Development of a telemetry pipeline for use on the Keck II pyramid wavefront sensor

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ABSTRACT

A new Adaptive Optics (AO) system utilizing a Pyramid Wavefront Sensor (WFS) is currently being commissioned on the Keck II Telescope. A new telemetry pipeline must be developed to analyze data produced by the WFS and AO system and to determine important parameters present in the observing process. The following project focuses on laying the groundwork for such a pipeline and providing measurements of a few parameters useful in the characterization of the atmosphere in real time. These parameters are the root mean square of the deformable mirror (DM) commands and residual wavefront and the value of the Fried parameter, from which a value of the seeing angle can be derived. To confirm the results of these measurements, simulated data was implemented. By proving the functionality of the code we are able to confirm the results. Further comparisons between the analysis of on sky data and measurements made on Mauna Kea confirm the results.

INTRODUCTION

As light travels from any extraterrestrial object, it must pass through the atmosphere on its way to the telescope. During the light’s propagation, it encounters irregularities in the atmosphere, caused by anything from wind to a change in temperature. Regardless, the turbulence introduces aberrations into the wavefront. The goal of a telescope’s AO system is to correct for these aberrations. By using a DM, the AO system is able to do just this. The residual wavefront is sent to two locations after encountering the DM. One is the science target. This is the scientific instrument that preforms the actual science on the object. The other location is the WFS. This sensor reads the residual wavefront and creates commands sent to the DM to preform the proper corrections. This closed loop operation produces a more stable science image and increases the resolving power of the telescope.

In modern AO systems, wavefront sensing is generally done in the visible spectrum. This works well for most science objects, but can lack the sensitivity needed to study faint, red objects like M-dwarf stars. To combat this, a new Pyramid Wavefront Sensor (WFS), pictured below, has been installed with an AO system on the Keck II telescope. The Pyramid WFS has shown improved sensitivity to wavefront aberrations over the industry standard.
Shack Hartmann WFS. Systems on the Large Binocular Telescope (LBT), Subaru’s extreme AO system SCExAO, and the Magellan telescope support this in the visible band (Bond et al. 2018). Keck II combines this improved sensitivity with low noise infrared detector technology to produce better performance in the AO system.

![Pyramid WFS Diagram](image)

**Figure 1:** A diagram of the Pyramid WFS (Chen et al. 2017) The light wavefront is incident upon the tip of a pyramid prism splitting the light onto four pupil images. By measuring the distribution of light in these images, the wavefront can be reconstructed.

Currently, the Pyramid WFS is being commissioned and has begun scientific demonstrations. However, there is no pipeline for analysis of the data collected from the WFS and AO system. The purpose of this project is to develop such a pipeline to extract and analyze useful parameters to assist in the commissioning of the Pyramid WFS. Through this analysis, the residual root mean squared (RMS) is calculated and a measurement of the seeing angle are made. These measurements are used to characterize the atmosphere in real time and to assess the performance of the AO system. The AO system design team will use these assessments to create optimization routines for the system. In this paper, the methods used to develop the pipeline and a discussion of the results of a sample test scenario are presented.

**METHODS**

The pipeline is written in the Python language. It is designed as a suite of functions to handle and analyze the stream of data from the WFS and the AO system. A Graphical User Interface (GUI) is implemented to simplify the data handling for the user. The user is able to specify which analysis they would like to perform as well as the time span they would like to analyze. This allows the user to select the times over which their science targets were being viewed and engineers to assess the performance of the AO system over the entirety of the night.

The analysis of the data is broken into separate modules. Making the code highly modular makes it more flexible to handle the changing needs of scientists and engineers. Initially, a
few simple statistical measurements are taken from the data. The RMS of the DM corrections and the residual wavelength are calculated. After these statistical measurements are made, more advanced parameters are extracted from the data. These included an estimate of the seeing and a measurement of the strength of Zernike modes in the residual.

The seeing is estimated utilizing an analysis of the DM corrections. These corrections are derived from the commands sent to the DM from the AO system. The commands are sent as a voltage signal, which can easily be converted into nanometers. An example of one frame of commands is shown below. In the AO system, the commands are sent to the actuators, which in turn vary the shape of the DM.

Figure 2: Sample DM command for a single frame presented in nanometers. Red denotes a positive position and blue denotes a negative position.

The true shape of the DM can be made more accurate using the influence function for the DM. This function describes how the DM responds to the push and pull of the actuators. Because the DM is a physical object, it warps under the influence of the actuators. These warps overlap to create the true shape of the DM. By applying the influence function to the DM commands, this shape can be found. The resultant wavefront of the above commands is shown below
Figure 3: Sample DM wavefront for a single frame presented in nanometers. Red denotes a positive position and blue denotes a negative position.

To estimate the seeing angle, the influence function is first applied to the DM commands, resulting in the true shape of the DM. This will give a more accurate estimate. The shape is then shifted from volts to nanometers, then from nanometers to phase of wavelength. This is done at the standard 500 nm wavelength. This phase map is then decomposed into the Zernike basis, a set of orthogonal polynomials defined on a unit circle. A representation of the Zernike basis is shown below.

Figure 4: The first 21 terms of the Zernike Basis including names of lower order terms (Comsol 2019).

The summation of these modes can be used to define any shape present over the unit circle. To find the coefficients Zernike polynomials, the following relationship is used:

$$\vec{\phi} = B \vec{C}$$  \hspace{1cm} (1)
Here, $\vec{\phi}$ denotes the phase vector, a 1D compression of the 2D phase map with length $N$, the total number of points present in the phase map. The matrix $B$ denotes the $N \times J_{\text{max}}$ matrix where each row describes a point on the phase map and each column describes a Zernike Polynomial. The integer $J$ is the Noll index of the Zernike polynomials, an index handling the radial and azimuthal degree in one number. The vector $\vec{C}$ denotes the coefficient vector holding the coefficients of the $J_{\text{max}}$ polynomials.

By computing $B$ and deriving $\vec{\phi}$ from the DM shape, we are able to compute $\vec{C}$ for each frame of the AO loop. The variances can easily be computed by arranging these coefficient vectors vertically into a matrix. Each row of this matrix represents the coefficients of a single Zernike polynomial. The variance of the Zernike polynomial coefficients for each Zernike mode is then used to estimate a value for the Fried parameter using Noll’s approximations, shown below (Noll 1975):

$$J \leq 10 : \sigma^2 = A_J \left( \frac{D}{r_0} \right)^{5/3}$$

$$J > 10 : \sigma^2 = 0.2944J^{-\sqrt{3}/2} \left( \frac{D}{r_0} \right)^{5/3}$$

$A_J$ is defined below:

$$A_J = \begin{pmatrix}
1.031 \\
0.582 \\
0.134 \\
0.111 \\
0.088 \\
0.065 \\
0.059 \\
0.053 \\
0.046 \\
0.040
\end{pmatrix}$$

As before, $J$ indicates the Noll index for each Zernike Mode, $D$ indicates the diameter of the pupil encountered by the wavefront, and $r_0$ indicates the value of the Fried parameter. Based on a visual analysis of the variances, certain Noll indices are excluded as "bad modes". These indices deviate greatly from the expected trend. This deviation is due to factors such as edge effects and aberrations due to the central obstruction on the telescope. These factors cause errors in certain modes which create much higher variances than expected. For this reason these modes are left out of the approximation. Similarly, lower and higher order modes are excluded. Lower order modes, such as tip and tilt are not corrected by the DM and therefore will not be present in the approximation of $r_0$. Higher order terms encounter great errors stemming from the decomposition of the wavefront shape.
into the Zernike basis. These higher orders are important for the decomposition process itself, but their own variances face high errors. Therefore, they are present in the decomposition, but are not used for approximation. For the approximation, modes 6 through 75 are used.

For each of the remaining Noll indexes, a fit of the Noll approximation curve is preformed. This fit produces an estimated value of the Fried parameter. This is then used to calculate the seeing angle.

\[ \omega_0 = 0.98 \frac{\lambda}{r_0} \text{rad} \]  

(4)

Here, \( \omega_0 \) indicates the seeing angle and \( \lambda \) indicates the wavelength being used. The standard 500nm is used in further calculations.

In order to test the functionality of the code, a simulation was run using the OOMAO Adaptive Optics Simulation Package and SOAPY Simulation Module. These packages are used to simulate various AO systems and to provide realistic data for use in on-sky developments. Simulations were run to recreate the performance of the Pyramid WFS and to produce simulated data similar to that generated by the system on Keck II. This test data was analyzed using the pipeline created to assess the performance of the code. The code was then modified to match the derived parameters used to configure the simulation. Further tests were performed to compare the seeing estimate with measurements made at the time of data collection from seeing monitors at nearby locations. Finally, the AO performance estimates taken from the data were compared with the on-sky performance at the time of data collection.
RESULTS

The analysis of a sample OOMAO simulation are presented below. First, the RMS of the DM commands is calculated.

![Figure 5: Simulated DM Command RMS in nm. The blue line indicates the RMS for each frame and the red line indicates the average over all frames.](image)

The RMS of the DM commands can be used as an indication of how large the wavefront being corrected appears on the DM. A perfectly flat wavefront would cause the DM commands to have an RMS of zero. However, because of atmospheric distortions, the actual RMS is much higher. After calculating the RMS of the DM commands, an estimation of the Fried parameter is calculated.

![Figure 6: Breakdown of simulated DM commands into Zernike Modes for \( r_0 = 0.16 \). Black line shows Noll’s approximation fit for \( r_0 = 0.162 \).](image)

For each Zernike Mode, the variance of the DM commands over the pupil are plotted. For
This simulation, $r_0 = 0.16$ m was used and $r_0$ is estimated to be $0.162 \pm 0.01$ m through the analysis. This corresponds to a seeing angle estimate of $0.625$ arcsecs at $500$ nm. The value of $r_0 = 0.16$ m was chosen because it corresponds to $\omega_0 \approx 0.6$ arcsecs. This is the average value on Mauna Kea, and therefore is a good estimate for the average value encountered by the Keck II telescope. Further simulated data from the SOAPY package was analyzed, and the results presented below.

<table>
<thead>
<tr>
<th>Simulation $r_0$</th>
<th>Estimated $r_0$</th>
<th>$r_0$ Error</th>
<th>$\omega$ @ 500nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1037</td>
<td>0.0111</td>
<td>0.9749</td>
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<td>0.13</td>
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<td>0.26</td>
<td>0.2578</td>
<td>0.0199</td>
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</table>

These values fell within an acceptable 2% error, proving the validity of the code. A set of on-sky data was fed through the pipeline to obtain sample results. This data was taken on April 20, 2019.

Figure 7: RMS of DM commands (Blue) and residual wavefront (Red) in nanometers.

This figure shows the effect of the DM on the wavefront. The low average of the residual RMS means that the wavefront has very few aberrations as it hits the WFS, meaning the DM is accurately correcting for wavefront aberrations. The spikes are an interesting feature of this particular data set. These are caused by extreme values in a pixel that greatly raise the RMS value for that frame. This is due to a saturation in the DM commands. The actuators can only receive a signal of $\pm 10$ volts, even if the commands exceed that value. Therefore, the DM cannot correct for such extreme aberrations. These aberrations
first appear on the DM as they are encountered and a correction is attempted. Since the correction fails, they are then present in the residual wavefront after traveling to the WFS.

The Fried parameter was also estimated for the on-sky data. In order to account for the hexagonal structure of the Keck II pupil, a circular region within the pupil was chosen for use in the analysis. This circular region was chosen to cover the $17 \times 17$ central actuators inside the total $21 \times 21$ actuators. This limits the edge effects of the hexagonal pupil and allows for a more accurate Zernike decomposition, which relies on the circularity of the polynomials.

![Graph](image)

Figure 8: Breakdown of simulated DM commands into Zernike Modes for on-sky data for the $17 \times 17$ central actuators.

For this set of on-sky data $r_0$ was calculated to be $0.0745 \pm 0.004$ m. This corresponds to a seeing angle of $1.36$ arcsecs. Measurements from DIMM and MASS for the same night are shown below.

![Graph](image)

Figure 9: Seeing measurements made on April 20, 2019. Blue data is from DIMM, green from MASS, and red from Keck II telemetry pipeline.
The measurement of the seeing angle from the pipeline is similar to that of other measurements made on the same night. The disagreement of the data derives from the independent sampling space for each measurement. Each measurement samples a different part of the sky; therefore, each encounters a different turbulence profile. This causes the measurements to vary over the same time period. Nevertheless, the pipelines offers another independent source of seeing data.

DISCUSSIONS AND CONCLUDING REMARKS

A telemetry pipeline for the analysis of the Pyramid WFS Adaptive Optics system on the Keck II telescope has been developed. This pipeline is written as a series of analysis modules used to extract specific parameters from the raw on-sky data. To test the validity of the analysis code, simulated data was generated through the OOMAO and SOAPY simulation packages. This data was put through the analysis pipeline. After analysing the simulated data, raw on-sky data was also analysed. The results of this analysis were then compared with independent outside measurements. RMS values for both the DM commands and residual wavefront showed good performance of the AO system. Estimations of the seeing angle were similar to those of independent nearby measurements. The accurate extraction of these parameters from raw on-sky data will be useful for the future of the Keck II Pyramid WFS and AO system. They will play a crucial role in the development of an automated optimization control for the AO system. Furthermore, the extraction of an independent seeing estimate will expand the effectiveness of astronomy performed on Mauna Kea. Adding a reliable, independent estimation will give astronomers a better understanding of the effects of the atmosphere on the mountain.

REFERENCES

Noll, R., "Zernike polynomials and atmospheric turbulence", (1975)
Comsol Ray Optics Module, (2019)