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Design of a Precision Calibration Unit for Keck NIRC2 AO Instrument

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TMT
THIRTY METER TELESCOPE

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INTRODUCTION

TYPICAL ASTROMETRY ERROR SOURCES

High-precision astrometry has the potential to address questions in planet formation, black hole science, Galactic structure, and more. Two factors that currently limit the accuracy of precision astrometry are (1) differential atmospheric refraction (DAR) especially achromatic DAR with a correction error of ~ ***1 mas*** under most conditions and ~ ***2 uas*** for crowded fields, and (2) the static component of the AO camera's geometrical distortions with a correction error of ~ ***1 mas*** for Keck NIRC2. The latter will compromise the astrometry precision by a factor of 10-100x and thus must be measured and corrected for each instrument. We focus on the ***geometrical distortions*** in this project.

KECK NIRC2 DISTORTION CALIBRATION OVERVIEW

2001: Pre-ship test with fine mask grids (43 x 43, 8 um-sized, 7 mm separation pinholes for Medium/Large field, another one for the Narrow field [2]. Images are taken with one static position of the mask grid and fitted to third-order polynomials. ***Problem: limited by the precision of the mask grid. Distortion residual > 2 mas.***

2001-2007: Internal mask or external catalog (preferred): images are taken and corrected as referenced by known external catalogs (e.g., stellar clusters from HST ACS with an accuracy of ~ 0.5 mas [3-4]). ***Problem: requires significant on-sky time (e.g., > ~ 1 night). Distortion residual ~ 1 mas.***

2007-2020: only external on-sky calibration is available.

DISTORTION CALIBRATION STATE-OF-THE-ART

To improve the distortion residual requires a technique called ***'self-calibration'***:

(1) External on-sky calibration, which ***requires translating and rotating the telescope to multiple positions*** to calibrate the distortion across the field: e.g., Gaia DR2, distortion residual ***< 0.04 mas [5]***. Significant on-sky time.
(2) Internal mask grid, which ***requires translating and rotating the mask grid to multiple positions similar as (1)***, distortion residual predicted ***~ 0.1 mas*** (Keck NIRC2), ~ 20-30 uas (TMT). Calibrated during the day.

Keck AO requires several times of distortion re-calibration during a year.

THIS WORK The goal of the ***Keck Precision Calibration Unit (Keck PCU, KPCU)*** project is to design, build and deliver two PCUs for both NIRC2 and OSIRIS instruments behind Keck AO using *self-calibrating internal mask grids.* As an upgrade of the current on-sky distortion calibration method, the two new units each contain ***a translatable and rotatable photo-lithographic pinhole grid*** that can be used to calibrate distortion solutions during the day, saving the expensive on-sky time (~1 night per time and >1 time per year), and will provide an order-of-magnitude (10x, ***0.1 mas***) improvement over the current calibration precision (***1-2 mas***). Similar design principles could be used worldwide and for the upcoming thirty meter class telescopes to meet their distortion calibration requirements.

PRELIMINARY DESIGN

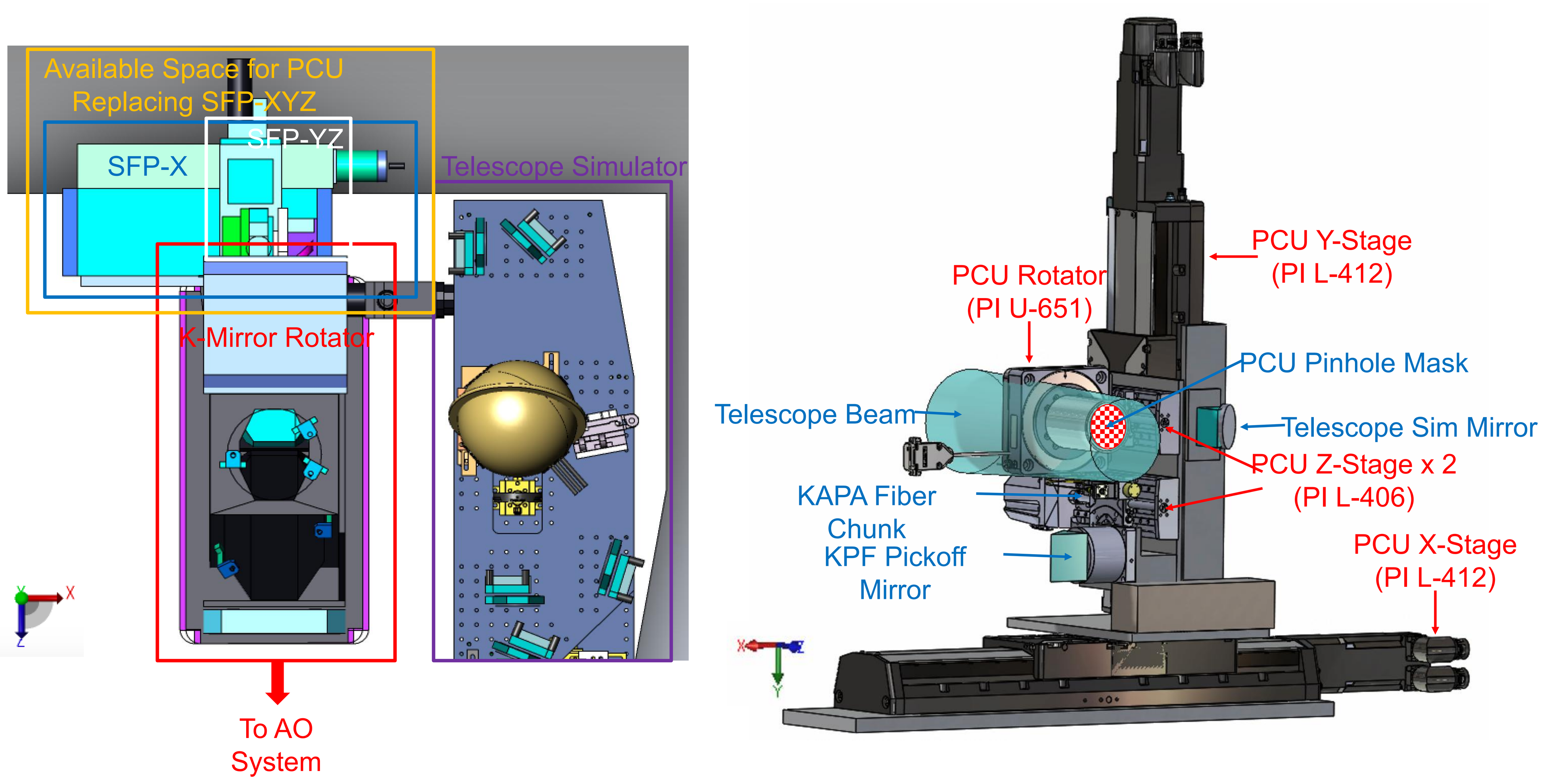
TOP-LEVEL REQUIREMENTS

The major challenge for solving any self-calibration model is the ***significant degeneracy*** between the fit parameters. Several precautions are recommended by Service et al. [1] to alleviate the degeneracy problem:

(1) The mask needs to be able to rotate 360 degrees continuously and translate ~ 15 % of the camera's field of view.
(2) Factors that affect the stability of scales (inaccuracies of movements along the optical-axis, mask deformation by flexures) need to be minimized.
(3) Any effect that flexes the mask with spatial correlations (choice of mount, temperature, manufacturing process) should be mitigated.
(4) Non-linear environmental instabilities (a changing temperature gradient and/or vibrations on the mask) need to be avoided.

Part	Topic	Requirement	Rationale	PDR status
Pinhole mask	Field of view (FOV)	≥ 40" x 40"	NIRC2 wide field camera	Under review
	Mask Pattern size	≥ 41 x 41 mm^2	To cover the NIRC2 FOV	
	Mask size	≥ 61 x 61 mm^2	Manufacturer requirements	
	Pinhole array pattern	≥ 10 x10	Sufficient for O(6) distortion model	
	Pinhole size	≥ 43 μm	SNR ≥ 600 within 120 s-exposure	12, 24, 56, 120 μm
X-/Y-stages	Precision & repeatability	≤ 5 μm	Stability of single-mode fibers	±1 μm
	Travel range X-stage	≥ 276 mm	Compatible with other projects	305 mm
	Travel range Y-stage	≥ 140 mm	Compatible with other projects	204 mm
Z-stages	Precision & repeatability	≤ 50 μm	~ 10^{-4} scale-variation	±5 μm
	Travel range	≥ 95.5 mm	Distance to the focal plane	102 mm
Rotation stage	Range	360°	360°	≥ 360°
	Clear aperture	≥ 41 mm	To cover the NIRC2 FOV	53 mm
	Angular repeatability	< 0.5 deg	Compatible with other projects	±3 mdeg
	Working temperature	0 ± 15°C	Bench requirement	5 − 40°C (specified), −20 − 40°C (conditional)

MECHANICAL DESIGN



Left. Location of the new PCU relative to the other components on the AO bench. It will replace the current SFP-XYZ stages at the entrance. When in use, dome light comes from the telescope, illuminates the pinhole mask at the first focus, and feeds into a field de-rotator K-mirror. The focal point is inside the K-mirror housing. ***Right.*** A SolidWorks rendering of the current PCU design.

STAGE MOVEMENTS

The PCU will provide support for the following existing and new modules through X-/Y-/rotation- and two Z-stage movements.

(1) Clear aperture for the telescope
(2) Pupil simulator
(3) Pinhole mask grid (this project)
(4) KAPA fibers
(5) KPF fiber injection unit
(6) HWPs for polarimetry

PROJECT TIMELINE

2018 Nov: initiated as a mini-project from the TMT Early Career Initiative (TECI) program
2019 Oct: initial design review
2020 Oct: preliminary design review

FUTURE MILESTONES

The team is working on resolving few potential risks brought up by the reviewers, purchasing and machining critical parts, and designing the software for motion control, data acquisition and interfacing with Keck. The anticipated assembly, testing and installation of the PCUs will be in 2021B/2022A.

REFERENCES

[1] Service et al., JATIS ***5*** (3), 1 – 13 (2019)
[2] Cameron and Kulkarni, AAS211,144–02 (2007)
[3] Yelda et al., ApJ ***725*** (1), 331 (2010)
[4] Service et al., PASP ***128*** (967), 095004 (2016)
[5] Lindergren, A&A ***616***, A2 (2018)