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ABSTRACT

We present evaluations of the Keck Telescope's adaptive optics (AO) performance on Milky Way Galactic center imaging and spectroscopic observations using three different AO setups: laser guide star with infrared (IR) tip-tilt correction, laser guide star with visible tip-tilt correction, and infrared natural guide star with a pyramid wavefront sensor. Observations of the Galactic Center can utilize a bright IR tip-tilt star ($K' = 7.4$ mag) for corrections, which is over 10 arcseconds closer than the optical tip-tilt star. The proximity of this IR star enables the comparison of the aforementioned AO configurations. We present performance metrics such as full-width-at-half-maximum (FWHM), Strehl ratio, and spectral signal to noise ratio and their relations to atmospheric seeing conditions. The IR tip-tilt star decreases the median spatial FWHM by 31% in imaging data and 30% in spectroscopy. Median Strehl for imaging data improves by 24%. Additionally, the IR star removes the seeing dependence from differential tip-tilt error in both imaging and spectroscopic data. This evaluation provides important work for ongoing upgrades to AO systems, such as the Keck All sky Precision Adaptive Optics (KAPA) upgrade on the Keck I Telescope, and the development of new AO systems for extremely large telescopes.

Keywords: Adaptive Optics, Imaging, Integral Field Spectroscopy

1. INTRODUCTION

The Keck Observatory's adaptive optics (AO) systems have played a crucial role in enhancing the scientific capabilities of the telescopes since 2000.[1,2] The AO systems originally used visible natural guide star corrections and then upgraded to laser guide star (LGS) capabilities in 2005.[3,4] Further improvements have included the installation of infrared (IR) tip-tilt[5] and pyramid sensors,[6] which enable increased access to more of the sky and allow observers to use stars closer to their science targets. Closer proximity of these tip-tilt stars to science targets will reduce tip-tilt error, thereby improving corrections and scientific quality. Integrating IR tip-tilt stars and the necessary IR sensors important components into ongoing upgrades to AO systems, such as the Keck All sky Precision Adaptive Optics (KAPA)[7] upgrade on the Keck I Telescope and the development of new AO systems for Extremely Large Telescopes (ELTs).

The Milky Way Galactic center (GC) is a key science case for the Keck Telescopes and is an ideal target to test AO systems performance due to the extremely crowded stellar surface density of the region. Ground-based optical telescopes need to use near-IR wavelengths to observe the GC because of extinction. The average extinction is $\sim$3 mag in K-band compared to on order of $\sim$20 mag in visible light.[8] The UCLA Galactic Center Orbits Initiative (GCOI, PI: A. Ghez) has used AO-fed near-IR imaging and astrometry to measure stellar orbits around the central supermassive black hole.[9,10] Since 2019, GCOI observations can use a bright infrared

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star named IRS7 ($K' = 7.4$ mag) located 5.5 arcseconds from the central supermassive black hole for tip-tilt corrections (see Figure 1). IRS7 is much closer than the optical tip-tilt star located about 20 arcseconds from the black hole.

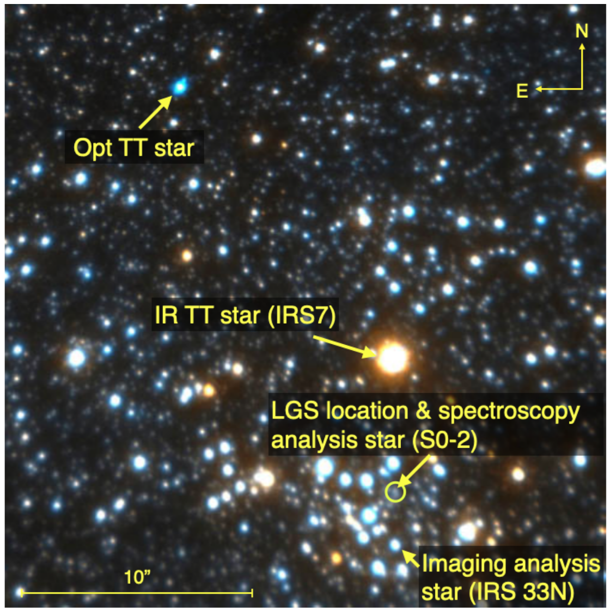

Figure 1. Image of the GC taken using Gemini with Hokupa'a/QUIRC AO. The locations of the points of interest are labeled on the image. The position of laser guide star (LGS), the central supermassive black hole, and star S0-2 are found in the yellow circle region. The IR tip-tilt star, IRS7, is within 8" of the stars used for measuring the imaging and spectroscopy performance analysis. The optical tip-tilt star is located 20" from the performance analysis stars.

The goal of this project is to evaluate the performance of the Keck Obsrvatory AO systems using different AO configurations on Milky Way Galactic Center data. This work builds on similar characterization investigations of Keck AO data, such as Ref 11. We also apply this characterization work to both imaging and spectroscopy datasets.

2. OBSERVATIONS AND DATA

All observations used in this analysis focus within the central 10" region of the Milky Way, approximately centered on the supermassive black hole, Saggitarius A* (ICRS Coordinates: RA 17 45 40.03599 DEC -29 00 28.1699).

2.1 Imaging Datasets

We compare the following imaging AO setups with the following labels:

1. **LGS-Opt:** LGS with optical tip-tilt star taken with NIRC2 (PI: K. Matthews) on the Keck II telescope.
2. **NGS-IR:** Natural IR guide star + pyramid wavefront sensor taken with NIRC2 on the Keck II telescope.
3. **LGS-IR:** LGS with IR tip-tilt star taken with the imager on OSIRIS (PI: J. Larkin[12]) on the Keck I telescope.

A summary table of the imaging datasets is included in Table 1. This table includes the primary information on how the observations were taken. All data were taken with the K' filter. The LGS-Opt and LGS-IR were both reduced in the same standard manner as reported in previous GCOI works such as Ref. 10. The LGS-IR

Table 1. Summary of the imaging datasets

AO Configuration	Instrument (Telescope)	TT Star Distance (")	t_{int} × Coadd (sec)	Observing Period	Frames	Median FWHM (mas)	Median Strehl
LGS-Opt	NIRC2 (Keck II)	20	2.8 × 10	2020-2021	888	72	0.23
NGS-IR	NIRC2 + PyWFS (Keck II)	8	2.1 × 14	2021	195	50	0.46
LGS-IR	OSIRIS (Keck I)	8	1.48 × 20	2021	33	50	0.44

data followed the same data reduction process as the other two datasets and used the Keck AO Imaging (KAI) data reduction pipeline.[13]

The LGS-Opt AO setup has been the primary configuration for GCOI papers.[10] To ensure comparison of the different AO modes under otherwise similar instrument conditions, we only include LGS-Opt data from 2020. This ensures that the LGS-Opt setup includes the latest equipment upgrades, such as the 20W laser.[14] Additionally, this temporal cut in the LGS-Opt data also accounts for the low-bandwith wavefront sensor (LBWFS) correcting for 45 Zernike modes, which is consistent with the NGS-IR and LGS-IR datasets.

We are also interested in analyzing the data given atmospheric seeing conditions and obtained our seeing data from the Mauna Kea Weather Center (MKWC).[15] Details on the descriptions of the seeing data are described in Ref. 11. In summary, we were most interested in the MASS (Multi-Aperture Scintillation Sensor) readings as a measurement for the seeing. We chose MASS because Ref. 11 found that MASS had a higher correlation to image FWHM and Strehl compared to DIMM (Differential Imaging Motion Monitor), which is the other seeing value published by the MKWC. Our imaging datasets go through another cut, where data points must have MASS readings within 2 minutes of the exposure time.

2.2 Spectroscopic Datasets

All spectroscopic data were taken with the OSIRIS integral field imaging spectrograph on the Keck I telescope. These data have a smaller field of view than the imaging data focuses on the central arcsecond around the supermassive black hole. We compare the following spectroscopic AO setups with the following labels:

1. **LGS-Opt:** LGS with optical tip-tilt star
2. **LGS-IR:** LGS with IR tip-tilt star

Additionally, we also compare two different pixel scales for each AO setup: 20 mas/pixel and 35 mas/pixel. This results in four different datasets, which are reported in Table 2. All data are taken with 900s exposures for each frame. Data were either taken in the K broadband filter or the K narrow-band filter, Kn3. To maintain consistency in datasets, we restrict all LGS-Opt data to after the start of 2016, when the OSIRIS detector was upgraded.[16]

Data are reduced in a similar manner as described in Ref. 10. Data cubes are constructed from the raw exposures using the Keck OSIRIS Data Reduction Pipeline.[17,18] Example datacubes for comparison between LGS-IR and LGS-Opt are shown in Figure 2.

3. EVALUATION OF IMAGING DATA

The star IRS33N is the object used for characterizing the quality of the dataset for the following reasons: 1) it is bright ($K' = 11.1$ mag) but its PSF core does not reach the non-linearity regime of the NIRC2 detector in our imaging setup and 2) it is isolated in the crowded region. IRS33N is identified in each reduced frame. In

Table 2. Summary of the spectroscopy datasets

AO Configuration	Pixel Scale (mas)	TT Star Distance (")	Observing Period	# Frames	Median FWHM (mas)	Median SNR
LGS-Opt	20	20	2020	4	75	16
LGS-IR	20	5.5	2020-2021	28	48	41
LGS-Opt	35	20	2016-2021	167	70	31
LGS-IR	35	5.5	2021	12	57	34

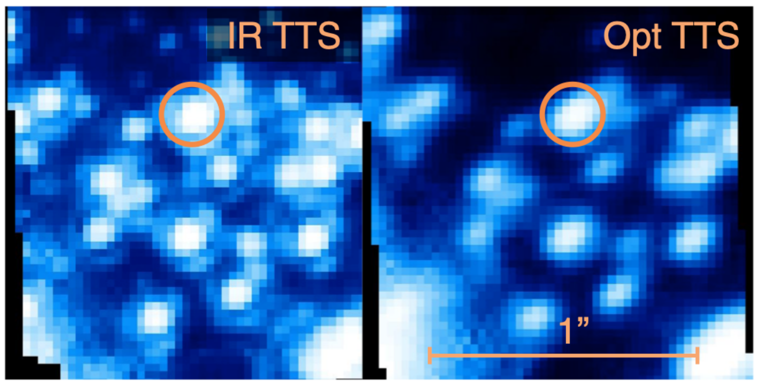

Figure 2. Comparison of spectroscopic data cubes taken with the IR tip-tilt sensor (left) and optical tip-tilt sensor (right). The star used for performance analysis, S0-2, is circled in each image. Both data cubes were taken on the same night in the Kn3 20mas plate scale setup. Each OSIRIS cube is taken with a 900s exposure.

each frame, we use the Strehl calculator in KAI run on the position of IRS 33N. To estimate the Strehl ratio, the calculator fits a two dimensional Gaussian function to the core of the star and compares the core peak with that of a diffraction limited PSF from Keck NIRC2 in the observation filter.

Figure 3 shows IRS33N's FWHM and Strehl for each individual frame for each given dataset. The IR tip-tilt star datasets show noticeable improvements in both FWHM (decrease of 31%) and Strehl (increase of 24%) when compared to data taken with the optical tip-tilt star. There are no significant differences between the NGS-IR and LGS-IR dataset performance metrics.

Each IRS33N FWHM and Strehl value are associated with a MASS reading value from the MKWC. Figure 4 shows the performance metrics with their associated MASS values. The FWHM and Strehl values of the IR tip-tilt datasets outperform those values of the optical tip-tilt dataset under similar seeing conditions. Additionally, we perform a fit to the data to investigate the relationship between MASS and performance metric. The slopes of FWHM vs MASS for the IR tip-tilt datasets are consistent with zero, showing that the FWHM are stable across seeing conditions.

4. EVALUATION OF SPECTROSCOPIC DATA

The best characterized star in the spectroscopic datasets is S0-2, a main-sequence B-type star (i.e. B0-B3) located within ∼0".25 arcseconds of the supermassive black hole.[19] This star is the primary science target of the spectroscopic GCOI observations and therefore is always placed in the field of view of OSIRIS.

After reduced OSIRIS data cubes are made, S0-2 is identified in each cube and its FWHM is calculated by fitting a Gaussian to S0-2's PSF. The spectral extraction process of S0-2 is detailed in GCOI works such as Ref. 10. To summarize, we use a radius of 52.5 mas to extract the spectrum for both the 20mas and 35mas pixel scales. An annulus outside the extraction radius is then used to identify the sky background, which is

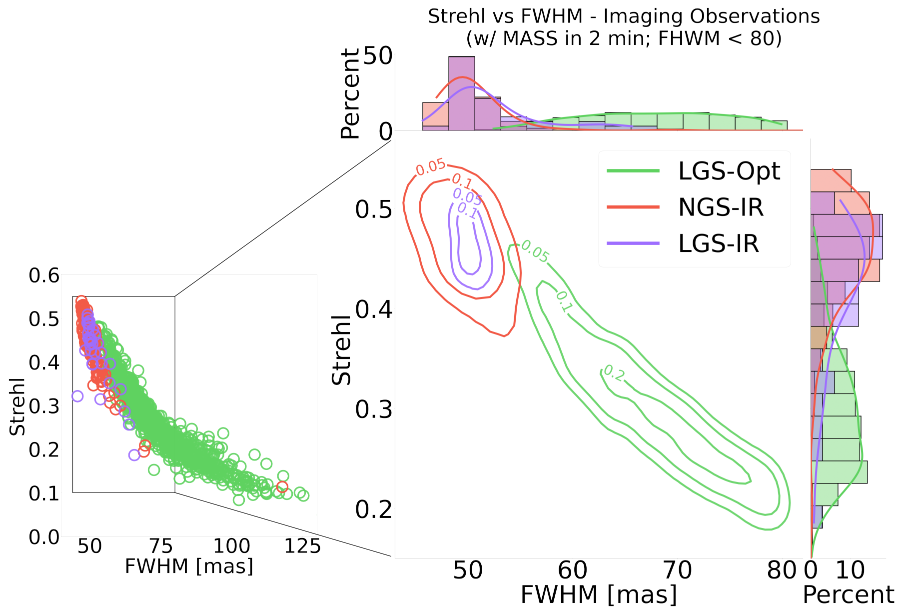

Figure 3. Strehl vs FWHM for each individual frame of the different imaging datasets. The star IRS33N is used for calculating these metrics. The zoom focuses on data with FWHM less than 80 mas and shows the data contours for ease of viewing. The two systems that use the IR tip-tilt star demonstrate improved Strehl and FWHM compared to the optical tip-tilt star data.

then subtracted from S0-2's spectrum. Thereafter, we take the inverse of the standard deviation of a wavelength region in the continuum of S0-2 (2.130-2.145 μm) to determine the spectral SNR.

Figure 5 shows S0-2's spectral SNR and FWHM for each cube in the different datasets. The IR tip-tilt star provides improves the median FWHM by 30% compared to the optical tip-tilt star data for both the 20mas and 35mas pixel scale. There is no obvious correlation between the spectral SNR and the tip-tilt star used.

We also associate each spectral frame with a MASS seeing value from the MKWC. We chose the MASS seeing value that most closely matches the start of the spectral frame integration. We explored that the average MASS value over the course of the 900 second exposure did not significantly differ from MASS value at the start of the integration.

We show S0-2's FWHM values with their corresponding MASS values in Figure 6. The FWHM of S0-2 remains stable over a range of seeing conditions for the LGS-IR system. This result contrasts with the LGS-Opt datasets, where FWHM degrades with increasing MASS values.

5. DISCUSSION AND FUTURE WORK

Analysis shows that the spatial resolution of both imaging and spectroscopy data benefit from the IR tip-tilt stars. These results support the prediction that wavefront error should decrease as the tip-tilt star approaches the science targets. This validation of AO correction improvements with IR tip-tilt stars on Galactic center data is encouraging for other science targets that can benefit with IR tip-tilt stars. Additional observations of the LGS-IR and NGS-IR with imaging and the LGS-IR with spectroscopy will be useful for further supporting these findings.

The spectroscopy results show no significant correlation between the spectral SNR and the tip-tilt star used. While the IR tip-tilt star provides improvement in the spatial FWHM in the OSIRIS data, a large scatter is seen in the spectral SNR parameter. This scatter may be a product of the 900 second integration time, which makes the spectroscopy datasets more susceptible to weather effects and AO system instabilities. In particular, the LGS-IR data taken with the 35 mas/pixel scale were impacted by clouds and short laser closures from satellites.

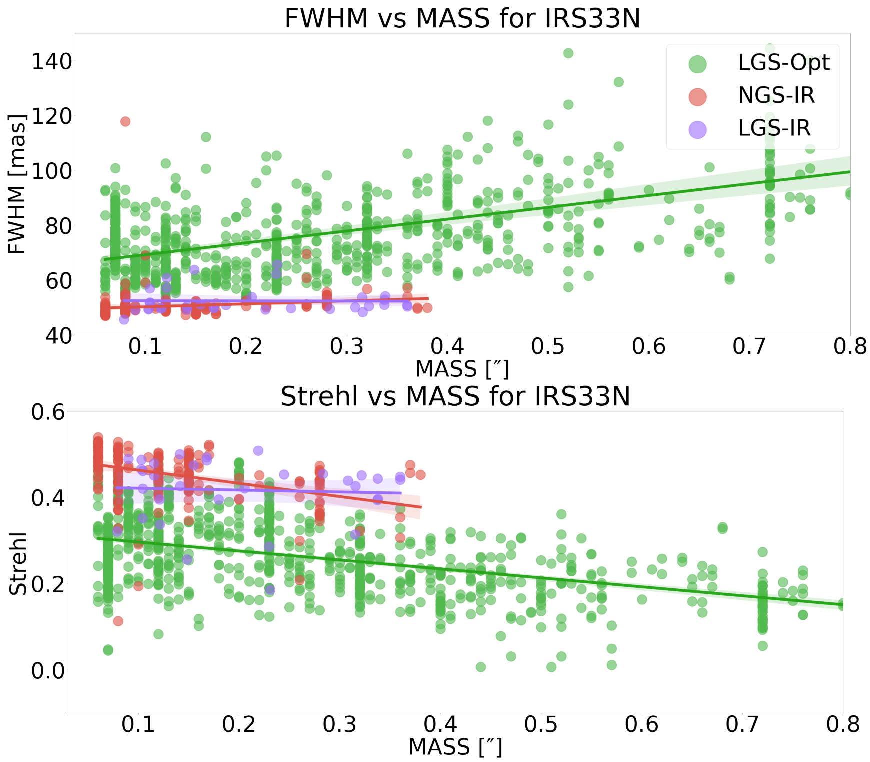

Figure 4. **Top:** FWHM vs MASS seeing for the imaging data sets. For comparable seeing conditions, the IR tip-tilt star systems produce smaller FWHM values compared to the optical tip-tilt star system. These FWHM values for IR tip-tilt star data are stable across seeing conditions. **Bottom:** The same comparison but for Strehl vs MASS seeing. The IR TT star systems produce better Strehl than the Opt TTS system.

These brief laser closures negatively impact the spectral SNR while not having as great of an effect on the spatial FWHM. More data taken with the LGS-IR configuration, especially in the 35 mas/pixel scale, will be helpful for investigating the impact of the IR tip-tilt stars on spectral SNR. Additionally, another region of the spectrum from the continuum, such as the Brγ absorption line, can be investigated as another metric of measuring spectral SNR.

These findings are encouraging as upgrades are made to current AO systems to incorporate IR tip-tilt stars, such as the KAPA upgrade on the Keck I telescope. Additionally, AO systems on ELTs will leverage the utility of IR tip-tilt stars for sky coverage.

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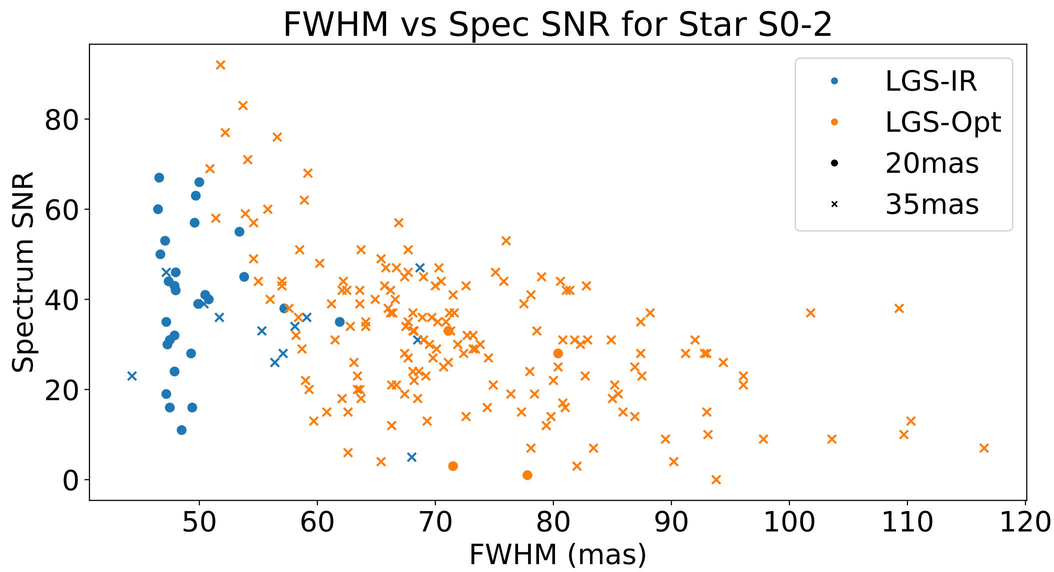

Figure 5. Star S0-2's spectrum SNR vs FWHM for each individual frame of the spectroscopy datasets. The IR TT star provides improved FWHM compared to the Opt TT star data for both the 20mas and 35mas pixel scale.

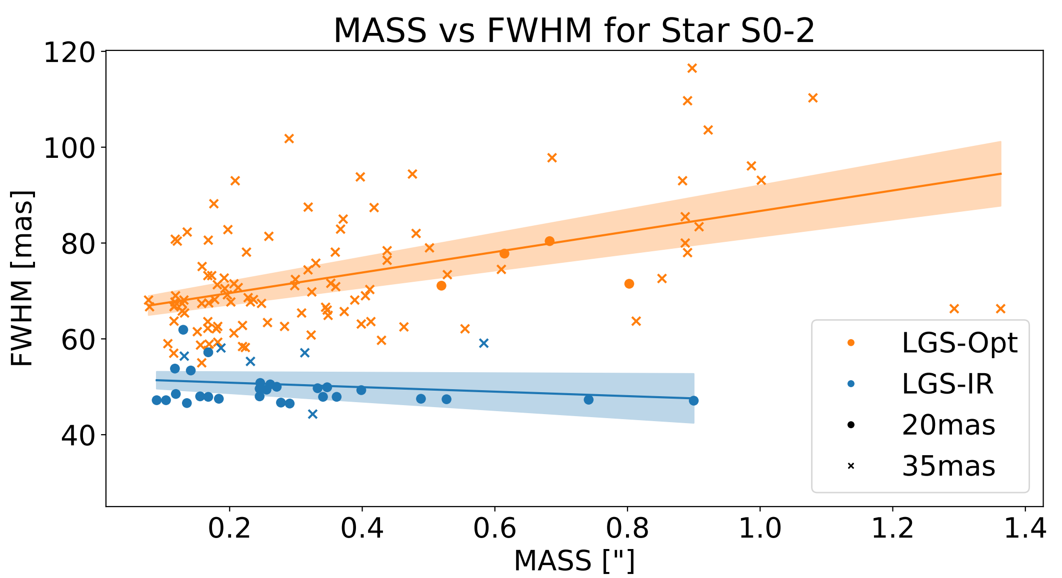

Figure 6. FWHM vs MASS seeing for the spectroscopy data sets. The IR TT star systems produce better Strehl than the Opt TT star system and is also stable across seeing conditions.

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