Fast modulation and dithering for the NFIRAOS Pyramid Wavefront Sensor

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ABSTRACT

The Narrow Field InfraRed Adaptive Optics System (NFIRAOS) for the Thirty Meter Telescope (TMT) will use a natural guide star (NGS) Pyramid Wavefront Sensor (PWFS). A 32-mm diameter Fast Steering Mirror (FSM) is used to modulate the position of the NGS image around the tip of the pyramid. The mirror traces out a circular tip/tilt pattern at up to 800 Hz (the maximum operating frequency of NFIRAOS), with a diameter chosen to balance sensitivity and dynamic range. A circular dither pattern at 1/4 the modulation frequency is superimposed to facilitate optical gain measurements. The timing of this motion is synchronized precisely with individual exposures on the PWFS detector, and must also be phased with other wavefront sensors, such as Laser Guide Star Wavefront Sensors (LGSWFS) and the On-Instrument Wavefront Sensors (OIWFS) of NFIRAOS client instruments (depending on the observing mode), to minimize latency. During trade studies it was decided to pursue a piezo actuator from Physik Instrumente (PI) using a monocrystalline piezo material, as more conventional polycrystalline devices would not meet the lifetime, stroke, and frequency requirements. Furthermore, PI claims excellent stability and hysteresis with similar piezo stages, rendering sensor feedback unnecessary. To characterize the performance of this mechanism, and to verify that it can function acceptably in open-loop, we have operated the stage on a test bench using a laser and high-speed position sensing devices (PSDs) both at room temperature and at the cold -30 C operating temperature of NFIRAOS. We have also prototyped the software and hardware triggering strategy that will be used to synchronize the FSM with the rest of NFIRAOS.

Keywords: fast steering mirror, piezo actuators, absolute timing, wavefront sensors

1. INTRODUCTION

The Narrow Field InfraRed Adaptive Optics System (NFIRAOS) will be the first-light adaptive optics (AO) system for the Thirty Meter Telescope (TMT).\textsuperscript{1} Wavefront sensing will be provided by 6 Laser Guide Star (LGS) wavefront sensors (WFS), a natural guide star (NGS) Pyramid Wavefront Sensor (PWFS), and also low-order NGS On-Instrument Wavefront Sensors (OIWFS) and On-[Science-]Detector Guide Windows (ODGW) provided by the three client instruments. The LGS WFS and PWFS sense visible light, while near-infrared light is passed downstream to the client instruments via a beam splitter. The PWFS will incorporate a 32-mm diameter Fast Steering Mirror (FSM) to modulate the position of the NGS on the tip of the pyramid. This mirror traces out a circular tip/tilt pattern at up to 800 Hz (the maximum operating frequency of NFIRAOS), with a diameter chosen to balance sensitivity and dynamic range. In addition, a slower, low-amplitude circular dither pattern at 1/4 the modulation frequency is superimposed to facilitate optical gain measurements. This process uses synchronous detection to assess the apparent radius of the dither circle from the PWFS Tip/Tilt measurements during observing. The tip and tilt measurements are correlated with sines and cosines at the dither frequency, and then the four correlation signals are time-averaged and added in quadrature to obtain the radius. This radius is compared with the known motion, which is precisely calibrated in the daytime versus a pinhole mask grid. The ratio of the measured and known radius is a scale factor to account for changes in

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optical gain caused by atmospheric turbulence.\textsuperscript{2} The timing of this motion must be synchronized perfectly with exposures of the PWFS detector, and must also be precisely phased with the rest of the AO system (including the LGS WFS, OIWFS and ODGW, depending on the observing mode). These motions and timing features are illustrated in Figure 1. Finally, the FSM must operate both at room temperature and the cold -30 C operating temperature of NFIRAOS,\textsuperscript{3} and provide good endurance (minimum 20 year service lifetime).

Trade studies during the NFIRAOS design phase led to the selection of a monocrystalline piezo actuator system, from Physik Instrument (PI), since more conventional polycrystalline devices would not meet the lifetime, stroke, and frequency requirements noted above. PI also claims excellent stability and hysteresis with similar piezo stages meaning that the FSM can function without sensor feedback.

In this paper we describe a prototype FSM based on the model P-915K925 stage and two-axis E-500/E-501 series piezo controller from PI\textsuperscript{*}, and characterize its performance in a series of experiments during which it is driven with a circular waveform:

- dynamic response, using driving waveforms at a range of frequencies,
- linearity, by varying the radii of the waveform,
- step response and measurements of mechanical delay,
- temperature performance, repeating experiments both at room temperature and at -30 C, and
- absolute time synchronization.

2. EXPERIMENTAL SETUP AND INITIAL CALIBRATION

A laser, simulating the NGS beam, is directed to the FSM assembly which consists both of the FSM itself and a beam splitter, both mounted on a rigid block, so as to produce a second reference beam of light. The waveforms used to drive the FSM were provided by a PI E-518 Digital Interface and Function module, that was packaged by PI in the same chassis with the E-500 amplifier. The beams travel nearly parallel to one another, first to a

\textsuperscript{*}\url{https://www.physikinstrumente.com/en/products/controllers-and-drivers/nanopositioning-piezo-controllers/e-500-e-501-modular-piezo-controller-601100/}
common fold mirror to increase the level arm, and then to a pair of 2-axis high-speed position sensing devices (PSDs), one for each beam. Differential measurements can thus be performed to remove the effects of thermal drifts and vibrations on the table and other optical components. The PSDs produce voltages proportional to the locations of the laser spots in the range ±10 V for each axis. The layout of the optical bench is shown in Figure 2. A Measurement Computing USB-1808X data acquisition unit (DAQ)† was used to digitize these signals at up to 200 kHz for later data analysis. Additional channels in the DAQ were used to concurrently digitize the external clock signal used to establish the absolute timing of the observations, and in a separate test, to sample the output voltages of the PI controller when not connected to the FSM (by means of a voltage divider, since the control voltages reach ±500 V). Both a GUI application and a lower-level software API are provided for interacting with the controller. For the initial calibration described in this section, vendor-supplied Windows GUIs were used to configure and operate both the PI Controller and DAQ.

![Figure 2. Optical bench setup, shown schematically on the left, and with the real devices on the right.](image)

Once the optical components had been mounted and aligned, the first task was to establish the correct waveform for each FSM axis to produce a circular pattern at the location of the PSDs. Due to the 45° incidence angle between the laser and the FSM, an elliptical pattern is thus required. A linear transformation between commanded $T = (x, y)$ coordinates in actuator space, and measured $C = (a, b)$ coordinates on the PSDs, using an Interaction Matrix $\mathbf{J}$ was established empirically:

$$
T_i = \begin{pmatrix} x_i \\ y_i \end{pmatrix}, \quad \mathbf{J} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}, \quad C_i = \begin{pmatrix} a_i \\ b_i \end{pmatrix},
$$

$$
T_i \mathbf{J} = C_i.
$$

The two axes of the stage were independently poked with both positive and negative values, and the resulting positions on the PSDs recorded. This procedure resulted in four sets of $T_i$ inputs and corresponding $C_i$ outputs, from which the coefficients of $\mathbf{J}$ could be uniquely determined.

Multiplying each side of the equation by the inverse of the interaction matrix one can determine the commands, $T_i$, that would produce the desired coordinates on the PSDs, $C_i$,

$$
T_i = C_i \mathbf{J}^{-1}.
$$

With this information in hand, output circular waveforms (sine and cosine waves) were converted into digitized input wavetable commands for each of the axes on the E-518 module. We initially used a free-running mode in

†https://www.mccdaq.com/data-acquisition-and-control/simultaneous-daq/USB-1808-Series.aspx
which, once requested to start via a software command, the E-518 steps through the wavetable at a maximum rate of 25.0 kHz using an internal clock, and repeats continuously until commanded to stop. The sample period is restricted to being an integer multiple of what the manual refers to as its internal “servo period” of 40 μs. In order to simulate a waveform that matches the peak NFIRAOS requirement (800 Hz), we settled on a 125-point wavetable containing four periods of the desired 800 Hz waveform, and command the E-518 to step through it at the maximum 25.0 kHz sample rate.

Once the E-518 was commanded to start, the DAQ would record several seconds of data, but only data taken after one second were used to mitigate the impact of startup transients for the initial analysis.

Noting that the measurements used to derive the Interaction Matrix relied on the step response of the x- and y-stages (they were commanded to a position, and were held there during the PSD observation), it was known in advance that the dynamic response of the system to the fast-sampled waveforms would differ due to, e.g., the inertia of the stage, electronic delays, etc. Therefore, the output amplitudes of the resulting waveforms for each axis, $A_x$ and $A_y$, and their phases, $\phi_x$, both with respect to the input demands, were calculated and applied to obtain the corrected waveforms, $T_c$:

$$T_c(t_i) = \left(\frac{A_x x(t_i - \phi_x)}{A_y y(t_i - \phi_y)}\right)$$

Figure 3. Measured PSD positional data (yellow dots) compared with the target shape (blue dots) following optimization of the phase and amplitude of the wavetables to account for the dynamic response of the system. The two sets of points are nearly indistinguishable due to the accuracy of the control system.

Iterating this procedure a handful of times (i.e., re-running using the corrections from the previous iteration) demonstrated the ability to drive the stage in a highly circular pattern with the desired amplitude, as shown in Figure 3.

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This works out to $(1/800 \text{ Hz})/(1/25000 \text{ Hz}) = 31.25$ samples per period. The four periods were selected so that the waveform would fit into an integer number of samples, $N = 125$. We also require four periods to include the dither signal.
3. STAGE CHARACTERIZATION

Having established a procedure for tuning the control waveform to achieve a particular output, we sought to answer several questions: (i) how does the dynamic response depend on the frequency of the driving waveform; (ii) how repeatably does the system behave; (iii) does the stage perform adequately at the -30°C temperature of NFIRAOS; (iv) how linear is the stage response; and (v) what is the startup (step) response. The tests described in the next subsections address these questions. Much of the data acquisition for these tests was orchestrated using Python scripts that communicate both with the DAQ and PI controller, using vendor-supplied APIs.

3.1 Dynamic response

Figure 4. Bode diagram for the FSM test system, measured at ambient temperature, at waveform frequencies ranging from 1 Hz to 2.8 kHz. The amplitude scale factors, $A$, and phase corrections, $\phi$, are determined iteratively.

To test the dynamic performance of the stage, we ran the stage with waveform frequencies ranging from 1 Hz to 2.8 kHz. In each case several seconds of data were acquired to ensure that the system had stabilized. The iterative procedure described previously was then used to determine the amplitude and phase shift fitting to several waveform periods of clean data.

Figure 4 plots the corrections as a Bode diagram (nothing that “amplitude” in this plot is the reciprocal of the amplitude correction factor). At the low-frequency end the results match the steady-state response originally
used to establish the interaction matrix; \( A = 1 \), and \( \phi = 90 \text{deg} \) (noting that 90 deg was the arbitrarily chosen zero-point for the phase in this plot).

The amplitude then grows steadily toward a clear resonant peak near 2.4 kHz. This result is consistent with PI’s assertion that there are “no resonant frequencies below 2.3 kHz”, and is acceptable for the FSM requirement to run at 800 Hz.

### 3.2 Repeatability

![Figure 5. Repeatability shown as time-series errors for the radial and azimuthal coordinates over five periods at a driving frequency of 800 Hz.](image)

Repeatability of the stage performance was established by running the experiment over long periods (hours), acquiring data for periods of several seconds (since the DAQ is incapable of buffering data for more than 10 s at the highest acquisition sample rate), and observing the error between the requested and measured waveforms. This experiment was repeated at a range of driving frequencies.

Figure 5 shows a representative example of the error signal in polar coordinates over five periods when driving the stage at 800 Hz. The radial error (amplitude) scaled into units of \( \lambda/D \) has an RMS of 0.01, and the angular error (phase) has an RMS of 0.08 deg. Both of these errors are within the requirements for the FSM.

### 3.3 Linearity

Another area of interest is the linearity of the stage, i.e., does the amplitude correction factor vary as the target waveform amplitude is changed? To this end, data were collected for target amplitudes ranging from 1 to 14 in units of \( \lambda/D \), and again iteratively obtain the correction factors for each run.

Figure 6 shows the full set of optimized amplitudes, for each axis. Note that the scale factor in X is approximately constant, though there is a clear variation in the correction factor in the Y-direction as the amplitude increases.

This observed asymmetric non-linearity could be due to the PSD, the drive electronics, or the actuator itself. Regardless of the cause, we have concluded that it will be possible to calibrate the system with a two-dimensional lookup table as a function of waveform radius and driving frequency.

### 3.4 Startup response

Next we characterize the startup response of the system. This is accomplished by measuring the absolute electromechanical lag of the stage following the initial command to start motion.

In order to provide an absolute time reference, both the DAQ and PI Controller were placed into externally-triggered start modes. Once primed, both units awaited a shared trigger (via a tee) provided by a separate
3.5 Cold tests

In addition to the warm testing mentioned above, the FSM was further operated in a cold room at -30°C to mimic the NFIRAOS environment. Repeating most of the previous tests, the stage was found to respond comparably in the cold. The main difference noted was that the amplitude scale factors increased slightly (for both axes), as did the frequency of the resonant peak. This behaviour is consistent with the idea that the piezo stage became stiffer
4. ABSOLUTE SYNCHRONIZATION

The previous tests that the PI stage itself performs adequately for the purposes of NFIRAOS (the response can be characterized, and it appears to be stable over time). A final consideration that we wished to address was whether the waveforms output but the E-518 could be synchronized with an external trigger. The unit offers two basic modes for making using of an external trigger that might support this operation: (i) as a start trigger (i.e., the unit free-runs once started) as used in Section 3.4; and (ii) as a clock signal. Option (i) was immediately ruled-out as the internal clock of the unit (used to step through the wavetable) cannot be tied to an external reference (such as the Precision Time Protocol for computers on a network), meaning that while one could start it at the correct absolute time, it would slowly drift with respect to the rest of the AO system. Option (ii) looked promising since each clock “tick” is used to step to the next sample in the wavetable. As long as the waveform playback is started at the correct time, and the clock signal detection is reliable (i.e., no ticks are dropped), the unit could be expected to operate in phase with the rest of the AO system.

![Glitch period 2.620 s width 0.018 s](image)

Figure 8. Output voltage for one of the controller axes over time, exhibiting a timing “glitch” while using an external 12.5 kHz lock signal to step through the wavetable (producing an 800 Hz waveform). The output is highly distorted in a burst lasting approximately 0.018 s after it settles to a random phase. These bursts were observed to occur periodically (once every \(\sim2.62\) s).

Unfortunately, testing with the 800 Hz waveform immediately revealed a strange behaviour: after initially running as expected for several seconds, there would be brief periods during which the unit would appear to miss several clock ticks. Shortly thereafter it would resume functioning normally, but now with a different (and random) phase. We experimented a great deal with the signal generator used to produce the clock signal, including different clock waveforms (i.e., ramps with various rise and fall times, and different amplitudes), and running the unit at a range of frequencies. Unfortunately we were never able to resolve the issue, though our working theory is that for small fraction of the internal 40 \(\mu\)s servo period the E-518 suffers a “dead window” during which it is incapable of sensing the clock signal. Since the internal clock of the E-518 and the external
trigger generator will slowly drift with respect to one another, one might expect a burst of clock signals to land repeatedly within this dead period if they occur with a frequency that is an integer multiple of the 40 \( \mu \)s servo period (i.e., until the clock drifts sufficiently for them to again land outside of the dead window). Furthermore, if the external clock runs at a **non-integer multiple** of the servo period, the times at which clock ticks are missed would tend to be more haphazard (i.e., one tick might land in the dead window, with subsequent ticks landing far outside of it).

Figure 8 shows the output voltage from the controller for one of the axes (passed through a voltage divider to enable digitization with the DAQ). For this test we again use a 125-sample wavetable, but this time with 8 periods of our desired 800 Hz waveform, with the clock running at 12.5 kHz (15,625 samples per period). Running with the slower clock enables us to see the shape of the digitized clock signal more clearly with the DAQ, but the results are qualitatively similar to those obtained with the higher-clock rate waveform described earlier. A Python script was written to step through the captured time series and identify the boundaries of each period from the zero-crossings. It was then possibly to identify outlier periods with respect to the median, which are shown with the red stars in the figure. Clearly the anomalous periods occur in a localized burst over an interval of roughly 0.018 s. Examining the same data on longer time-scales it was found that these bursts occur regularly, with a period of about 2.620 s. If we assume that this period corresponds to the controller clock drifting with respect to the external function generator by a 40 \( \mu \)s servo period, that works out to a drift rate of 40 \( \mu \)s/2.620 s = 15.3 \( \mu \)s/s, which is plausible. Multiplying the observed burst interval by this drift rate gives us an estimate of the width of this hypothesized dead window, 0.018 s \times 15.3 \( \mu \)s/s = 0.275 \( \mu \)s. Re-running this test on different days showed qualitatively similar behaviour, though the period of the bursts varied slightly (e.g., sometimes slightly above 3 s, sometimes below). Again, this is consistent with the hypothesis that the problem is correlated with clock drift (with a rate that, itself, can also drift).

Finally, we repeated this test using a number of other external clock rates that do not correspond to integer multiples of the servo period. Though not shown here, we found that the anomalous periods would typically not occur in bursts as described above, lending further support to our theory.

Unfortunately we were not able to remedy this issue with the manufacturer, and will have to consider other methods for establishing absolute time synchronization.

### 5. SUMMARY AND FUTURE WORK

The NFIRAOS team is satisfied that the selected monocrystalline piezo stage and E-500 controller from PI meet the basic requirements of the FSM. The mirror was shown to accurately reproduce the desired circular waveform at up to 800 Hz, both at ambient temperature and at the -30°C temperature of NFIRAOS. A procedure was established for calibrating the stage (coordinate transformations, amplitude and phase corrections), and the prototype exhibited good long-term stability. The only outstanding issue is synchronizing its motion with an external trigger; unfortunately we were unable to use the integrated PI E-518 module in external clocking mode due to it periodically failing to detect some clock ticks. Both our team and our contacts at PI agree that we will have to bypass the integrated E-518 digital waveform module and directly feed the E-500 amplifiers with analog signals from a custom function generator.

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REFERENCES

[1] Crane, J., Herriot, G., Andersen, D., Atwood, J., Byrnes, P., Densmore, A., Dunn, J., Fitzsimmons, J., Hardy, T., Hoff, B., Jackson, K., Kerley, D., Lardièvre, O., Smith, M., Stocks, J., Véran, J.-P., Boyer, C., Wang, L., Trancho, G., and Trubey, M., “NFIRAOS adaptive optics for the Thirty Meter Telescope,” in [Adaptive Optics Systems VI], Close, L. M., Schreiber, L., and Schmidt, D., eds., Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 10703, 107033V (July 2018).

[2] Esposito, S., Puglisi, A., Pinna, E., Agapito, G., Quirós-Pacheco, F., Véran, J. P., and Herriot, G., “On-sky correction of non-common path aberration with the pyramid wavefront sensor,” A&A 636, A88 (Apr. 2020).

[3] Densmore, A., Herriot, G., Fitzsimmons, J., Byrnes, P. W. G., Welle, I., Holma, J., Tiedje, M., Burbee, J., and Winter, C., “CO2-based refrigeration system for the NFIRAOS optics enclosure,” in [Ground-based and Airborne Instrumentation for Astronomy VIII], Proc. SPIE 11447-339 (Dec. 2020).