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L-band nulling interferometry at the VLTI with Asgard/NOTT: status and plans

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ABSTRACT

NOTT (formerly Hi-5) is the L'-band (3.5-4.0 μm) nulling interferometer of Asgard, an instrument suite in preparation for the VLTI visitor focus. The primary scientific objectives of NOTT include characterizing (i)

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young planetary systems near the snow line, a critical region for giant planet formation, and (ii) nearby main-sequence stars close to the habitable zone, with a focus on detecting exozodiacal dust that could obscure Earth-like planets. In 2023-2024, the final warm optics have been procured and assembled in a new laboratory at KU Leuven. First fringes and null measurements were obtained using a Gallium Lanthanum Sulfide (GLS) photonic chip that was also tested at cryogenic temperatures. In this paper, we present an overall update of the NOTT project with a particular focus on the cold mechanical design, the first results in the laboratory with the final NOTT warm optics, and the ongoing Asgard integration activities. We also report on other ongoing activities such as the characterization of the photonic chip (GLS, LiNbO₃, SiO), the development of the exoplanet science case, the design of the dispersion control module, and the progress with the self-calibration data reduction software.

Keywords: Nulling interferometry, VLTI, exoplanets, exozodiacal disks, high contrast imaging, high angular resolution, optical fibers, long baseline interferometry

1. INTRODUCTION

Asgard/NOTT¹⁻³ is the L-band nuller of Asgard, an instrument suite officially recommended in June 2023 by ESO's Scientific Technical Committee (STC) for the visitor focus of the VLTI.⁴ Asgard/NOTT follows a series of nulling interferometers⁵ that have been deployed over the past three decades on state-of-the-art facilities, both across single telescopes and as separate aperture interferometers.⁶ These include the Bracewell Infrared Nulling Cryostat,⁷ the Keck Interferometer Nuller,⁸ the Palomar Fiber Nuller,^{9,10} the Large Binocular Telescope Interferometer,^{11,12} and DRAGONFLY/GLINT on Subaru/SCEXAO.¹³

Leveraging the experience gained with these nulling instruments, Asgard/NOTT will be the first nulling interferometer for the *Very Large Telescope Interferometer* (VLTI). Thanks to the VLTI state-of-the-art infrastructure, long baselines, and recent GRAVITY+ upgrade, Asgard/NOTT has the potential to carry out several exoplanet programmes to study young Jupiter-like exoplanets at the most relevant angular separations^{14,15} (i.e., close to the snow line) and better understand how planets form and evolve. In 2023-2024, the warm optical design has been finalized¹⁶ and all warm components besides the dispersion corrector have been procured. The dispersion corrector has been designed and presented elsewhere in these proceedings (see Laugier et al.). The instrument assembly in a new laboratory at KU Leuven and first null measurements are presented in a companion paper in these proceedings (Garreau et al.). In parallel, the photonic beam combiner has been manufactured and tested using three different technologies and/or materials: GLS (see Sanny et al. in these proceedings), LiNbO₃ (see Bonduelle et al. in these proceedings), and SiO manufactured by the VTT company. The designs of the cold mechanical components and cryostat have progressed towards maturity and the first images from the HAWAII-2RG detector have been obtained using the MACIE electronics. The software has been further developed, both a flexible Python-based scripting approach for engineering purposes and an ESO-compliant framework in collaboration with the Asgard consortium.

In addition to the technical and laboratory activities, progress has been made on both the exoplanet science case based on new end-to-end performance simulations¹⁷ and the nulling self-calibration pipeline (presented separately in these proceedings, see Martinod et al.) The NOTT project received funding from OPTICON for a preliminary study² (2016-2020) and was later funded by the European Research Council (2020-2025). In this paper, we give an update of the project, its science case and current status.

2. NOTT SCIENCE CASE

The main NOTT science cases cover exozodiacal disks,³ the characterization of hot Jupiters,² and planet formation.¹⁸⁻²⁰ In this paper, we only present an update of the exoplanet science case based on Dandumont et al. (in prep). We refer readers interested in exozodiacal dust to the pertinent literature.²¹⁻²⁷ Using core accretion (CA) and a gravitational instability (GI) models, we generated putative exoplanets and brown dwarves around a sample of 1484 nearby (<150pc) young (<300Myr) stars²⁸ and computed their detectability with our end-to-end performance simulator.¹⁷ In short, this simulator computes sensitivity maps in the NOTT field of view for given star magnitudes and declinations, taking into account the covariance matrix of the errors and statistical detection tests (based on likelihood ratios). These sensitivity maps, which provide the maximum magnitude of detectable

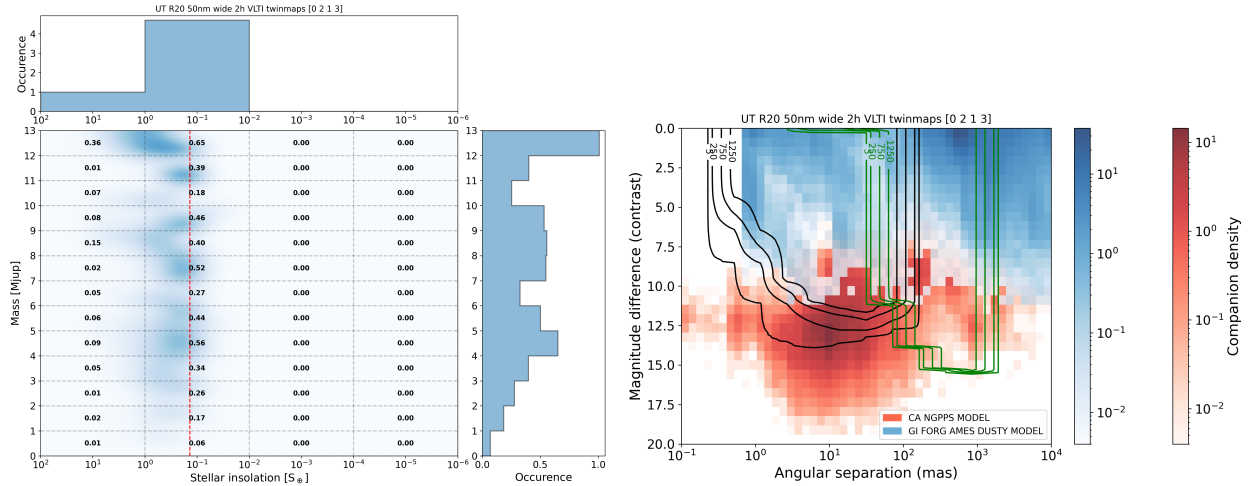


Figure 1. *Left*: Mass-stellar insolation range for the CA-detected planets with the UTs around all stars in the catalog (integration time of 2h per star). The number in each dotted square represents the corresponding planet's occurrence rate. The top and left histograms are the integrated values (sum over the axis). The red dotted line represented the snow line region. *Right*: NOTT depth of search for the UTs (black curves), compared to the one from SHINE²⁹ (green curves). The contour lines give the number of stars around which the instrument is sensitive as a function of contrast (differential magnitude between the host star and the planet) and semi-major axis. The planetary population comprises two formation scenarios. Their probability density is represented, from white to blue for the GI formation model, and from white to red for the CA formation model.

companions in the field of view, are compared to the planets generated with the planet formation models. Some examples can be found on the Github page*. The results are shown in Figure 1 for the UTs. Thanks to the long VLTi baselines, Asgard/NOTT could observe exoplanets closer to their host stars than classical direct imaging instrument such as SPHERE. Considering all sub-stellar companions generated by the planet formation models, NOTT should be able to detect about four CA planets with the UTs. These planets are more massive than Jupiter and mostly located near the snow line of their host star (see Figure 1, left). For GI sub-stellar companions, NOTT could lead to the detection of around ten brown dwarves with the ATs. Future work will focus on defining and optimizing the observing strategy as well as updating the yield when GAIA DR4 become available.

3. INSTRUMENTAL OVERVIEW

3.1 Assembly and first fringes with warm optics

The complete NOTT optical design was completed in 2022 and reviewed in June 2023 as part of an overall Asgard review. After a few revisions, the final design was published with a tolerance analysis.^{16,30} The design is implemented to be highly symmetric, in order to avoid polarization or phase mismatch between the four arms. In 2023-2024, the final warm optics have been procured and assembled in a new laboratory on the ground floor at KU Leuven. The only missing component is the dispersion corrector, which is discussed separately in these proceedings (see Laugier et al.).

Figure 2 shows the top view of the Asgard visitor table (only lower level) and corresponding pictures taken in the laboratory at KU Leuven. The four VLTi beams (purple) first go through the HEIMDALLR module^{31,32} to perform fringe tracking and wavefront correction with adaptive optics. Four dichroics made of calcium fluoride (CaF₂) then transmit the L'-band toward the NOTT instrument. Mirrors are then used to direct the four beams along the edge of the optical table. There are two Tip/Tilt Mirrors (TTMs) and one delay line for each beam. Using four mirror slices, called "slicer", and Off-Axis Paraboloids (OAPs), the system recombines the four pupils of the beams before the injection into the chip. The combined pupil plane is located at the same position as the aperture stop before the injection lens. The delay lines and Pupil Recombination Optics are both assembled on

*Nulling VLTi simulator: <https://github.com/rlaugier/SCIFYsim>

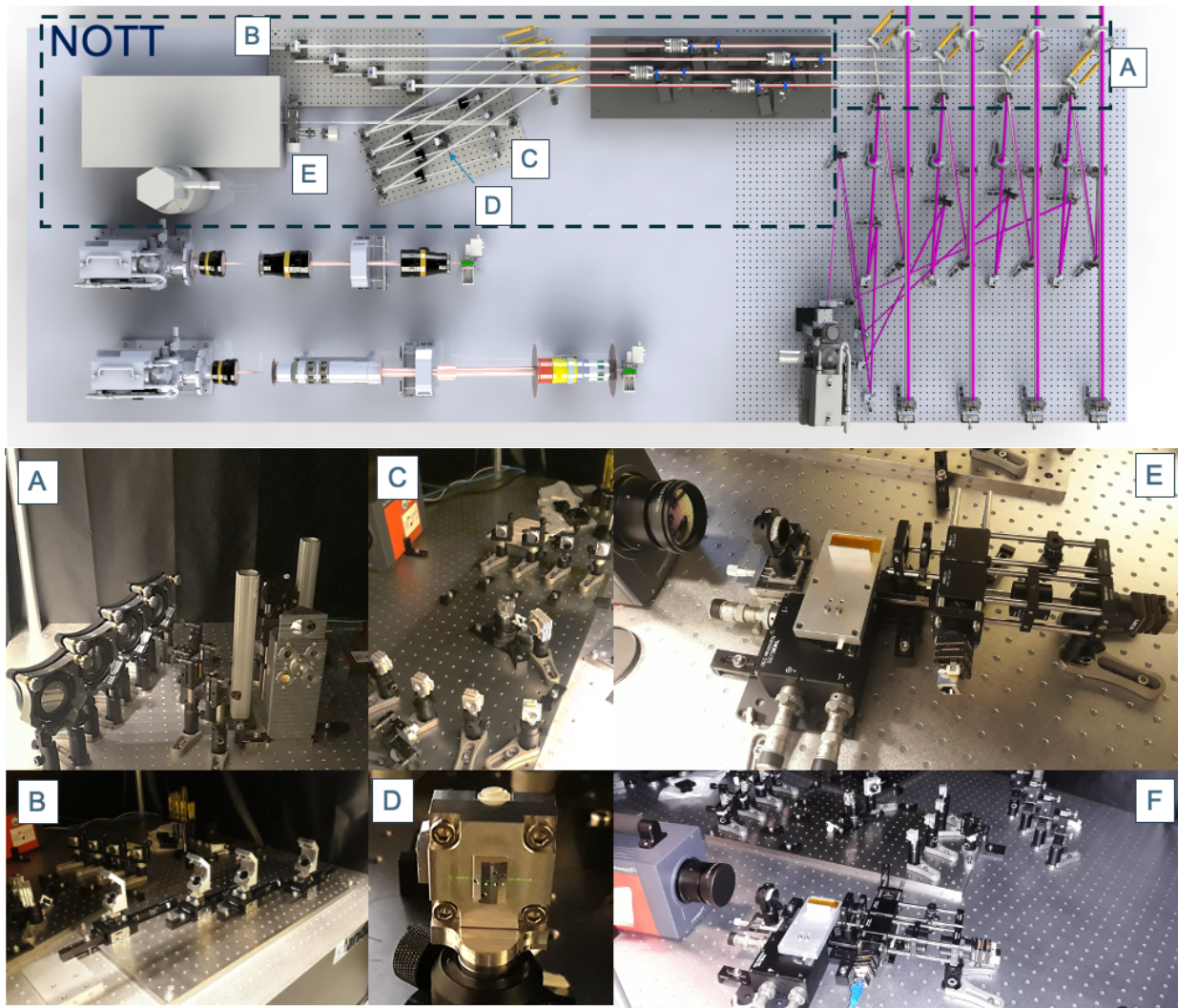


Figure 2. *Top*: top view design of Asgard on the visitor table (only lower level), showing NOTT within the dashed blue lines. After wavefront and pathlength correction with HEIMDALLR, the four beams coming from the VLTI (purple lines) are transmitted to the NOTT optics via CaF₂ dichroics from Rocky Mountain Instruments (see top right part). The beams are then reflected on tip/tilt mirrors (see A) along the edge of the optical table, reflected on the delay lines (see B), and directed to the injection system (see C). The injection system uses a mirror slicer (see D) from the Weylandts company. Finally, the four beams are injected into the photonic chip (see E). *Bottom*: Corresponding pictures of the current laboratory implementation at KU Leuven.

their own respective breadboards to facilitate their moving to Paranal. More information, including the complete list of optics and an overview of first NOTT fringes, can be found in a companion paper in these proceedings (Garreau et al.).

3.2 Mechanical design of the cold optics

The optical design and requirements of the NOTT spectrograph have been completed in 2022.³³ Here, we present an update of the mechanical design as shown in Figure 3. The mechanical structure includes:

- supporting structure, consisting of two holding clamps and two round horizontal bars;
- the support of the photonic chip, which can be rotated by 180 degrees and is connected to a temperature sensor;

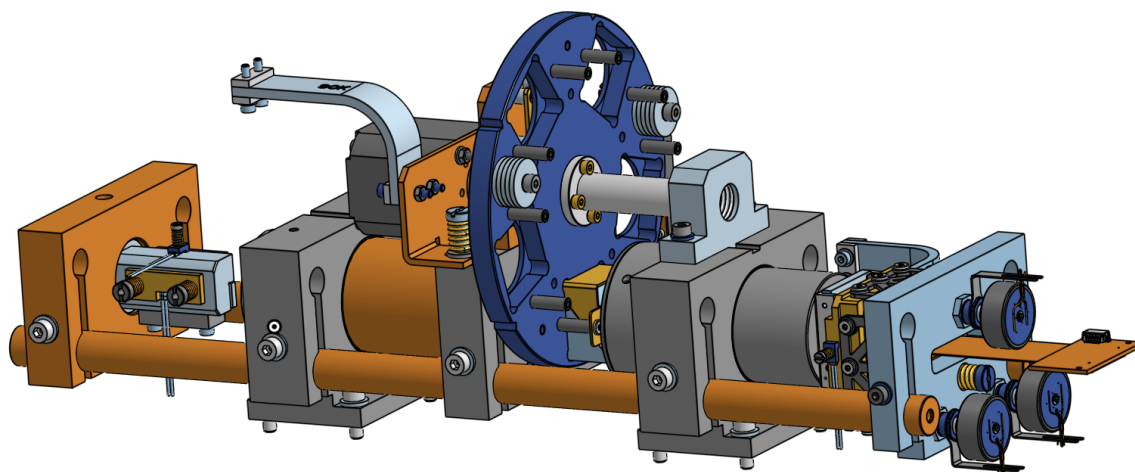


Figure 3. Mechanical design of the NOTT mechanical assembly showing from left to right: the support of the photonic chip, the collimator and Wollaston support assembly, the filter wheel for the grisms and shutters, the imager assembly, the detector support mounted on a focusing stage.

- the collimator and Wollaston support assembly, which holds the three lenses of the collimator. The Wollaston prism is used to split the polarizations;
- the filter wheel with grisms of different spectral resolutions and a cold shutter;
- the imager assembly, which holds the four lenses of the imager;
- the focusing stage, which holds the the HAWAII-2RG® detector and is mounted on piezo translation stage;

All mechanical parts are made of aluminium. The screws, springs and washers are made of stainless steel. The supporting structure has a holding clamp which is near the focusing stage and is rigidly bolted down to the base plate; the other clamp and the focusing stage are held down to the base plate with disc springs. This enables some parts of the supporting structure to move relative to the base plate if the coefficient of thermal expansion (CTE) of the material of the base plate and the material of the mechanical parts differ.

Each lens is held firmly against its seat with a flexible centering ring. Each centering ring is split and has a number of cutouts in order to make it more flexible. The centering rings are pressed against the beveled surfaces of the lenses with small helical springs. This solution has the following advantages:

- The axial position of each lens is determined by the position of its flat seating surface only. It is not sensitive to the manufacturing tolerances of either the lens or the centering ring. Therefore the axial position of the lenses after cooling down to 90K can be very accurately predicted.
- Each lens is always perfectly centered because there is no gap between the lens and the centering ring and there is no gap between the centering ring and the tube.
- The lenses are never subjected to excessive forces either at room temperature or at 90K (or anywhere in between) because the centering rings can slide inside the tube and compensate for dimensional changes. Only the spring preload will change slightly.

Because all parts of the supporting structure are made of aluminium, the shrinkage of the aluminium parts from 293K to 90K must be calculated. A simple method would be to calculate with the coefficient of thermal

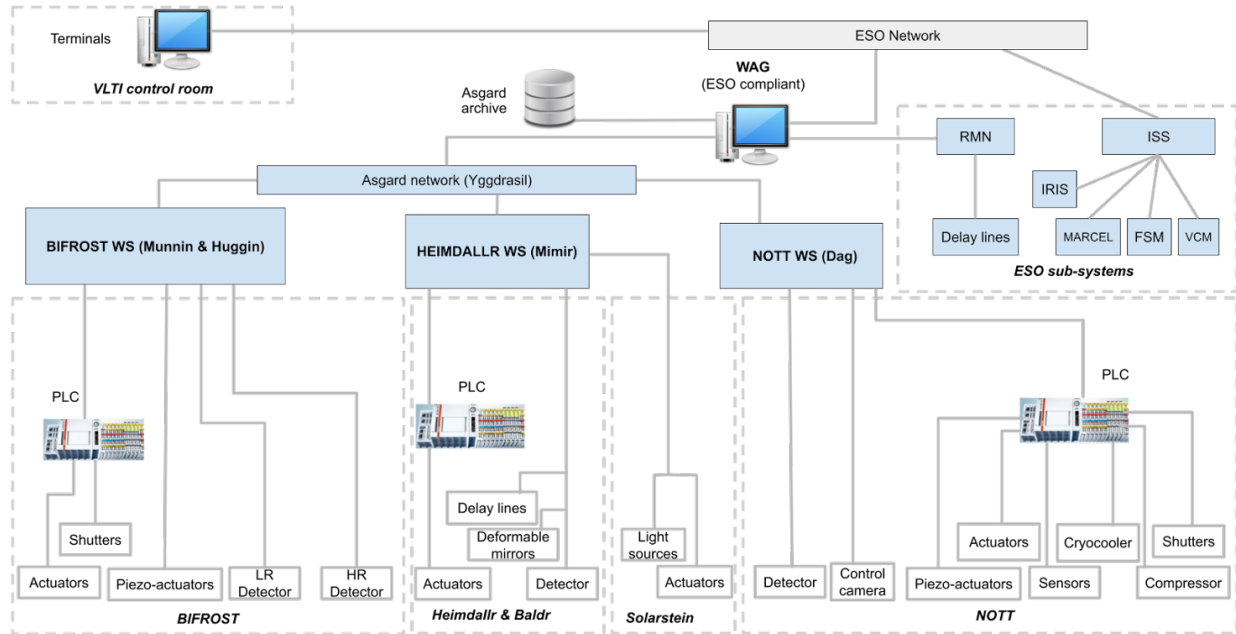


Figure 4. Control architecture of Asgard. WAG is an ESO-compliant machine that can communicate with ESO facility (in particular the RMN and the ISS) and control every Asgard subsystem through their respective workstations. Each instrument has one or two workstations to control its optics and cameras via programmable logic controllers (PLC). The users operate Asgard from terminals located in the VLTI control room that will connect to the WAG workstation. NOTT is controlled by a R7515 Dell server running Linux called *Dag* and two PLCs.

expansion for aluminium ($23.6 \times 10^{-6} C^{-1}$). This would give $23.6 \times 10^{-6} \times (293-90) = 0.00479 = 0.479\%$ contraction. However at cryogenic temperatures the coefficient of thermal expansion itself changes so a more accurate method is required. Using the linear expansion coefficient as a function of temperature, we get 0.38% contraction from 293K to 90K. This means that the dimensions of the parts of the supporting structure must be 1.00381 times longer at room temperature if we want to maintain the correct distances between the lens elements at 90K.

3.3 Software and control

The overall Asgard control architecture is shown in Figure 4. The hardware architecture is designed so that all the instruments can be operated from the terminals in the VLTI control room. This centralisation allows the observer to run all the instruments simultaneously and to communicate with the VLTI systems. Asgard low-level IT hardware and software are non-ESO compliant, hence must be kept separate. In addition, they need to communicate with each other; hence, they are connected to each other on a server-client system. Asgard instruments need to interact with ESO systems such as the Reflective Memory Network (RMN), the delay lines and the calibration sources. The solution is to connect all instruments' workstations, via a local network called *Yggdrasil*, to an ESO compliant machine, the instrument Workstation of AsGard, (WAG, formerly Hermod workstation) which is on ESO's network. WAG will interact with ESO systems, the RMN, and transmit data to and from Asgard's modules that require such data. WAG respects ESO's standards for hardware and software. From the ESO network point of view, Asgard is operated from a single computer represented by WAG. Each instrument has one or two workstations called *Module Control Units* (MCU). The NOTT module control unit, named *Dag*, controls the camera and the opto-mechanical devices of NOTT. It is a R7515 Dell server running Linux. Besides controlling some sub-systems directly, the workstations are also using *Programmable Logic Controllers* (PLC). The choice of driving a sub-system directly from the workstation or a PLC is motivated by the latency, frequency of usage and the most convenient way to drive the component while respecting constraints such as interface or power consumption. In 2024, a first version of the ESO-compliant WAG software has been deployed on the NOTT workstation and is currently being tested. More information on the overall Asgard control architecture and software can be found in a companion paper in these proceedings (see Martinod et al.).

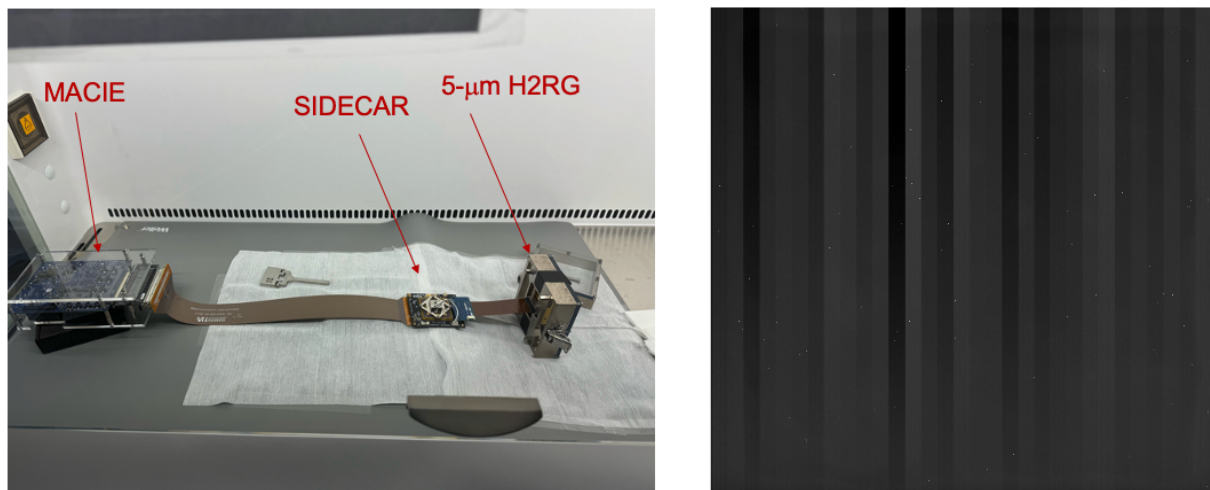


Figure 5. *Left*: Laboratory setup of the Teledyne's 5-micron HAWAII-2RG® detector with SIDECAR cold electronics and Markury Scientific MACIE warm electronics. *Right*: First image obtained at warm temperature in slow mode.

3.4 Detector characterization

During the winter 2023, we installed the 5-micron HAWAII-2RG (H2RG) detector in a cleaned lab space at KU Leuven for testing and characterization. The setup consists of Teledyne's 5-micron H2RG with SIDECAR ASIC cold electronics controlled by Markury Scientific's MACIE warm electronics that can be accessed from the internal network. The setup and first image of the detector are shown in Figure 5. Current work consists in characterizing the detector cosmetics and implementing the different observing modes based on the software used in LBTI/LMIRCam.³⁴

4. DATA REDUCTION PIPELINE

State-of-the-art nulling interferometers use the so-called nulling self-calibration (NSC) technique to achieve high-contrast interferometric nulling. This method has shown a gain in contrast by a factor 10 on the Palomar Fiber Nuller,^{10,35,36} the LBTI^{37,38} and GLINT.^{13,39} The NSC approach is a simulation-based inference method. Monte-Carlo simulations with a simulator of the instrument are carried out to reproduce the measured distributions. This method generates sequences of quantities based on measured or assumed distributions of the sources of noise and the astrophysical null depth, and propagates them throughout the simulator to obtain a simulated sequence of nulled flux. The generated data are sorted into a histogram, which is then fit to the histogram of the real data to find the best-fit parameters. This process enables the self-calibration, providing the simulator can correctly model the dominant effects of the instrument response. By relying on a Monte-Carlo approach and a clearly defined instrumental function, this technique can be used on any nuller. In the context of the NOTT project, we have developed a Generic data Reduction for nulling Interferometry Package[†] (GRIP) based on the experience gained with existing nulling interferometers. More information can be found in a companion paper in these proceedings (Martinod et al.). In parallel, we also investigated the use of Principal Component analysis to improve background subtraction.⁴⁰ Further work is currently being carried out develop a uniform nulling data standard[‡].

5. SUMMARY AND FUTURE WORK

NOTT is the L'-band (3.5-4.0 μm) high-contrast imager of Asgard, an instrument suite in preparation for the visitor focus of the VLTI. Together with the other Asgard instruments, NOTT was reviewed by an internal expert

[†]Nulling self-calibration package: <https://github.com/mamartinod/grip>

[‡]Nulling data standard: <https://github.com/rlaugier/nifits>

panel in June 2023 and is currently under review by ESO staff for software and hardware interfaces, with targeted integration at Paranal in 2025. In this paper, we present an update on the project, including the first fringes and null measurements in the laboratory, the development of the cold mechanical design, the development of the ESO-compliant control software, the detector characterization, progress with the exoplanet science case, and a new generic data reduction pipeline. Short term work is now focused on integration activities, the finalization of the cryostat design, and the procurement of all cold mechanical and optical components.

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REFERENCES

- [1] Defrère, D., Absil, O., Berger, J.-P., Boulet, T., Danchi, W. C., Ertel, S., Gallenne, A., Hénault, F., Hinz, P., Huby, E., Ireland, M., Kraus, S., Labadie, L., Le Bouquin, J.-B., Martin, G., Matter, A., Mérand, A., Mennesson, B., Minardi, S., Monnier, J. D., Norris, B., de Xivry, G. O., Pedretti, E., Pott, J.-U., Reggiani, M., Serabyn, E., Surdej, J., Tristram, K. R. W., and Woillez, J., “The path towards high-contrast imaging with the VLTI: the Hi-5 project,” *Experimental Astronomy* **46**, 475–495 (Dec. 2018).
- [2] Defrère, D., Ireland, M., Absil, O., Berger, J.-P., Danchi, W. C., Ertel, S., Gallenne, A., Hénault, F., Hinz, P., Huby, E., Kraus, S., Labadie, L., Bouquin, J.-B. L., Martin, G., Matter, A., Mennesson, B., Mérand, A., Minardi, S., Monnier, J. D., Norris, B., Xivry, G. O. d., Pedretti, E., Pott, J.-U., Reggiani, M., Serabyn, E., Surdej, J., Tristram, K. R. W., and Woillez, J., “Hi-5: a potential high-contrast thermal near-infrared imager for the VLTI,” in [*Optical and Infrared Interferometry and Imaging VI*], **10701**, 223–237, SPIE (July 2018).
- [3] Defrère, D., Bigioli, A., Dandumont, C., Garreau, G., Laugier, R., Martinod, M.-A., Absil, O., Berger, J.-P., Bouzerand, E., Courtney-Barrer, B., Emsenhuber, A., Ertel, S., Gagne, J., Glauser, A., Gross, S., Ireland, M. J., Kenchington, H.-D., Kluska, J., Kraus, S., Labadie, L., Laborde, V., Léger, A., Leisenring, J., Loicq, J., Martin, G., Morren, J., Matter, A., Mazzoli, A., Missiaen, K., Muhammad, S., Ollivier, M., Raskin, G., Rousseau, H., Sanny, A., Verlinden, S., Vandenbussche, B., and Woillez, J., “L-band nulling interferometry at the VLTI with Asgard/Hi-5: status and plans,” in [*Optical and Infrared Interferometry and Imaging VIII*], **12183**, 184–199, SPIE (Aug. 2022).
- [4] Martinod, M.-A., Defrère, D., Ireland, M., Kraus, S., Martinache, F., Tuthill, P., Bigioli, A., Bouzerand, E., Bryant, J., Chhabra, S., Courtney-Barrer, B., Crous, F., Cvetojevic, N., Dandumont, C., Ertel, S., Gardner, T., Garreau, G., Glauser, A. M., Labadie, L., Lagadec, T., Laugier, R., Mazzoli, A., Mortimer, D., Norris, B., Raskin, G., Robertson, G., Sanny, A., and Taras, A., “High-angular resolution and high contrast observations from Y to L band at the Very Large Telescope Interferometer with the Asgard Instrumental suite,” *Journal of Astronomical Telescopes, Instruments, and Systems* **9**, 025007 (Apr. 2023). ADS Bibcode: 2023JATIS...9b5007M.
- [5] Bracewell, R. N., “Detecting nonsolar planets by spinning infrared interferometer,” *Nature* **274**, 780 (Aug. 1978).
- [6] Spalding, E., Defrère, D., and Ertel, S., “Unveiling exozodiacal light,” *Physics Today* **75**, 46–52 (Apr. 2022). ADS Bibcode: 2022PhT...75d..46S.
- [7] Hinz, P. M., Angel, J. R. P., Hoffmann, W. F., McCarthy, D. W., McGuire, P. C., Cheselka, M., Hora, J. L., and Woolf, N. J., “Imaging circumstellar environments with a nulling interferometer,” *Nature* **395**, 251–253 (Sept. 1998). Number: 6699 Publisher: Nature Publishing Group.
- [8] Serabyn, E., Mennesson, B., Colavita, M. M., Koresko, C., and Kuchner, M. J., “THE KECK INTERFEROMETER NULLER,” *The Astrophysical Journal* **748**, 55 (Mar. 2012).

- [9] Mennesson, B., Hanot, C., Serabyn, E., Liewer, K., Martin, S. R., and Mawet, D., “HIGH-CONTRAST STELLAR OBSERVATIONS WITHIN THE DIFFRACTION LIMIT AT THE PALOMAR HALE TELESCOPE,” *The Astrophysical Journal* **743**, 178 (Dec. 2011).
- [10] Serabyn, E., Mennesson, B., Martin, S., Liewer, K., and Kühn, J., “Nulling at short wavelengths: theoretical performance constraints and a demonstration of faint companion detection inside the diffraction limit with a rotating-baseline interferometer,” *Monthly Notices of the Royal Astronomical Society* **489**, 1291–1303 (Oct. 2019).
- [11] Hinz, P. M., Defrère, D., Skemer, A., Bailey, V., Stone, J., Spalding, E., Vaz, A., Pinna, E., Puglisi, A., Esposito, S., Montoya, M., Downey, E., Leisenring, J., Durney, O., Hoffmann, W., Hill, J., Millan-Gabet, R., Mennesson, B., Danchi, W., Morzinski, K., Grenz, P., Skrutskie, M., and Ertel, S., “Overview of LBTI: a multipurpose facility for high spatial resolution observations,” **9907**, 990704 (Aug. 2016).
- [12] Ertel, S., Hinz, P. M., Stone, J. M., Vaz, A., Montoya, O. M., West, G. S., Durney, O., Grenz, P., Spalding, E. A., Leisenring, J., Wagner, K., Anugu, N., Power, J., Maier, E. R., Defrère, D., Hoffmann, W., Perera, S., Brown, S., Skemer, A. J., Mennesson, B., Kennedy, G., Downey, E., Hill, J., Pinna, E., Puglisi, A., and Rossi, F., “Overview and prospects of the LBTI beyond the completed HOSTS survey,” **11446**, 1144607 (Dec. 2020). Conference Name: Optical and Infrared Interferometry and Imaging VII ADS Bibcode: 2020SPIE11446E..07E.
- [13] Norris, B. R. M., Cvetojevic, N., Lagadec, T., Jovanovic, N., Gross, S., Arriola, A., Gretzinger, T., Martinod, M.-A., Guyon, O., Lozi, J., Withford, M. J., Lawrence, J. S., and Tuthill, P., “First on-sky demonstration of an integrated-photonics nulling interferometer: the GLINT instrument,” *Monthly Notices of the Royal Astronomical Society* **491**, 4180–4193 (Jan. 2020).
- [14] Fernandes, R. B., Mulders, G. D., Pascucci, I., Mordasini, C., and Emsenhuber, A., “Hints for a Turnover at the Snow Line in the Giant Planet Occurrence Rate,” *The Astrophysical Journal* **874**, 81 (Mar. 2019). arXiv: 1812.05569.
- [15] Fulton, B. J., Rosenthal, L. J., Hirsch, L. A., Isaacson, H., Howard, A. W., Dedrick, C. M., Sherstyuk, I. A., Blunt, S. C., Petigura, E. A., Knutson, H. A., Behmard, A., Chontos, A., Crepp, J. R., Crossfield, I. J. M., Dalba, P. A., Fischer, D. A., Henry, G. W., Kane, S. R., Kosiarek, M., Marcy, G. W., Rubenzahl, R. A., Weiss, L. M., and Wright, J. T., “California Legacy Survey. II. Occurrence of Giant Planets beyond the Ice Line,” *The Astrophysical Journal Supplement Series* **255**, 14 (July 2021).
- [16] Garreau, G., Bigioli, A., Laugier, R., Raskin, G., Morren, J., Berger, J.-P., Dandumont, C., Goldsmith, H.-D. K., Gross, S., Ireland, M., Labadie, L., Loicq, J., Madden, S., Martin, G., Martinod, M.-A., Mazzoli, A., Sanny, A., Shao, H., Yan, K., and Defrère, D., “Asgard/NOTT: L-band nulling interferometry at the VLTI. II. Warm optical design and injection system,” *Journal of Astronomical Telescopes, Instruments, and Systems* **10**, 015002 (Jan. 2024). ADS Bibcode: 2024JATIS..10a5002G.
- [17] Laugier, R., Defrère, D., Woillez, J., Courtney-Barrer, B., Dannert, F. A., Matter, A., Dandumont, C., Gross, S., Absil, O., Bigioli, A., Garreau, G., Labadie, L., Loicq, J., Martinod, M.-A., Mazzoli, A., Raskin, G., and Sanny, A., “Asgard/NOTT: L-band nulling interferometry at the VLTI. I. Simulating the expected high-contrast performance,” *Astronomy and Astrophysics* **671**, A110 (Mar. 2023). ADS Bibcode: 2023A&A...671A.110L.
- [18] Wallace, A. L. and Ireland, M. J., “The Likelihood of Detecting Young Giant Planets with High Contrast Imaging and Interferometry,” *Monthly Notices of the Royal Astronomical Society* **490**, 502–512 (Nov. 2019). arXiv: 1909.05878.
- [19] Wallace, A. L., Ireland, M. J., and Federrath, C., “Constraints on Planets in Nearby Young Moving Groups Detectable by High-Contrast Imaging and Gaia Astrometry,” *Monthly Notices of the Royal Astronomical Society* **508**, 2515–2523 (Oct. 2021). arXiv: 2101.11130.
- [20] Dandumont, C., Laugier, R., Emsenhuber, A., Gagne, J., Absil, O., Bigioli, A., Bonavita, M., Garreau, G., Ireland, M., Martinod, M. A., Loicq, J., and Defrère, D., “VLTI/Hi-5: detection yield predictions for young giant exoplanets,” **12183**, 1218327 (Aug. 2022). Conference Name: Optical and Infrared Interferometry and Imaging VIII ADS Bibcode: 2022SPIE12183E..27D.

- [21] Ertel, S., Absil, O., Defrère, D., Le Bouquin, J.-B., Augereau, J.-C., Marion, L., Blind, N., Bonsor, A., Bryden, G., Lebreton, J., and Milli, J., “A near-infrared interferometric survey of debris-disk stars. IV. An unbiased sample of 92 southern stars observed in H band with VLTI/PIONIER,” *Astronomy and Astrophysics* **570**, A128 (Oct. 2014).
- [22] Ertel, S., Defrère, D., Absil, O., Bouquin, J.-B. L., Augereau, J.-C., Berger, J.-P., Blind, N., Bonsor, A., Lagrange, A.-M., Lebreton, J., Marion, L., Milli, J., and Olofsson, J., “A near-infrared interferometric survey of debris-disk stars - V. PIONIER search for variability,” *Astronomy & Astrophysics* **595**, A44 (Nov. 2016). Publisher: EDP Sciences.
- [23] Absil, O., Marion, L., Ertel, S., Defrère, D., Kennedy, G. M., Romagnolo, A., Bouquin, J.-B. L., Christiaens, V., Milli, J., Bonsor, A., Olofsson, J., Su, K. Y. L., and Augereau, J.-C., “A near-infrared interferometric survey of debris-disk stars - VII. The hot-to-warm dust connection,” *Astronomy & Astrophysics* **651**, A45 (July 2021). Publisher: EDP Sciences.
- [24] Ertel, S., Defrère, D., Hinz, P., Mennesson, B., Kennedy, G. M., Danchi, W. C., Gelino, C., Hill, J. M., Hoffmann, W. F., Rieke, G., Shannon, A., Spalding, E., Stone, J. M., Vaz, A., Weinberger, A. J., Willems, P., Absil, O., Arbo, P., Bailey, V. P., Beichman, C., Bryden, G., Downey, E. C., Durney, O., Esposito, S., Gaspar, A., Grenz, P., Haniff, C. A., Leisenring, J. M., Marion, L., McMahon, T. J., Millan-Gabet, R., Montoya, M., Morzinski, K. M., Pinna, E., Power, J., Puglisi, A., Roberge, A., Serabyn, E., Skemer, A. J., Stapelfeldt, K., Su, K. Y. L., Vaitheeswaran, V., and Wyatt, M. C., “The HOSTS Survey—Exozodiacal Dust Measurements for 30 Stars,” *The Astronomical Journal* **155**, 194 (May 2018).
- [25] Ertel, S., Defrère, D., Hinz, P., Mennesson, B., Kennedy, G. M., Danchi, W. C., Gelino, C., Hill, J. M., Hoffmann, W. F., Mazoyer, J., Rieke, G., Shannon, A., Stapelfeldt, K., Spalding, E., Stone, J. M., Vaz, A., Weinberger, A. J., Willems, P., Absil, O., Arbo, P., Bailey, V. P., Beichman, C., Bryden, G., Downey, E. C., Durney, O., Esposito, S., Gaspar, A., Grenz, P., Haniff, C. A., Leisenring, J. M., Marion, L., McMahon, T. J., Millan-Gabet, R., Montoya, M., Morzinski, K. M., Perera, S., Pinna, E., Pott, J.-U., Power, J., Puglisi, A., Roberge, A., Serabyn, E., Skemer, A. J., Su, K. Y. L., Vaitheeswaran, V., and Wyatt, M. C., “The HOSTS Survey for Exozodiacal Dust: Observational Results from the Complete Survey,” *The Astronomical Journal* **159**, 177 (Mar. 2020). Publisher: American Astronomical Society.
- [26] Kirchschlager, F., Ertel, S., Wolf, S., Matter, A., and Krivov, A. V., “First L band detection of hot exozodiacal dust with VLTI/MATISSE,” *Monthly Notices of the Royal Astronomical Society: Letters* **499**, L47–L52 (Oct. 2020).
- [27] Pearce, T. D., Kirchschlager, F., Rouillé, G., Ertel, S., Bensberg, A., Krivov, A. V., Booth, M., Wolf, S., and Augereau, J.-C., “Hot exozodis: cometary supply without trapping is unlikely to be the mechanism,” *Monthly Notices of the Royal Astronomical Society* **517**, 1436–1451 (Nov. 2022).
- [28] Gagné, J. and Faherty, J. K., “BANYAN. XIII. A First Look at Nearby Young Associations with Gaia Data Release 2,” *The Astrophysical Journal* **862**, 138 (July 2018). Publisher: The American Astronomical Society.
- [29] Vigan, A., Fontanive, C., Meyer, M., Biller, B., Bonavita, M., Feldt, M., Desidera, S., Marleau, G.-D., Emsenhuber, A., Galicher, R., Rice, K., Forgan, D., Mordasini, C., Gratton, R., Le Coroller, H., Maire, A.-L., Cantalloube, F., Chauvin, G., Cheetham, A., Hagelberg, J., Lagrange, A.-M., Langlois, M., Bonnefoy, M., Beuzit, J.-L., Boccaletti, A., D’Orazi, V., Delorme, P., Dominik, C., Henning, T., Janson, M., Lagadec, E., Lazzoni, C., Ligi, R., Menard, F., Mesa, D., Messina, S., Moutou, C., Müller, A., Perrot, C., Samland, M., Schmid, H. M., Schmidt, T., Sissa, E., Turatto, M., Udry, S., Zurlo, A., Abe, L., Antichi, J., Asensio-Torres, R., Baruffolo, A., Baudoz, P., Baudrand, J., Bazzon, A., Blanchard, P., Bohn, A. J., Brown Sevilla, S., Carbillet, M., Carle, M., Cascone, E., Charton, J., Claudi, R., Costille, A., De Caprio, V., Delboulbé, A., Dohlen, K., Engler, N., Fantinel, D., Feautrier, P., Fusco, T., Gigan, P., Girard, J. H., Giro, E., Gisler, D., Gluck, L., Gry, C., Hubin, N., Hugot, E., Jaquet, M., Kasper, M., Le Mignant, D., Llored, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Möller-Nilsson, O., Mouillet, D., Moulin, T., Origné, A., Pavlov, A., Perret, D., Petit, C., Pragt, J., Puget, P., Rabou, P., Ramos, J., Rickman, E. L., Rigal, F., Rochat, S., Roelfsema, R., Rousset, G., Roux, A., Salasnich, B., Sauvage, J.-F., Sevin, A., Soenke, C., Stadler, E., Suarez, M., Wahhaj, Z., Weber, L., and Wildi, F., “The SPHERE infrared survey for exoplanets (SHINE). III. The demographics of young giant exoplanets below 300 au with SPHERE,” *arXiv e-prints* **2007**, arXiv:2007.06573 (July 2020).

- [30] Garreau, G., Bigioli, A., Raskin, G., Berger, J. P., Dandumont, C., Kenchington Goldsmith, H. D., Gross, S., Ireland, M., Labadie, L., Laugier, R., Loicq, J., Madden, S., Martin, G., Mazzoli, A., Morren, J., Shao, H., Yan, K., and Defrère, D., “Design of the VLTI/Hi-5 light injection system,” **12183**, 1218320 (Aug. 2022). Conference Name: Optical and Infrared Interferometry and Imaging VIII ADS Bibcode: 2022SPIE12183E..20G.
- [31] Ireland, M. J., Defrère, D., Martinache, F., Monnier, J. D., Norris, B., Tuthill, P., and Woillez, J., “Image-plane fringe tracker for adaptive-optics assisted long baseline interferometry,” **0701**, 1070111 (July 2018).
- [32] Taras, A. K., Robertson, J. G., Allouche, F., Courtney-Barrer, B., Carter, J., Crous, F., Cvetojevic, N., Ireland, M., Lagarde, S., Martinache, F., McGinness, G., N'Diaye, M., Robbe-Dubois, S., and Tuthill, P., “Heimdallr, baldr, and solarstein: designing the next generation of vlti instruments in the asgard suite,” *Appl. Opt.* **63**, D41–D49 (May 2024).
- [33] Dandumont, C., Mazzoli, A., Laborde, V., Laugier, R., Bigioli, A., Garreau, G., Gross, S., Ireland, M., Kenchington Goldsmith, H. D., Labadie, L., Martinod, M. A., Raskin, G., Sanny, A., Loicq, J., and Defrère, D., “Technical requirements and optical design of the Hi-5 spectrometer,” **12183**, 121831Y (Aug. 2022). Conference Name: Optical and Infrared Interferometry and Imaging VIII ADS Bibcode: 2022SPIE12183E..1YD.
- [34] Leisenring, J. M., Skrutskie, M. F., Hinz, P. M., Skemer, A., Bailey, V., Eisner, J., Garnavich, P., Hoffmann, W. F., Jones, T., Kenworthy, M., Kuzmenko, P., Meyer, M., Nelson, M., Rodigas, T. J., Wilson, J. C., and Vaitheeswaran, V., “On-sky operations and performance of LMIRcam at the Large Binocular Telescope,” 84464F (Sept. 2012).
- [35] Hanot, C., Mennesson, B., Martin, S., Liewer, K., Loya, F., Mawet, D., Riaud, P., Absil, O., and Serabyn, E., “Improving Interferometric Null Depth Measurements using Statistical Distributions: Theory and First Results with the Palomar Fiber Nuller,” *The Astrophysical Journal* **729**, 110 (Mar. 2011).
- [36] Mennesson, B., Serabyn, E., Hanot, C., Martin, S. R., Liewer, K., and Mawet, D., “NEW CONSTRAINTS ON COMPANIONS AND DUST WITHIN A FEW AU OF VEGA,” *The Astrophysical Journal* **736**, 14 (July 2011).
- [37] Defrère, D., Hinz, P. M., Mennesson, B., Hoffmann, W. F., Millan-Gabet, R., Skemer, A. J., Bailey, V., Danchi, W. C., Downey, E. C., Durney, O., Grenz, P., Hill, J. M., McMahon, T. J., Montoya, M., Spalding, E., Vaz, A., Absil, O., Arbo, P., Bailey, H., Brusa, G., Bryden, G., Esposito, S., Gaspar, A., Haniff, C. A., Kennedy, G. M., Leisenring, J. M., Marion, L., Nowak, M., Pinna, E., Powell, K., Puglisi, A., Rieke, G., Roberge, A., Serabyn, E., Sosa, R., Stapelfeldt, K., Su, K., Weinberger, A. J., and Wyatt, M. C., “Nulling Data Reduction and On-sky Performance of the Large Binocular Telescope Interferometer,” *The Astrophysical Journal* **824**, 66 (June 2016).
- [38] Mennesson, B., Defrère, D., Nowak, M., Hinz, P., Millan-Gabet, R., Absil, O., Bailey, V., Bryden, G., Danchi, W., Kennedy, G. M., Marion, L., Roberge, A., Serabyn, E., Skemer, A. J., Stapelfeldt, K., Weinberger, A. J., and Wyatt, M., “Making high-accuracy null depth measurements for the LBTI exozodi survey,” **9907**, 99070X (Aug. 2016).
- [39] Martinod, M.-A., Tuthill, P., Gross, S., Norris, B., Sweeney, D., and Withford, M. J., “Achromatic photonic tricouplers for application in nulling interferometry,” *Applied Optics* (May 2021). arXiv: 2106.00251.
- [40] Rousseau, H., Ertel, S., Defrère, D., Faramaz, V., and Wagner, K., “Improving mid-infrared thermal background subtraction with Principal Component Analysis,” (May 2024). Publication Title: arXiv e-prints ADS Bibcode: 2024arXiv240518043R.