High Contrast and High Angular Imaging at Subaru Telescope

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ABSTRACT

Adaptive Optics projects at Subaru Telescope span a wide field of capabilities ranging from ground-layer adaptive optics (GLAO) providing partial correction over a 20 arcmin FOV to extreme adaptive optics (ExAO) for exoplanet imaging. We describe in this paper current and upcoming narrow field-of-view capabilities provided by the Subaru Extreme Adaptive Optics (SCExAO) system and its instrument modules, as well as the upcoming 3000-actuator upgrade of the Nasmyth AO system.

Keywords: Adaptive Optics, High Contrast Imaging, Coronagraphy, Exoplanets

1. ADAPTIVE OPTICS AT SUBARU TELESCOPE: OVERVIEW

Adaptive optics at the Subaru Telescope\textsuperscript{1} started with the 36-element curvature system at the telescope's Cassegrain focus.\textsuperscript{2} A more capable 188-element system with both LGS and NGS modes was deployed in the 2000s at the telescope's infrared Nasmyth focus,\textsuperscript{3,4} and is still in operation, feeding the Infrared Camera and Spectrograph (IRCS)\textsuperscript{5–7} and Subaru Coronagraphic Extreme AO (SCExAO)\textsuperscript{8,9} instruments.

New adaptive optics capabilities are currently in development, focusing on three major directions:

- **Ground-Layer Adaptive Optics (GLAO)**, providing \(\approx 0.2\)-arcsec image quality over a 20-arcmin field of view at the telescope's Cassegrain focus using laser guide stars (LGSs) and an adaptive secondary mirror. GLAO development is the core part of the ULTIMATE\textsuperscript{10,11} project currently in development phase, with first light anticipated in 2028.

- **Laser Tomography Adaptive Optics (LTAO)**, delivering diffraction-limited imaging over \(\approx 20\)-arcsec field of view at the telescope's IR Nasmyth focus using LGSs for full sky coverage. LTAO is part of the ULTIMATE project, and will be deployed in year 2023 at the IR Nasmyth platform with the ULTIMATE-START\textsuperscript{12} project.

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• **Extreme Adaptive Optics (ExAO)** providing high image quality for high contrast imaging and visible-light diffraction limited imaging over small field of views. ExAO is implemented in the Subaru Coronagraphic Extreme AO (SCExAO) platform and its instrument modules.

We describe in this paper the current and near-future capabilities of narrow-field adaptive optics modes, with a focus on ExAO and including LTAO, and their implementation on the telescope’s Nasmyth IR (NasIR) platform. We describe in §2 the NasIR instrument configuration, including the upcoming deployment of the NasIR beam switcher, which allows for multiple instrument to be AO-fed. Observing capabilities are discussed in §3. The main development activities and future perspectives are discussed in §4.

2. NASMYTH IR PLATFORM OPTICAL CONFIGURATION

2.1 Current Configuration

Figure 1. Subaru Telescope’s infrared Nasmyth (NasIR) platform hosts its narrow-field adaptive optics instrumentation. The NasIR platform is one of two large gravity-invariant platforms on the telescope’s side (right). A recent picture of the platform (left) shows the AO188 and SCExAO instrument configuration. Both images are in approximately the same 3D orientation.

Narrow-field AO instrumentation is hosted at the telescope’s NasIR platform, as shown in Figure 1. The current 188-element facility AO system provides NGS and LGS correction for the IRCS and SCExAO instruments. IRCS provides diffraction-limited imaging and spectroscopy in near-IR while SCExAO includes a second-stage Extreme AO correction with a 2000-element MEMS deformable mirror.

The IRCS and SCExAO observing modes are mutually exclusive and cannot be scheduled within the same night. Switching between both instruments requires physically swapping the instruments between the storage and in-focus locations. The picture in Figure 1 shows the SCExAO configuration, while the IRCS configuration would have IRCS at the AO188 focus. Switching between the two modes is done in daytime with a overhead crane (partially visible in Figure 1 above AO188). This limitation will be addressed by deploying the Nasmyth beam switcher (NBS) behind the facility AO system.

2.2 Beam Switcher Configurations

The Nasmyth beam switcher\(^{13}\) (NBS) will be deployed by 2024 to allow for on-the-fly switching between SCExAO and IRCS without requiring instrument craning, and will also support expanding the suite of AO-fed instruments. The NBS also allows for simultaneous operation of instrument modules by using dichroic beam splitters.

Figure 2 shows the NasIR instrument platform layout, and Figure 3 shows the light path through adaptive optics key elements and instruments.
3. OBSERVING MODES AND CAPABILITIES

3.1 Adaptive Optics Correction

All adaptive optics instrumentation at NasIR is first corrected by the AO3k system. AO3k is an upgrade of the current 188-element system, where the 188-actuator bimorph DM is replaced by a 64x64 magnetic DM.
Figure 3. Adaptive Optics instruments and overall beam path. Instrument modules currently available for open use include IRCS, SCExAO/VAMPIRES, SCExAO/CHARIS, SCExAO/MEC, SCExAO/FastPDI, and REACH/IRD. The NINJA, SCExAO/GLINT, SCExAO/FIRST and AO3k/Kyoto3DII are in development phase and be available to observers in the near future. SPIDERS, SCExAO/RHEA and SCExAO/PhotonicLantern are currently focused on technology validation of novel instrument concepts.

ALPAO DM3228), and high order visible and NIR wavefront sensors are added. AO3k supports the following modes:

- Visible light NGS single conjugated AO (NGS-VIS-SCAO)
- Near-infrared light NGS single conjugated AO (NGS-NIR-SCAO)
- LGS Single conjugated AO (LGS-SCAO)
- Laser tomographic AO (LTAO)

The high order visible light high-order WFS will be a non-linear curvature WFS, located within the AO3k enclosure. The NIR pyramid WFS and LTAO LGS Shack-Hartman WFSs are located at the output of AO3k, before the NBS.

Second-stage correction is performed by SCExAO with a 2000-actuator MEMS type mirror (model: Boston Micromachines 2k, to be upgraded in 2024 to a segmented 3k device), which provides high-speed high precision wavefront control for high contrast imaging and visible-light AO.

### 3.2 Near-IR instrumentation

The AO3k NIR corrected beam can be fed to the IRCS camera and spectrograph or the SCExAO NIR modules. IRCS provides wide field imaging (20mas or 50mas FOV) and spectroscopy over the full NIR wavelength range from J-band to M-band. The instrument supports both low-resolution GRISM spectroscopy and high
Figure 4. Example NIR high contrast imaging observations with SCExAO. Left: Discovery image of protoplanet AB Aur b\textsuperscript{16} with SCExAO/CHARIS. Right: Discovery image of HIP 109427 b\textsuperscript{17} with SCExAO/MEC using stochastic speckle discrimination.

resolution (R\approx 20k) echelle spectroscopy. IRCS’s relatively wide field of view is a good match to the upcoming LTAO correction mode.

Narrower field of view capabilities are provided by SCExAO instrument modules which benefit from ExAO correction. Four high contrast imaging instrument modules are currently available for open use, all compatible with SCExAO’s coronagraphy mode:

- The CHARIS\textsuperscript{18} integral field spectrograph, providing R=20 to 70 spectro-imaging over a 2 arcsecond field of view.
- The Fast-PDI\textsuperscript{19} H-band high-speed polarimetric imaging camera
- The MKIDS exoplanet camera (MEC),\textsuperscript{20} a high speed photon-counting energy resolving camera
- The REACH high resolution spectroscopy\textsuperscript{21} mode proving R = 100k NIR spectroscopy of exoplanets and companions

Together, these four modes provide exoplanet and disk detection and characterization by imaging, spectroscopy and polarimetry in NIR.\textsuperscript{16,17,22-26} Example science observations are shown in Figure 4.

The GLINT\textsuperscript{27,28} instrument, currently in development, is a NIR nulling interferometer providing access to exoplanet and faint sources in the 0.5 to 2 \( \lambda/D \) separation range. GLINT will extend high contrast imaging capabilities to smaller angular separations than possible with conventional coronagraphy.

A photonic lantern is under development for exoplanet imaging\textsuperscript{29} and high precision spectro-astrometry.\textsuperscript{30}

### 3.3 Visible Light instrumentation

Visible-light instrumentation includes the SCExAO/VAMPIRES dual-band imager, the SCExAO/FIRST spectro-interferometer and the Kyoto3DII integral field spectrograph. Kyoto3DII\textsuperscript{31} was previously used behind AO188 and will be re-deployed on the top port of the NBS. It will benefit from AO3k correction in NGS, LGS and LTAO modes, which will provide near-diffraction-limited imaging performance in visible light with full sky coverage.
SCExAO’s extreme-AO correction delivers high quality diffraction-limited imaging at visible wavelengths for the VAMPIRES and FIRST instruments. VAMPIRES\textsuperscript{32} is available for open use observations, and supports polarimetric differential imaging,\textsuperscript{33,34} H-\(\alpha\) differential imaging,\textsuperscript{35} and coronagraphic imaging.\textsuperscript{36} VAMPIRES routinely operates at the diffraction limit, providing sub-20mas angular resolution, as illustrated in Figure 5 (left).

Figure 5. Visible-light imaging of the Capella double star with SCExAO/VAMPIRES (left) and SCExAO/FIRST (right). The two components, separated by \(\approx\) 40mas, are easily resolved with VAMPIRES’s imaging mode. With FIRST’s sub-mas astrometric accuracy, orbital motion can be detected within hr-timescale, as shown with measurements acquired on two consecutive nights (right).

The FIRST\textsuperscript{37} fiber-fed spectro-interferometer, under development, provides high precision imaging below the telescope’s diffraction limit, as illustrated on Figure 5 (right). FIRST is being upgraded with a stable compact integrated optics device feeding a R=4000 spectrograph designed for H-\(\alpha\) spectro-imaging.\textsuperscript{38–42}

4. CONCLUSIONS AND PERSPECTIVES

The AO188 system at Subaru Telescope feeds light to a wide range of visible and NIR instruments for imaging, spectroscopy and polarimetry. The upcoming upgrade of the 188-element system into a 3000-element system supporting NIR wavefront sensing, LGS and LTAO modes will provide significantly improved image quality over a wide range of targets. The Nasmyth beam switcher will allow efficient and simultaneous operation of multiple instruments modules, and support additional observing modes.

Adaptive Optics developments at Subaru Telescope are both expanding scientific capabilities and prototyping new instrument concepts and techniques for future efforts. The ULTIMATE-Start LTAO effort is validating wide-field AO sensing and control solutions for the more ambitious ULTIMATE Subaru project. In high contrast imaging, SCExAO is prototyping techniques for future exoplanet-imaging systems to be installed on 30-m class telescopes,\textsuperscript{9} including the Thirty Meter Telescope (TMT).

The SCExAO system is supporting development of promising WFS/C techniques for high contrast imaging, including focal plane speckle control\textsuperscript{43} and PSF reconstruction\textsuperscript{44} as illustrated in Figure 6. High frame rate science cameras in the system are also used for wavefront sensing.\textsuperscript{45,46} Thanks to the AO188 upgrade to AO3k, these advanced modes of operation will be deployed on-sky to provide improved high contrast detection capabilities. SCExAO is also validating astrophotonics technologies for high angular resolution and high contrast imaging.\textsuperscript{47} This includes the GLINT and FIRST instruments that use coherent waveguides and photonic chips for high precision spectro-interferometric imaging, and new wavefront sensing concepts using dispersed interferometry,\textsuperscript{48,49} and Photonic Lantern.\textsuperscript{50,51}
Figure 6. Wavefront control development: examples. Top: High-contrast imaging with focal plane wavefront sensing/control demonstrated on SCExAO using its internal source. Right: On-sky demonstration of PSF reconstruction using pyramid WFS telemetry.

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REFERENCES

[1] Ono, Y. H., Minowa, Y., Guyon, O., Clergeon, C. S., Mieda, E., Lozi, J., Hattori, T., and Akiyama, M., “Overview of AO activities at Subaru Telescope,” Proc. SPIE 11448, 114480K (Dec. 2020).

[2] Takami, H., Takato, N., Hayano, Y., Iye, M., Oya, S., Kamata, Y., Kanzawa, T., Minowa, Y., Otsubo, M., Nakashima, K., Gaessler, W., and Saint-Jacques, D., “Performance of Subaru Cassegrain Adaptive Optics System,” Publications of the ASJ 56, 225–234 (Feb. 2004).

[3] Hayano, Y., Takami, H., Guyon, O., Oya, S., Hattori, M., Saito, Y., Watanabe, M., Murakami, N., Minowa, Y., Ito, M., Colley, S., Eldred, M., Golota, T., Dinkins, M., Kashikawa, N., and Iye, M., “Current status of the laser guide star adaptive optics system for Subaru Telescope,” Proc. SPIE 7015, 701510 (July 2008).

[4] Hayano, Y., Takami, H., Oya, S., Hattori, M., Saito, Y., Watanabe, M., Guyon, O., Minowa, Y., Egner, S. E., Ito, M., Garrel, V., Colley, S., Golota, T., and Iye, M., “Commissioning status of Subaru laser guide star adaptive optics system,” Proc. SPIE 7736, 77360N (July 2010).

[5] Tokunaga, A. T., Kobayashi, N., Bell, J., Ching, G. K., Hodapp, K.-W., Hora, J. L., Neill, D., Onaka, P. M., Rayner, J. T., Robertson, L., Warren, D. W., Weber, M., and Young, T. T., “Infrared camera and spectrograph for the SUBARU Telescope,” Proc. SPIE 3354, 512–524 (Aug. 1998).

[6] Terada, H., Kobayashi, N., Tokunaga, A. T., Pyo, T.-S., nedachi, K., Weber, M., Potter, R., and Onaka, P. M., “Performance update of the infrared camera and spectrograph for the Subaru Telescope (IRCS),” Proc. SPIE 5492, 1542–1550 (Sept. 2004).

[7] Kobayashi, N., Tokunaga, A. T., Terada, H., Goto, M., Weber, M., Potter, R., Onaka, P. M., Ching, G. K., Young, T. T., Fletcher, K., Neil, D., Robertson, L., Cook, D., Imanishi, M., and Warren, D. W., “IRCS: infrared camera and spectrograph for the Subaru Telescope,” Proc. SPIE 4008, 1056–1066 (Aug. 2000).

[8] Jovanovic, N., Martinache, F., Guyon, O., Clergeon, C., Singh, G., Kudo, T., Garrel, V., Newman, K., Doughty, D., Lozi, J., Males, J., Minowa, Y., Hayano, Y., Takato, N., Morino, J., Kuhn, J., Serabyn, E., Norris, B., Tuthill, P., Schworer, G., Stewart, P., Close, L., Huby, E., Perrin, G., Lacour, S., Gauchet, L., Vievard, S., Murakami, N., Oshiyama, F., Baba, N., Matsuo, T., Nishikawa, J., Tamura, M., Lai, O., Marchis, F., Duchene, G., Kotani, T., and Woillez, J., “The Subaru Coronagraphic Extreme Adaptive Optics System: Enabling High-Contrast Imaging on Solar-System Scales,” Publications of the ASP 127, 890 (Sept. 2015).

[9] Lozi, J., Guyon, O., Vievard, S., Sahoo, A., Deo, V., Jovanovic, N., Norris, B., Martinod, M.-A., Mazin, B., Walter, A., Fruitwala, N., Steiger, S., Davis, K., Tuthill, P., Kudo, T., Kawahara, H., Kotani, T., Ireland, M., Anagnos, T., Schwab, C., Cvetovec, N., Huby, E., Lacour, S., Barjot, K., Groff, T. D., Chilcote, J., Kasdin, J., Martinache, F., Laugier, R., N’Diaye, M., Knight, J., Males, J., Bos, S., Snik, F., Doelman, D., Miller, K., Bendek, E., Belikov, R., Pluzhnik, E., Currie, T., Kuzuhara, M., Uyama, T., Nishikawa, J., Murakami, N., Hashimoto, J., Minowa, Y., Clergeon, C., Ono, Y., Takato, N., Tamura, M., Takami, H., and Hayashi, M., “Status of the SCExAO instrument: recent technology upgrades and path to a system-level demonstrator for PSI,” Proc. SPIE 11448, 114480N (Dec. 2020).

[10] Minowa, Y., Koyama, Y., Ono, Y., Tanaka, I., Hattori, T., Clergeon, C., Akiyama, M., Kodama, T., Motohara, K., Rigaut, F., d’Orgeville, C., Wang, S.-Y., and Yoshida, M., “ULTIMATE-Subaru: enhancing the Subaru’s wide-field capability with GLAO,” Proc. SPIE 11203, 112030G (Jan. 2020).

[11] Minowa, Y., Koyama, Y., Yanagisawa, K., Motohara, K., Tanaka, I., Ono, Y., Hattori, T., Clergeon, C., Hayano, Y., Akiyama, M., Kodama, T., d’Orgeville, C., Rigaut, F., Wang, S.-Y., and Yoshida, M., “ULTIMATE-Subaru: system performance modeling of GLAO and wide-field NIR instruments,” Proc. SPIE 11450, 114500O (Dec. 2020).

[12] Akiyama, M., Minowa, Y., Ono, Y., Terao, K., Ogane, H., Oomoto, K., Izuka, Y., Oya, S., Mieda, E., and Yamamuro, T., “ULTIMATE-START: Subaru tomography adaptive optics research experiment project overview,” Proc. SPIE 11448, 1144810 (Dec. 2020).

[13] Zheng, J., Binos, N., Gillingham, P., McGregor, H., Lawrence, J., Smedley, S., Hattori, T., Minowa, Y., and Guyon, O., “Optical design for Subaru Nasmyth Beam Switcher,” Proc. SPIE 12182 (2022).

[14] Lozi, J., Ahu, K., Clergeon, C., Deo, V., Guyon, O., Hattori, T., Minowa, Y., Nishiyama, S., Ono, Y., and Vievard, S., “AO3000 at Subaru: Combining for the first time a NIR WFS using First Light’s C-RED ONE and ALPAO’s 64x64 DM,” Proc. SPIE 12185 (2022).
[15] Guyon, O., “High Sensitivity Wavefront Sensing with a Nonlinear Curvature Wavefront Sensor,” Publications of the ASP 122, 49 (Jan. 2010).

[16] Currie, T., Lawson, K., Schneider, G., Lyra, W., Wisniewski, J., Grady, C., Guyon, O., Tamura, M., Kotani, T., Kawahara, H., Brandt, T., Uyama, T., Muto, T., Doug, R., Kudo, T., Hashimoto, J., Fukagawa, M., Wagner, K., Lozi, J., Chilcote, J., Tobin, T., Groff, T., Ward-Duong, K., Januszewski, W., Norris, B., Tuthill, P., van der Marel, N., Sitko, M., Deo, V., Vievard, S., Jovanovic, N., Martinache, F., and Skaf, N., “Images of embedded Jovian planet formation at a wide separation around AB Aurigae,” Nature Astronomy 6, 751–759 (Apr. 2022).

[17] Steiger, S., Currie, T., Brandt, T. D., Guyon, O., Kuzuhara, M., Chilcote, J., Groff, T. D., Lozi, J., Walter, A. B., Fruitwala, N., Bailey, John I., I., Zobrist, N., Swimmer, N., Lipartito, I., Smith, J. P., Bockstiegel, C., Meeker, S. R., Coiffard, C., Dodkins, R., Szypryt, P., Davis, K. K., Daal, M., Bumble, B., Vievard, S., Sahoo, A., Deo, V., Jovanovic, N., Martinache, F., Doppmann, G., Tamura, M., Kasdin, N. J., and Mazin, B. A., “SCExAO/MEC and CHARIS Discovery of a Low-mass, 6 au Separation Companion to HIP 109427 Using Stochastic Speckle Discrimination and High-contrast Spectroscopy,” Astronomical Journal 162, 44 (Aug. 2021).

[18] Groff, T. D., Kasdin, N. J., Limbach, M. A., Galvin, M., Carr, M. A., Knapp, G., Brandt, T., Loomis, C., Jarosik, N., Mede, K., McElwain, M. W., Leviton, D. B., Miller, K. H., Quijada, M. A., Guyon, O., Jovanovic, N., Takato, N., and Hayashi, M., “The CHARIS IFS for high contrast imaging at Subaru,” Proc. SPIE 9605, 96051C (Sept. 2015).

[19] Lozi, J., Guyon, O., Kudo, T., Zhang, J., Jovanovic, N., Norris, B., Martinod, M.-A., Groff, T. D., Chilcote, J., Tamura, M., Bos, S., Snik, F., Vievard, S., Sahoo, A., Deo, V., Martinache, F., and Kasdin, J., “New NIR spectro-polarimetric modes for the SCExAO instrument,” Proc. SPIE 11448, 114487C (Dec. 2020).

[20] Walter, A. B., Fruitwala, N., Steiger, S., Bailey, John I., I., Zobrist, N., Swimmer, N., Lipartito, I., Smith, J. P., Meeker, S. R., Bockstiegel, C., Coiffard, C., Dodkins, R., Szypryt, P., Davis, K. K., Daal, M., Bumble, B., Collura, G., Guyon, O., Lozi, J., Vievard, S., Jovanovic, N., Martinache, F., Currie, T., and Mazin, B. A., “The MKID Exoplanet Camera for Subaru SCExAO,” Publications of the ASP 132, 125005 (Dec. 2020).

[21] Kotani, T., Kawahara, H., Ishizuka, M., Jovanovic, N., Vievard, S., Lozi, J., Sahoo, A., Guyon, O., Yoneta, K., and Tamura, M., “Extremely high-contrast, high spectral resolution spectrometer REACH for the Subaru Telescope,” Proc. SPIE 11448, 1144878 (Dec. 2020).

[22] Kuzuhara, M., Currie, T., Takarada, T., Brandt, T. D., Sato, B., Uyama, T., Janson, M., Chilcote, J., Tobin, T., Lawson, K., Hori, Y., Guyon, O., Groff, T. D., Lozi, J., Vievard, S., Sahoo, A., Deo, V., Martinache, F., and Kasdin, J., “SCExAO/CHARIS Near-infrared Integral Field Spectroscopy of the HD 15115 Debris Disk,” Astronomical Journal 160, 163 (Oct. 2020).

[23] Lawson, K., Currie, T., Wisniewski, J. P., Tamura, M., Schneider, G., Augereau, J.-C., Brandt, T. D., Guyon, O., Kasdin, N. J., Groff, T. D., Lozi, J., Chilcote, J., Hodapp, K., Jovanovic, N., Martinache, F., Skaf, N., Akiyama, E., Henning, T., Knapp, G. R., Kwon, J., Mayama, S., McElwain, M. W., Sitko, M. L., Asensio-Torres, R., Uyama, T., and Wagner, K., “Multiband Imaging of the HD 36546 Debris Disk: A Refined View from SCExAO/CHARIS,” Astronomical Journal 162, 293 (Dec. 2021).

[24] Currie, T., Brandt, T. D., Kuzuhara, M., Chilcote, J., Guyon, O., Marois, C., Groff, T. D., Lozi, J., Vievard, S., Sahoo, A., Deo, V., Jovanovic, N., Martinache, F., Wagner, K., Dupuy, T., Wahl, M., Letawsky, M., Li, Y., Zeng, Y., Brandt, G. M., Michalik, D., Grady, C., Janson, M., Knapp, G. R., Kwon, J., Lawson, K., McElwain, M. W., Uyama, T., Wisniewski, J., and Tamura, M., “SCExAO/CHARIS Direct Imaging...
Discovery of a 20 au Separation, Low-mass Ratio Brown Dwarf Companion to an Accelerating Sun-like Star,” *Astrophysical Journal, Letters* 904, L25 (Dec. 2020).

[26] Chausthev, A., Sallum, S., Chilcote, J., Groff, T., Guyon, O., Lozi, J., Norris, B., and Skemer, A., “Spectral differential imaging with SCExAO/CHARIS kernel phase,” *Proc. SPIE* 12183 (2022).

[27] 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-photonic nulling interferometer: the GLINT instrument,” *Monthly Notices of the RAS* 491, 4180–4193 (Jan. 2020).

[28] Martinod, M.-A., Norris, B., Tuthill, P., Lagadec, T., Jovanovic, N., Cvetojevic, N., Gross, S., Arriola, A., Gretzinger, T., Withford, M. J., Guyon, O., Lozi, J., Vievard, S., Deo, V., Lawrence, J. S., and Leon-Saval, S., “Scalable photonic-based nulling interferometry with the dispersed multi-baseline GLINT instrument,” *Nature Communications* 12, 2465 (Jan. 2021).

[29] Lin, J., Xin, Y., Norris, B., Kim, Y. J., Sallum, S., Betters, C., Leon-Saval, S., Lozi, J., Vievard, S., Guyon, O., Gat&kine, P., Jovanovic, N., Mat&Wd, D., and Fitzgerald, M., “Exoplanet Detection with Photonic Lanterns for Focal-Plane Wavefront Sensing and Control,” *Proc. SPIE* 12185 (2022).

[30] Kim, Y. J., Sallum, S., Lin, J., Xin, Y., Norris, B., Betters, C., Leon-Saval, S., Lozi, J., Vievard, S., Gat&kine, P., Guyon, O., and Mat&Wd, D., “Spectroastrometry with photonic lanterns,” *Proc. SPIE* 12184 (2022).

[31] Sugai, H., Hattori, T., Kawai, A., Ozaki, S., Hayashi, T., Ishigaki, T., Ishii, M., Ohtani, H., Shimono, A., Okita, Y., Matsubayashi, K., Kosugi, G., Sasaki, M., and Takeyama, N., “The Kyoto Tridimensional Spectrograph II on Subaru and the University of Hawaii 88 in Telescopes,” *Publications of the ASP* 122, 103 (Jan. 2010).

[32] Norris, B., Schworer, G., Tuthill, P., Jovanovic, N., Guyon, O., Stewart, P., and Martinache, F., “The VAMPIRES instrument: imaging the innermost regions of protoplanetary discs with polarimetric interferometry,” *Monthly Notices of the RAS* 447, 2894–2906 (Mar. 2015).

[33] Norris, B. R. M., Tuthill, P., Jovanovic, N., Lozi, J., Guyon, O., Cvetojevic, N., and Martinache, F., “Diffraction-limited polarimetric imaging of protoplanetary disks and mass-loss shells with VAMPIRES,” *Proc. SPIE* 11203, 112030S (Jan. 2020).

[34] Safonov, B., Millar-Blanchaer, M., Zhang, M., Norris, B., Guyon, O., Lozi, J., and Sallum, S., “Differential speckle polarimetry with SCExAO VAMPIRES,” *Proc. SPIE* 12183 (2022).

[35] Uyama, T., Norris, B., Jovanovic, N., Lozi, J., Tuthill, P., Guyon, O., Kudo, T., Hashimoto, J., Tamura, M., and Martinache, F., “High-contrast Hα imaging with Subaru/SCExAO + VAMPIRES,” *Journal of Astronomical Telescopes, Instruments, and Systems* 6, 045004 (Oct. 2020).

[36] Lucas, M., Bottom, M., Guyon, O., Lozi, J., Norris, B., Deo, V., Vievard, S., Ahn, K., Skaf, N., and Tuthill, P., “A visible-light Lyot coronagraph for SCExAO/VAMPIRES,” *Proc. SPIE* 12184 (2022).

[37] Vievard, S., Huby, E., Lacour, S., Barjot, K., Martin, G., Cvetojevic, N., Deo, V., Guyon, O., Lozi, J., Kotani, T., Jovanovic, N., Marchis, F., Duchêne, G., Lapeyrere, V., Rouan, D., and Perrin, G., “FIRST, a pupil-remapping fiber interferometer at the Subaru Telescope: on-sky results,” *Proc. SPIE* 11446, 1144629 (Dec. 2020).

[38] Lallement, M., Huby, E., Lacour, S., Barjot, K., Vievard, S., Cvetojevic, N., Deo, V., Guyon, O., Kotani, T., Marchis, F., Martin, G., and Perrin, G., “Halpha imaging of protoplanets with the spectro-interferometer FIRST at the Subaru Telescope,” in *SF2A-2021: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics. Eds.: A. Siebert*, Siebert, A., Baillie, K., Lagadec, E., Lagarde, N., Malzac, J., Marquette, J. B., N’diaye, M., Richard, J., and Venot, O., eds., 135–138 (Dec. 2021).

[39] Barjot, K., Huby, E., Vievard, S., Lallement, M., Lacour, S., Martin, G., Cvetojevic, N., Deo, V., Guyon, O., Lozi, J., Kotani, T., Cassagnettes, C., Billat, A., Marchis, F., Lapeyrère, V., and Rouan, D., “First light of the upgraded FIRST visible fibered interferometer at the Subaru telescope,” *Proc. SPIE* 12183 (2022).

[40] Martin, G., Foin, M., Phatak, S., Beldjoudi, M., Billat, A., Cassagnettes, C., Coste, A., Courjal, N., Lallement, M., Barjot, K., Cvetojevic, N., Vievard, S., Lacour, S., Déo, V., and Guyon, O., “Hybrid electro-optic visible multi-telescope beam combiner for next generation FIRST/SUBARU instruments,” *Proc. SPIE* 12188 (2022).

Proc. of SPIE Vol. 12185 121856J-10
[41] Martin, G., Barjot, K., Lacour, S., Lallement, M., Cvetojevic, N., Viévard, S., Déo, V., Guyon, O., Huby, E., Cheng, G., Zhang, G., Stoian, R., and Morand, A., “FIRST 5T 3D: A laser written device for FIRST/SUBARU reducing crosstalk and propagation losses,” *Proc. SPIE* 12188 (2022).

[42] Lallement, M., Huby, E., Lacour, S., Barjot, K., Viévard, S., Guyon, O., Cvetojevic, N., Déo, V., and Perrin, G., “Photonic chip for visible interferometry: laboratory characterization and comparison with the theoretical model,” *Proc. SPIE* 12188 (2022).

[43] Ahn, K., Guyon, O., Lozi, J., Vievard, S., Deo, V., Skaf, N., Bragg, J., Haffert, S. Y., Males, J. R., and Currie, T., “Laboratory demonstrations of efc and spatial ldfc on subaru/scexao,” *Proc. SPIE* 12185 (2022).

[44] Guyon, O., Ahn, K., Currie, T., Deo, V., Haffert, S., Lozi, J., Males, J., Martinod, M.-A., Norris, B., Skaf, N., Tuthill, P., and Vievard, S., “High Contrast Imaging at the Photon Noise Limit with WFS-based PSF Calibration,” *Proc. SPIE* 12185 (2022).

[45] Vievard, S., Bonnefois, A., Cassaing, F., Mugnier, L., Sauvage, J.-F., Guyon, O., Lozi, J., Deo, V., Ahn, K., and Skaf, N., “Linearized Analytical Phase Diversity : towards lab and on-sky demonstration on the Subaru Telescope,” *Proc. SPIE* 12185 (2022).

[46] Deo, V., Vievard, S., Cvetojevic, N., Ahn, K., Huby, E., Guyon, O., Lacour, S., Lozi, J., Martinache, F., Norris, B., Skaf, N., and Tuthill, P., “Controlling petals using fringes: wavefront sensing through sparse aperture interferometry at Subaru/SCExAO,” *Proc. SPIE* 12185 (2022).

[47] Vievard, S., Ahn, K., Arriola, A., Barjot, K., Cvetojevic, N., Deo, V., Gretzinger, T., Gross, S., Guyon, O., Huby, E., Jovanovic, N., Kotani, T., Lacour, S., Lagadec, T., Lallement, M., La Peyrere, V., Lozi, J., Marchis, F., Martin, G., Martinod, M. A., Norris, B., Perrin, G., Rouan, D., Skaf, N., Tuthill, P., Withford, M., and Duchêne, G., “Very high resolution spectro-interferometry with wavefront sensing capabilities on Subaru/SCExAO using photons,” *Proc. SPIE* 11823, 118230C (Sept. 2021).

[48] Vievard, S., Déo, V., Huby, E., Lacour, S., Guyon, O., Cvetojevic, N., Barjot, K., Martin, G., Lallement, M., Lozi, J., Kotani, T., Marchis, F., Rouan, D., Ahn, K., Skaf, N., and Perrin, G., “Interferometric wavefront sensing at FIRST/SCExAO : self-calibrated fibered pupil-remapping spectroscopy using a metrology laser source,” *Proc. SPIE* 12183 (2022).

[49] Norris, B., Martinod, M.-A., Tuthill, P., Gross, S., Cvetojevic, N., Jovanovic, N., Lagadec, T., Klinner-teo, T., Guyon, O., Lozi, J., Deo, V., Vievard, S., Arriola, A., Gretzinger, T., Lawrence, J., and Withford, M., “Optimal self-calibration and fringe tracking in photonic nulling interferometers using machine learning,” *Proc. SPIE* 12188 (2022).

[50] Lin, J., Lozi, J., Vievard, S., Norris, B., Betters, C., Leon-Saval, S., Xin, Y., Kim, Y. J., Sallum, S., Gatkine, P., Jovanovic, N., Mawet, D., and Fitzgerald, M., “Experimental Measurements of AO-Fed Photonic Lantern Coupling Efficiencies,” *Proc. SPIE* 12185 (2022).

[51] Norris, B., Wei, J., Betters, C., Leon-Saval, S., Xin, Y., Lin, J., Kim, Y. J., Sallum, S., Lozi, J., Vievard, S., Guyon, O., Gatkine, P., Jovanovic, N., Mawet, D., and Fitzgerald, M., “Demonstration of a photonic-lantern focal-plane wavefront sensor using fiber mode conversion and deep learning,” *Proc. SPIE* 12188 (2022).