Analyzing long-term performance of the Keck-II adaptive optics system

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Abstract

We present an analysis of the long-term performance of the W. M. Keck Observatory Laser Guide Star Adaptive Optics (LGS-AO) system and explore factors that influence the overall AO performance most strongly. Astronomical surveys can take years or decades to finish, so it is worthwhile to characterize the AO performance on such timescales in order to better understand future results. Keck Observatory has two of the longest-running LGS-AO systems in use today and represents an excellent test-bed for investigating large amounts of AO data. Here, we use LGS-AO observations of the Galactic Center (GC) from 2005 to 2019, all taken with the NIRC2 instrument on the Keck-II telescope, for our analysis. We combine image metrics with AO telemetry files, MASS/DIMM turbulence profiles, seeing information, and weather data in one cohesive dataset to highlight areas of potential performance improvement and train a simple machine learning algorithm to predict the delivered image quality given current atmospheric conditions. The complete dataset will be released to the public as a resource for testing new predictive control and PSF-reconstruction algorithms.

Observations

We compile data for this project from four different sources:
GC data: FITS images from a 14-year survey (2005-2019) of the galactic center from the Keck-II telescope at the W. M. Keck Observatory, all taken with the laser guide star adaptive optics (LGS-AO) system and the NIRC2 camera (PI: K. Matthews) in the K-band (see [1] for details).
AO telemetry: Recordings of the performance of the AO system and wavefront sensor (WFS) throughout the science observation.
CFHT data: Meteorological readings from the Canada-France-Hawaii Telescope (CFHT) weather tower.
Seeing data: MASS/DIMM seeing information from the Mauna Kea Weather Center (MKWC) [2] on the same observing nights as the NIRC2 images.

This data is compiled into a single table, with each row representing one NIRC2 observation. Image quality is measured by the *Strehl ratio* - the ratio of the central intensity of a point source to the ideal, diffraction-limited intensity - and the *FWHM* - the full width at half the maximum intensity of the point-spread function. We use different filtering methods for different types of analysis, as shown in Figure 1.

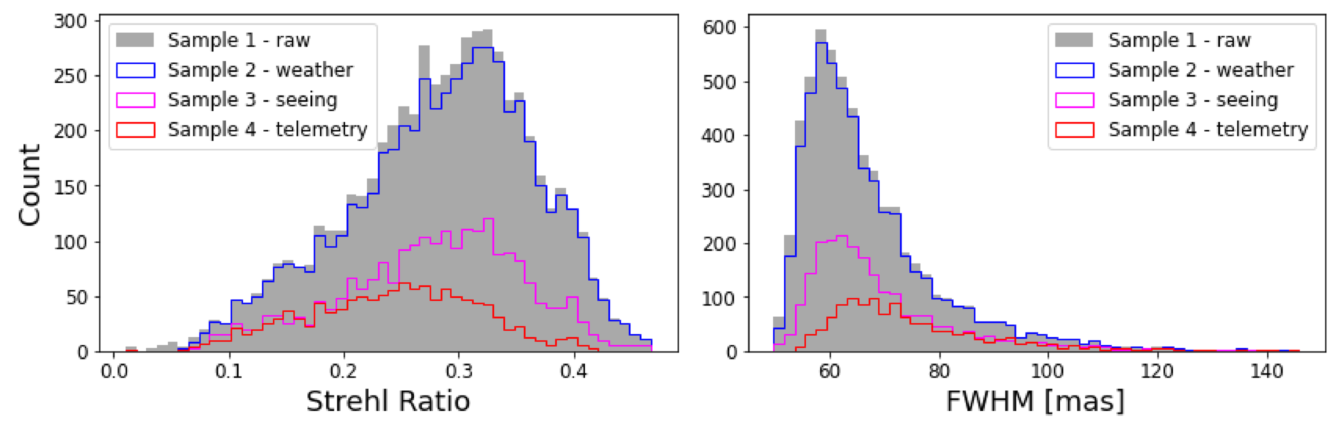

Fig. 1: Histograms of Strehl and FWHM data filtered for valid weather, seeing, and telemetry values (see legend).

Goals

1. **Investigate the NIRC2, telemetry, weather and seeing data for areas of potential performance improvement.**

   A thorough analysis of the NIRC2 data and telemetry, paired with weather and seeing information, could help to identify current problems with the Keck-II AO system which can be fixed for better performance. It could also reveal which improvements to the system would boost performance the most, allowing for better prioritization of repairs.

2. **Train a Machine Learning (ML) algorithm to predict the image quality based on current weather and seeing conditions.**

   Testing an ML algorithm on the current data will give us an idea of how feasible it is to predict image quality prior to an observation. If the results are promising enough, we will use the same process to develop an observing tool for use in real-time observations with Keck-II. An observer would then be able to choose targets with higher predicted image quality on any given night, which, for large astronomical surveys, would gradually improve the quality of results over time.

Analysis

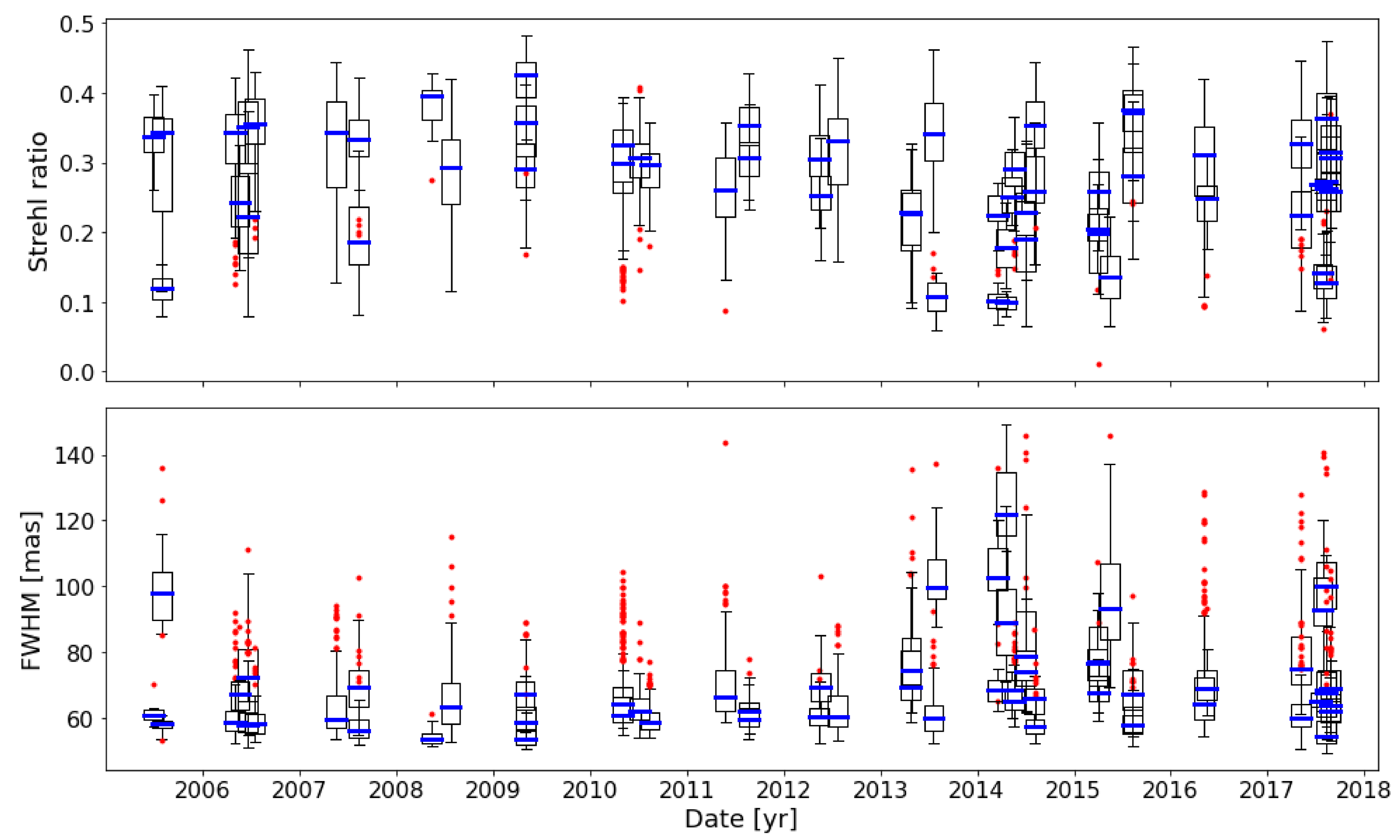

Fig. 2: Image quality measurements for each observing night, with outliers shown in red and medians shown in blue.

One unexpected factor we discovered in our analysis was that the **overall image quality has degraded over the length of the survey** instead of improving. Figure 2 shows the image quality per night as a box and whisker plot, and, starting in late 2013 or early 2014, there seems to be a significant increase in median FWHM values and a decrease in median Strehl ratios. There are more outliers in later years, indicating that the current performance is not as consistent as in the past.
Investigation of other variables in the data revealed that **the image quality also has a weak linear dependence on both the outdoor and indoor temperatures** ($r \sim 0.3$), which is unexpected, as the AO system should be able to perform roughly the same regardless of the outdoor temperature.

Analysis Results

The sudden onset of highly variable image quality indicates that this is **likely due to instrumentation problems** rather than natural phenomena, and the dependence of image quality on temperature may be a result of **turbulence introduced into the beam path** through the Keck-II AO hatch (similar to [3]). However, more research is needed to confirm these findings. In future work, we will check the AO engineering logs for Keck-II to determine whether any new instruments could be detracting from performance, and we will gather more temperature data from around the Keck-II dome, mirror, and AO bench in order to investigate possible turbulence in the AO pipeline.

Acknowledgements

We acknowledge support from the W.M. Keck Foundation, the Heising-Simons Foundation, and the National Science Foundation. (*AST-1518273, GRFP Grant No. 2018268910*)

Prediction

In order to get a model that is useful for predicting image quality, we must limit the data we use to train our ML algorithm to that which would be available *before* an observation on any given night (i.e. weather and seeing data only). We select **nine features** to use for our preliminary tests based on their correlation with image quality, which are listed in the table below.

Features	Targets
Wind speed	Strehl ratio
Wind direction	FWHM
Temperature	
Humidity	
Pressure	
Azimuth	
Airmass	
MASS seeing	
DIMM seeing	

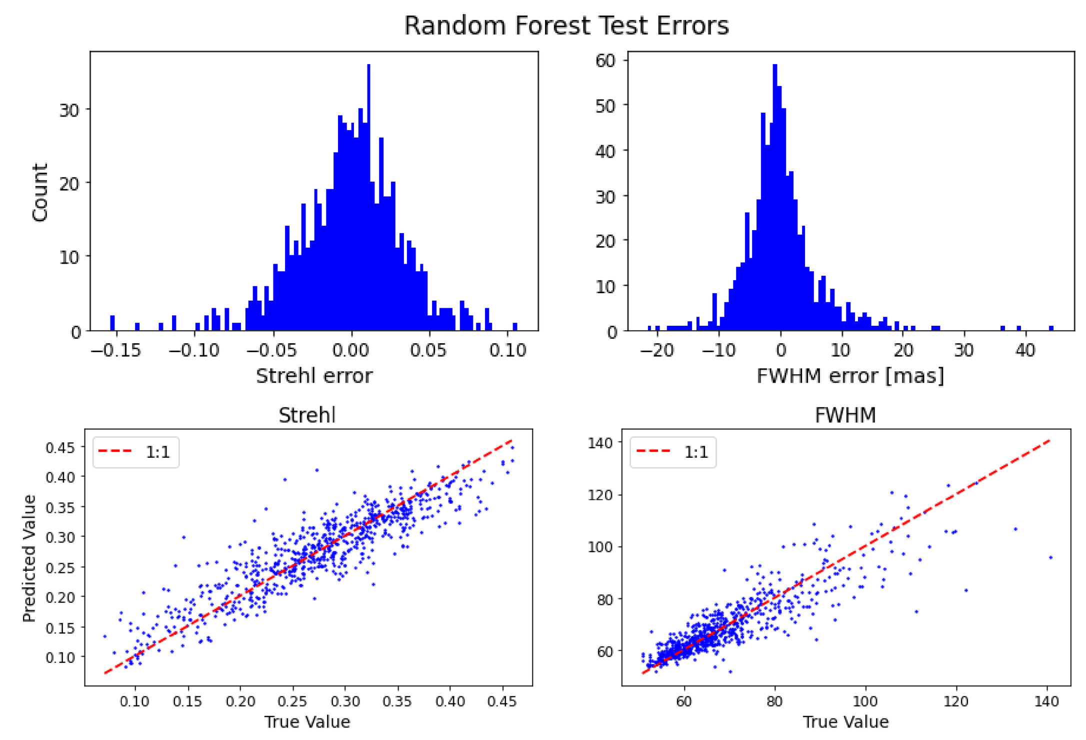

Fig. 4: Test errors for the Random Forest algorithm.

We use the `sklearn` package to train each quality-prediction algorithm and test them on a set of observations not used during training, which gives an estimate of the real-time performance. In preprocessing, we use a Principal Component Analysis to ensure that the features are independent, and we use a Grid Search to find the best parameters for each model. We compare three ML algorithms: a Support Vector Regressor, a Random Forest Regressor, and a Multi-Layer Perceptron (a type of Neural Network) and find that the algorithm with the best performance is the **Random Forest Regressor**, with the lowest average test error (see Figure 4).

Prediction Results

The average **Strehl error is 0.03** and the average **FWHM error is 5.42 mas** for our current dataset, which is a very promising result for a relatively simple test run. This algorithm alone could significantly improve observation runs in practice, but with more complicated models and more data included, we can increase the accuracy even more in future work.

References

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