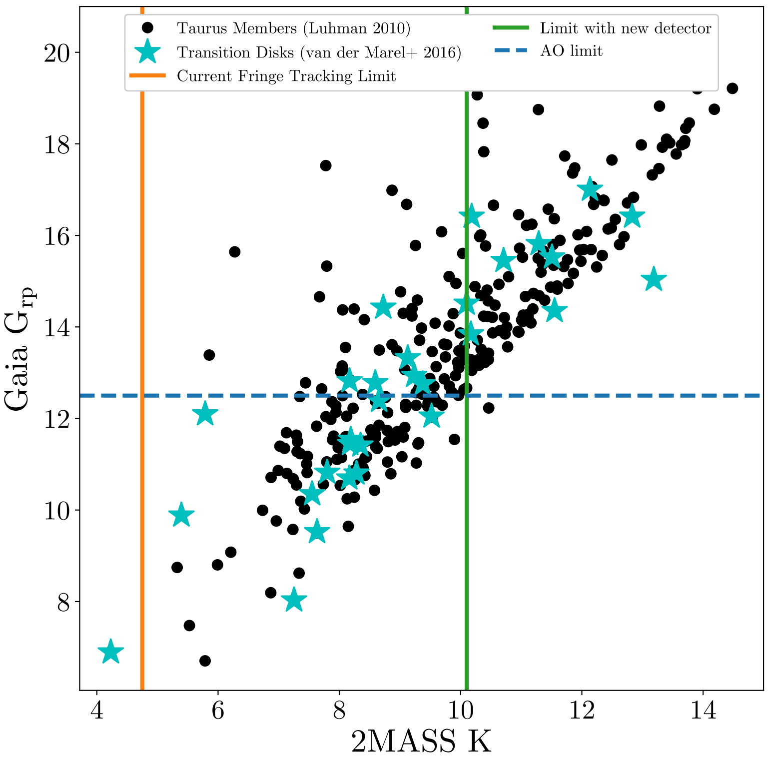

Figure 8. Young stellar objects in Taurus plotted in the relevant magnitude-magnitude diagram of LBTI limiting magnitudes. The Gaia magnitude is relevant for the AO system which is sensitive in the *R* and *I* bands. PhaseCam operates in the *H* and *K* bands. Targets below the blue, dashed line can be observed with very good AO performance. Stars left of the orange line can be used as fringe tracking references with PhaseCam's current limiting magnitude. Targets left of the green line are in the expected PhaseCam range after the upgrade.

Science PIs are invited to join observing runs in person or remotely. This is an excellent opportunity to gain observing experience (e.g., for students) and experience on how to use the instrument most effectively in the future. It is not a requirement for getting observations executed and does not significantly affect the scheduling priorities.

Data are then delivered to PIs within a few days of observing. The LBTI provides assistance with the data reduction on a best-effort basis. We request that team members who have significantly contributed to the enabling, planning, and executing the observations, or with data reduction be given the opportunity to further contribute to the publication of the data and thereby to be co-authors of the resulting publications.

5. OUTLOOK

The LBTI is expected to further mature over the coming years with more modes entering routine operation. The instrument is being integrated further into LBT operations and is ultimately expected to be handed over to the observatory. While a specific plan is still under development and a specific funding source is yet to be identified, the process is already ongoing on a best-effort basis between the LBT observatory and the LBTI team. The observatory is taking more responsibility in the maintenance and operation of the instrument, thereby ensuring continued and broad availability of the instrument to its user community. In return, the LBTI team is investing resources in training and documentation and standardizing the operations of the instrument, thus facilitating more general use of the instrument without deep background knowledge from the instrument team. Further integration of the instrument into the LBT hardware and software architecture for standardized maintenance and support is reducing the resources required for upkeep and operations of the instrument. The creation of redundant expertise through cross-training of team members secured knowledge and the continued success of the

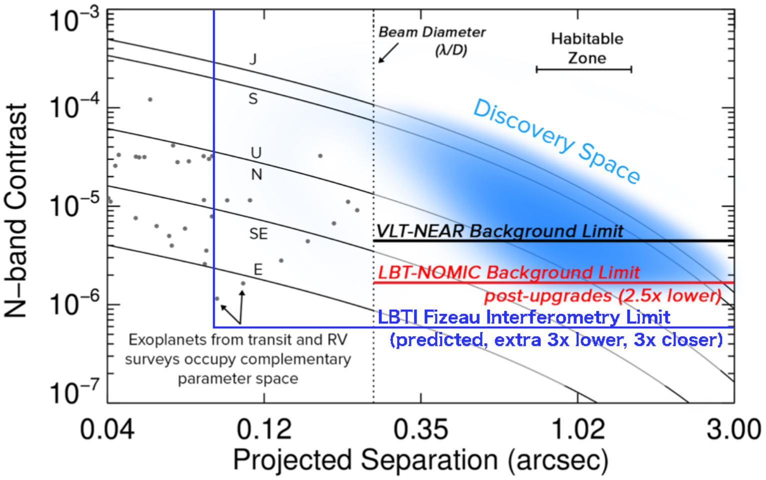

Figure 9. Sensitivity of the NEAR experiment and expected sensitivity of similar observations with the LBTI on the example of Sirius. The expected improvement from using Fizeau interferometry is also shown, assuming an ELFN-free detector.

project. An avenue for further instrumentation projects will be left open in addition to routine operations. The LBTI team will continue to support general observer science and will expand this support through collaboration with the LBT observatory. Our team will also continue to develop a strong science and instrumentation program for the exploitation of the instrument.

The LBTI team has recently been awarded NASA/XRP funding (PI: S. Ertel) to characterize the detected exozodiacal dust disks from the HOSTS survey. Observations are expected to start in fall 2021 and span over three years. We will use the LBTI's existing capabilities (and take advantage of ongoing upgrades) to observe the targets at 8 μm and 12 μm and with a large position angle coverage of the interferometric baseline to constrain the radial and azimuthal distribution of the dust and the spectral slope of its emission.[40]

The largest upgrade project currently in progress is the replacement of the PhaseCam detector (lead: J. Stone). The camera is currently equipped with a PICNIC detector. We have obtained funding to install a new SAPHIRA array (install expected for summer 2022). Together with other, smaller improvements of the system, this will significantly improve the limiting magnitude at which fringe tracking can be achieved (currently $K \sim 4.5$, expected $K \sim 10$). The main science driver of this upgrade is to perform Fizeau imaging interferometry and phased NRM of circumstellar disks and planets around young stellar objects in nearby star forming regions with the angular resolution of future 30-m-class telescopes. Fig. 8 shows a sample of Taurus targets that can be reached with the current AO limiting magnitude and the expected PhaseCam limiting magnitude after the upgrade. In addition, this upgrade will open the door for a wide range of applications of 23 m imaging at the LBT.

We are currently also commissioning a mode to use NOMIC for the sensitive direct imaging search for HZ planets around very nearby stars (PI: K. Wagner). We expect to reach a sensitivity 2.5× better than the NEAR experiment[66] at ESO's VLT due to (1) the larger collecting area of the two 8.4 m LBT mirrors, (2) the rotator-free, common-mount design of the LBTI producing lower background fluctuations because there are no relative rotations between telescope, instrument, and detector with sky position, (3) the thermal design of the LBTI, and (4) the lower winter temperatures on Mt. Graham compared to Paranal. Currently, the observations use the two apertures of the LBT individually for 8.4 m resolution imaging. The use of Fizeau interferometry would in principle improve both the inner working angle and the sensitivity by an additional factor of ~ 3.[67] However, since chopping cannot be combined with phased interferometry (but can be used with single-aperture imaging), the sensitivity is currently limited by the ELFN of the NOMIC detector. An ELFN free detector would open up the possibility for exploiting the LBTI's full resolution and collecting area for this program. Fig. 9 illustrates the expected sensitivity of the LBTI compared to NEAR for observations of Sirius at a comparable observing time.

In the long-term, the possibility is being considered of extending the LBTI's capabilities toward shorter wavelengths, including LBTI Visible Extension (LIVE) project.[68]

6. SUMMARY

The LBTI has successfully completed it's NASA-funded core mission, the HOSTS survey. Critical information on the typical amount of exozodiacal dust around nearby stars has been provided for future exo-Earth imaging missions, showing that even smaller missions are able to achieve their detection goals, while the constraints were insufficient to guarantee the successful spectroscopic characterization of detected candidates with missions smaller than the LUVOIR concepts. Critical scientific information about the dust was derived such as a clear correlation between HZ dust and a cold debris disk in the system. At the same time, the LBTI has achieved the first detections of small amounts of exozodiacal dust around Sun-like stars and in particular stars without a cold debris disk. We have identified telescope vibrations and detector excess low frequency noise as the main limitations to the nulling interferometric sensitivity and are working on mitigating these uncertainties. A sensitivity improvement by a factor of 3 can realistically be expected if these improvements are implemented.

Since the completion of the HOSTS survey, the LBTI team has focussed on consolidating the project and maturing a range of observing modes. The goal is to make the LBTI an efficient general observer instrument and to ultimately hand the instrument over to the LBT observatory as a facility instrument. We have reviewed the general design of the LBTI and the available observing modes. We have discussed their commissioning status and exemplary science results and outlined a vision for the future of the instrument.

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