OSA Training

Second Day
• Quick review of yesterday ...
• The blurring effects of the atmosphere limit resolution on an 8-meter to what can be achieved on a 0.4 meter:
• The wave front generated by the star light coming into the atmosphere is flat:

![Diagram of wave front and atmospheric effects](image)

• But the blurring effects of the atmosphere turn it into a crumpled bed sheet:

• How big are the flat spots on in the bed sheet?
• About 20 cm, or on a great site on a great night, about 40 cm.
• In broad terms, achieved resolution (e.g., FWHM) is determined by this ratio:

\[ d_{\text{lim}} \approx \frac{\lambda}{D} \]

The left hand side is an angular measurement that quantifies “see more clearly” or “observe at higher resolution”

The top is the wavelength (e.g. K-band)

The bottom is the size of the aperture (the diameter of the primary mirror; 8 meters for example)
\( D \) is the effective aperture ...

Without AO \( D = r_0 < 0.4 \) meters

\[
d_{\text{lim}} \approx \frac{\lambda}{D}
\]

With AO \( D = 8 \) meters

\[
d_{\text{lim}} \approx \frac{\lambda}{D}
\]
• Before diving into how AO systems work, let’s watch the potato chip movie again ...
Let’s switch from the potato chip analogy back to the bed sheet.
We saw in the movie that the shape of the potato chip (bed sheet) is measured rapidly (500 Hz more or less).
How?

The incoming “bed-sheet” is “digitized” by measuring ‘slopes’ at some spatial frequency laid out across a regular grid.
OK, how can you measure slopes in the atmosphere???
• Slopes are measured by one of two possible optical methods:

- Shack Hartman
- Pyramid

• To the software, it does not really matter
• Either way, you receive a grid of quad-cell measurements:

\[
\begin{align*}
\Delta x &= \frac{(I_{11} + I_{21}) - (I_{12} + I_{22})}{I_{11} + I_{12} + I_{21} + I_{22}} \\
\Delta y &= \frac{(I_{11} + I_{12}) - (I_{21} + I_{22})}{I_{11} + I_{12} + I_{21} + I_{22}}
\end{align*}
\]
Once the slopes have been measured, commands are sent to the deformable mirror (DM) to “re-flatten the bed sheet”

How do we go from slopes to DM actuator commands?
Here is the schematic for a simple wave front controller (WFC):

Inside the WFC, data flows through these 6 basic transforms between the measurement and control.

- Wavefront Sensor (pyramid or ShackHartman)
- Detector (CCD or infrared)
- Clean the Data (chap. 4, fig. 1)
- Compute Slopes (see table 3)
- Matrix Vector Multiply (see figure 10)
- Control Law Servo (e.g., apply gain)
- DM HW interface (e.g., reflective memory)
- Deformable Mirror (local or M2)

This is the heart of the system.
• How does the WFC go from slopes to DM voltages?

The heart of the system is the reconstructor

\[
\begin{array}{c}
\text{WFS with 700 "subapertures"} \\
700 \times 1400 \text{ reconstructor} \\
\text{700 actr vals} \\
\text{DM with 700 "actuators"}
\end{array}
\]

The size of the reconstructor is:

\(<\# \text{ of slopes} > \times <\# \text{ of actuators}>\)

• The WFC must perform this Matrix vector multiply (MVM) at rates up to 1 or 2 Khz
• The WFC is a synchronous real time system
• The reconstructor maps slopes to voltages …

To take us from seeing limited images to AO images:

• How do we generate the reconstructor? Where does it come from?
Here’s the trick:
- If you want a matrix to convert slopes to DM shape …
- First determine the matrix that does the opposite
  (i.e., the matrix that converts DM shape to slopes)
- Then invert it.

\[ R = B^{-1} \]

- How do you “determine the matrix does the opposite”?
- There are two approaches:
  - zonal
  - modal
• To calibrate the **interaction matrix** using the **zonal method**, we first “poke” one actuator so that it protrudes noticeably above the otherwise flat surface of the DM.

• Then measure the slopes with the mirror illuminated in this configuration.
  • This forms the first column of your interaction matrix.

• The resulting matrix would then convert DM shape to slopes. To get the reconstructor, just invert it (!).

\[
R = B^{-1}
\]
• For a *modal* system (like ours), instead of poking single actuators to measure the interaction matrix, the entire DM is commanded to take on the shape of *mode* in a modal basis set.
• OK, what’s a *mode* and what’s a *modal basis set*?
• Broadly, any possible surface shape can be produced by adding together elements (modes) of a modal basis set.
• The most common basis set used in optics is the Zernike basis set …
Terminology is familiar from trips to the optometrist
In a **zonal** system, actuator commands come directly from the single MVM …

\[
\begin{bmatrix}
R \\
\text{1400 MIPs}
\end{bmatrix}
= 700 \text{ act'r vals}
\]

In a **modal** system, a second “mode to command” matrix is needed to complete the MVM …

\[
\begin{bmatrix}
m2c \\
\text{400 MIPs}
\end{bmatrix}
\begin{bmatrix}
R \\
\text{1400 MIPs}
\end{bmatrix}
= 700 \text{ act'r vals}
\]
• Why use *modal*?
• You can see what the system is doing in understandable units.
• For example, you can ask how much correction is being applied just to compensate for astigmatism?
THE END

QUESTIONS?
Hidden Slides Follow
IT'S NEVER DONE THAT BEFORE
Zernike Polynomials (cont.)

A few terms are graphed to visualize their relationship to **third-order optical aberrations**.

Reflecting telescopes of the Cassegrain design have a central obscuration, which requires an extremely large number of Zernike coefficients—more than can be adequately described. A set of annular Zernike polynomials can be obtained from **Gram-Schmidt orthogonalization**; this series is generally used for optical systems with central obscurations.
Modal and Zonal Fitting Error

When a typical deformable mirror cannot exactly fit the spatial structure of stochastic atmospheric turbulence, modes are used and applied to the deformable mirror, causing the residual wavefront error to be reduced. Where \( N_{\text{Zern}} \) is the number of completely corrected Zernike modes, and \( D \) is the aperture diameter, the RMS modal wavefront error is found from

\[
\sigma_{\text{fitting(waves)}} = \sqrt{\frac{0.2944 N_{\text{Zern}}^{3/2} (D/r_0)^{5/3}}{2\pi}}
\]

If many actuators across a continuous faceplate are used, the residual wavefront error can be reduced. The distance between actuators, in the same space as the measurement of \( r_0 \), is \( s_{\text{Act}} \). Fitting constant \( \kappa \) is related to the stiffness of the deformable mirror faceplate as follows:

\[
\sigma_{\text{fitting(waves)}} = \frac{1}{2\pi} \left[ \kappa \left( \frac{s_{\text{Act}}}{r_0} \right)^{5/3} \right]^{1/2}
\]

To evaluate fitting error, determine the residual wavefront variance after the adaptive optics system removes Zernike modes from the disturbed wavefront. When Kolmogorov turbulence is a wavefront variance as a function of removed and the \( D/r_0 \) ratio. A few terms:

\[
\begin{align*}
\sigma_{1 \text{ mode (1-axis tilt)}}^2 & = 1.029 \\
\sigma_{2 \text{ modes (2-axis tilt)}}^2 & = \\
\sigma_{3 \text{ modes (defocus and tilt)}}^2 & = 0.2944
\end{align*}
\]

For a larger number of modes, we expect Zernike modes completely.

Great improvements are seen by correction of only a few Zernike modes, 95% of the energy of the aberrations in a Kolmogorov wavefront is contained within the first 13 modes.
The on-axis intensity $I_0$ of a uniform circular beam after it propagates a distance $L$ is

$$I_0 = \frac{\pi^2(D/2)^4}{\lambda^2L^2} - I_{\text{Aper}}$$

where $L \gg D$, the diameter of the aperture, and $I_{\text{Aper}}$ is the intensity at the circular aperture (W/m²). With aberrations represented by a wavefront error variance $(\Delta \phi)^2$ (units of optical path distance), the reduction of on-axis intensity, the Strehl ratio, is approximately

$$S = \exp \left[ -\left( \frac{2\pi}{\lambda} \right)^2 (\Delta \phi)^2 \right]$$

To use this approximation, the wavefront error variance should be less than a quarter-wave.

The on-axis intensity with aberrations is then

$$I_0 = S \frac{\pi^2(D/2)^4}{\lambda^2L^2} - I_{\text{Aper}}$$

Astronomical Strehl ratios without adaptive optics are typically very small. With adaptive optics, the Strehl ratio can be improved by orders of magnitude. For a well-conditioned beam in weak turbulence, the Strehl ratio without adaptive optics can be 20%, but is improvable to 90% or better with adaptive optics.

The definition of Strehl ratio in the classic text *Principles of Optics* (Born and Wolf, 1975) does not include defocus or tilt (jitter) terms in the definition. However, for adaptive optics system calculations, the absorption of these effects into the overall Strehl ratio is convenient.
Strehl Ratio

When beam jitter is present, the optic axis is swept over a small cone, and the average intensity in the center of the beam is reduced. When the jitter is assumed to be Gaussian, where \( \alpha_{\text{jitter}} \) is the RMS single-axis beam jitter (in radians), the intensity is multiplied by the factor

\[
\frac{1}{1 + \left( \frac{2.22 \alpha_{\text{jitter}} D}{\lambda} \right)^2}
\]

to find the further reduction in on-axis intensity. Sometimes the combined effects of wavefront error and beam or image jitter are combined into the Strehl ratio. Rewriting the wavefront error variance in radians squared gives

\[
\sigma^2 = \left( \frac{2\pi}{\lambda} \right)^2 (\Delta \phi)^2
\]

\[
S_{\text{jitter}} = \frac{e^{\sigma^2}}{1 + \left( \frac{2.22 \alpha_{\text{jitter}} D}{\lambda} \right)^2}
\]

Because the wavefront variance can be considered a Gaussian variable uncorrelated between various sources, spatial and temporal effects can be efficiently combined using this general definition of Strehl ratio.

In 1902, K. Strehl coined the term Definitionshelligkeit, which means definition of brightness in German and is now known as the Strehl ratio.
To avoid the errors associated with focal anisoplanatism, a laser guide star is placed at a higher altitude. At an altitude of around 90 km, a layer of atomic sodium can produce backscatter at its resonant wavelength of 589.1583 nm.

**Detected sodium-line photon flux:**

\[ F_{\text{Sodium}} = \eta T^2 \frac{\sigma_{\text{Na}} \rho_{\text{Col}} \lambda_{\text{LGS}} E}{4\pi^2 L_{\text{GS}}^2} \]

where \( \sigma_{\text{Na}} \) is the resonant backscatter cross section and \( \rho_{\text{Col}} \) is the column abundance. The product of the cross section and the abundance is about 0.02.

Dr. William Happer was the first to suggest using resonant backscatter sodium laser guide stars when he served on JASON, a group of scientists and engineers who advise agencies of the U.S. Government on matters of defense, intelligence, energy policy, and other technical issues.
Angular Isoplanatic Error

The amount of wavefront error is dependent on the difference between the direction of the wavefront beacon and the science object. The variance of the wavefront (in radians squared) is

\[
\sigma_{\text{iso}}^2 = \left( \frac{\theta}{\theta_0} \right)^{5/3}
\]

where \( \theta \) is the angle between the beacon and the science object and \( \theta_0 \) is the isoplanatic angle. The isoplanatic angle is the angle where the wavefront error between the beacon path and the science path differs by 1 radian, or about 1/6 of a wave. The edge of the isoplanatic “patch” does not have a sharp cutoff but rolls off gradually.
Deformable Mirror Influence Function Models

Two expressions are widely used to describe the influence function of a continuous-faceplate deformable mirror. The deflection normal to the mirror surface can have a cubic relationship:

$$\phi_{\text{Cubic}}(x,y) = A_{\text{Infl}} \left[ \left(1 - 3x^2 + 2x^3\right) \left(1 - 3y^2 + 2y^3\right) \right]$$

where \((x,y)\) are Cartesian coordinates, and \(A_{\text{Infl}}\) is the amplitude of the influence function. The origin is at the actuator location.

The other expression has a Gaussian form:

$$\phi_{\text{Gaus}}(x,y) = A_{\text{Infl}} \exp \left[ \frac{\ln c_a}{r_c^2} r^2 \right]$$

where \(r\) is the polar radial coordinate in the mirror plane, \(r_c\) is the interactuator spacing, and \(c_a\) is the coupling between actuators expressed as a number between 0 and 1. The coupling is the movement of the surface at an unpowered actuator expressed as a fraction of the motion of its nearest-neighbor actuator.

![Mirror surface displacement graph](image)

**Mirror surface displacement (Units normalized)**

- Cubic
- Gaussian

Distance from actuator center

\(x\) or \(r\) (Units normalized)
Adaptive Optics System Feedback Configuration

A standard configuration for feedback control of an adaptive optics system is shown in the figure using discrete-time subsystems.

In this block diagram, \( z \) is the Z-transform variable, \( K \) is the digital controller, \( G \) is the deformable mirror transfer function, \( r \) is the reference input (which is nominally 0), \( u \) is the control signal, \( y \) is the corrected output beam, \( d \) is the input aberrated beam, \( n \) is the wavefront sensor noise input, \( e \) is the error signal, and \( D \) contains all of the system latencies.

This diagram uses a positive-feedback loop because the reconstructor is typically designed to enforce negative feedback.

Because adaptive optics systems are concerned with correcting the input aberrated beam, of primary interest is the sensitivity function \( S \), which is the disturbance rejection function and defines the transfer function from \( d \) to \( y \):

\[
S = [I + GK]^{-1}
\]

The complementary sensitivity or closed-loop transfer function \( T \) from \( r \) to \( y \) is also important:

\[
T = [I + GK]^{-1} GK
\]
Estimation from Controller Gains

To generate a first-order estimate of the system frequency solely from the loop and leak coupling the plant dynamics. If the plant dynamics are significant at low frequencies relative to the loop gain, this estimate is accurate.

For a single-channel controller model, substituting solving for \( \omega_c \) in Hz yields

\[
\omega_c = \cos^{-1} \left( \frac{g_{s}^2 + 1 - g_{l}^2}{2g_2} \right) \frac{f_s}{2\pi}
\]

The forward loop gain, \( g_2 \) is the leak gain, and \( \omega_c \) is the sampling frequency.

Calculate the system gain or compensation at state) by simply setting \( z = 1 \) in the controller

\[
g_{DC} = \frac{g_1}{1 - g_2}
\]

This is infinite with no leak, and finite with a leak which means that the leak term rolls off the steady state correction. This is consistent with finding that a pure integrator (leak gain = 1) provides more or discrete time is used for forcing the error to zero.

In practice, \( \omega_c \approx 240 \text{ Hz and } g_{DC} \approx 40 \text{ dB} \) for the cases previously and are close to the simulated values.

When generating influence functions, the measurements should be delayed until the actuator has reached its final position. At that time, multiple measurements should be taken to average for noise reduction.

The influence function for the \( i \)th actuator is the \( i \)th column in the poke matrix, normalized by the actuator command used as a poke \( \alpha \) to maintain the correct scaling.

\[
B = \begin{bmatrix} b_1 & b_2 & \ldots & b_n \\ \alpha & \alpha & \ldots & \alpha \end{bmatrix}
\]

The poke command \( \alpha \) should be large enough to provide good SNR without saturating the commands or measurements.

The poke matrix defines the system geometry and includes the effects of static coupling between the actuators. This is a static-system representation as there is no dynamic coupling between neighboring actuators.

Field Guide to Adaptive Optics, 2nd Ed.
Tilt Removal

Piston and Waffle Removal

Piston is an unobservable mode defined as a global average height; for any surface shape we can have an infinite number of piston values. Piston should always be removed, as it quickly reduces available dynamic range. The piston basis vector $b_p$ is generated by creating a vector of 1s and dividing by the square root of the number of actuators to normalize it.

The projection matrix $P_p$, which projects the actuator commands onto the basis vector $b_p$, is found by multiplying the basis vector by its transpose:

$$P_p = b_p b_p^T$$

Waffle is an unobservable mode in standard configurations that results in commands at the Nyquist spatial frequency. The waffle basis vector $b_w$ is defined by alternating positive and negative 1s on neighboring actuators and can be normalized by dividing by the square root of the number of actuators. As with the piston case, the waffle projection matrix $P_w$ is $b_w$ multiplied by its transpose:

$$P_w = b_w b_w^T$$

The waffle and piston bases are not necessarily orthogonal, so we use the Gram–Schmidt orthogonalization process, which simply subtracts the piston component (average value) from the waffle basis:

$$P_{wp} = P_w - \frac{1}{N} \sum_{i=1}^{N} P_w(i)$$

We can remove piston, waffle, tip, and tilt in a single step to form a calibrated poke matrix $B_c$:

$$B_c = (I - P_t) B_t (I - P_p) (I - P_{wp})$$

Tilt is a sensor mode, so it is removed on the output (left-hand) side of the matrix; piston and waffle are actuator modes and are removed on the input (right-hand) side of the matrix.
Reconstructor Generation: Least Squares

The reconstructor is essentially an inverse of the poke matrix, and generating the reconstructor is therefore an inverse problem. Approaches to generating reconstructors for adaptive optics systems typically follow least-squares techniques, which minimize the sum of the squares of the errors in the inversion. For a traditional least-squares approach, the cost function $J$ to be minimized is given by

$$J = \| B_c a - e \|_2^2$$

where $a$ is the vector of active actuator commands and $e$ is the associated vector of measured wavefront errors. The solution to this problem is the Moore–Penrose pseudo-inverse, which is given by

$$R_r = \left( B_c^T B_c \right)^{-1} B_c^T$$

The negative sign enforces negative feedback and is included in all of the reconstructors described. This pseudo-inverse can also be formulated using SVD:

$$B_c = U \Sigma V^T$$
$$R_r = -V \Sigma^{-1} U^T$$

The standard least-squares approaches outlined here are sensitive to numerical issues caused by poor conditioning and only penalize the fitting error. Regularization can improve the numerical stability of the inversion process and provides a method to penalize particular actuator modes.

Least-squares techniques were originally developed by Carl Friedrich Gauss at the end of the 18th century and are still widely used in science and engineering.

Reconstructor Generation: Regularization

Using a singular system representation, the reconstructor is given as

$$a = R_e e = V \Sigma^{-1} U^T e = \sum_i \frac{(U^T e)_i}{s_i} v_i$$

From this equation, we see that small singular values result in large amplification of the corresponding singular vector. In other words, small singular values induce large commands for poorly observable controllable modes that can degrade performance and cause loop instability.

To avoid issues due to small singular values, a regularizing filter $w(s^2)$ is used to remove the small values while retaining the large ones.

The singular system representation with an applied regularizing filter is given as

$$a = \sum_i w(s_i^2) \frac{(U^T e)_i}{s_i} v_i$$

Two commonly used filters are the truncated Tikhonov filter. The truncated SVD applies a threshold to the singular values:

$$w(s^2) = \begin{cases} 1 & \text{if } s^2 > \alpha \\ 0 & \text{if } s^2 \leq \alpha \end{cases}$$

A regularized pseudo-inverse using the truncated SVD method is given as

$$R_r = -V \Sigma_i^{-1} U^T$$

where $\Sigma_i^{-1}$ contains the inverses of the filter values along its diagonal.

The MATLAB® command `pinv(A, alpha)` is used for this method with `alpha` used as the threshold.

The Tikhonov filter is given as

$$w(s^2) = \frac{s^2}{s^2 + \alpha^2}$$

This filter provides a damped least-squares form where we include a penalty on the solution.
Loop Wavefront Estimation

Wavefront measurements are not perfect, an open-loop minimal minimator follows the regularized least-squares previously outlined and is given as

$$
\hat{f} = (\Gamma^T \Gamma + \sigma_d^2 Q_d^{-1})^{-1} \Gamma^T
$$

The covariance matrix of the atmospheric wavefront is a geometry matrix defining the measurements and subapertures, and a measurement noise is assumed to be Gaussian with variance $\sigma_e^2$. By using the inverse of this matrix in this equation we are increasing the estimator to expected turbulence.

The geometry matrix is the poke matrix, the reconstructor. If the covariance matrix is defined in reduced actuator space so that we include the estimator in the reduced

$$
(B_c^T B_c + W + \sigma_d^2 Q_d^{-1})^{-1} B_c^T
$$

An optimal constrained estimator for an open-loop estimator, if it does not include knowledge of the state or command inputs and is used in closed-loop conditions. When the plant and processing delay are large enough, the open-loop estimator performance is order.

Kalman Filtering

A Kalman filter is the minimum variance estimator for general linear systems. Consider the system with states given as the true values of the wavefront sensor measurements

$$
x_{k+1} = Ax_k + Bu_k + d_k
$$

$$
y_k = Cx_k + n_k
$$

The disturbance and measurement noise covariances are

$$
Q_d = \langle d_k d_k^T \rangle \quad Q_n = \langle n_k n_k^T \rangle
$$

We can define the steady state Kalman filter by first solving the discrete-time algebraic Riccati equation for the propagation error covariance matrix $P$

$$
P = APA^T + Q_d - APC^T Q_n^{-1} CPA^T
$$

The Kalman gain $K$ is given by

$$
K = APC^T \left[ CPC^T + Q_n \right]^{-1}
$$

The estimator is implemented by

$$
\hat{x}_{k+1} = A\hat{x}_k + Bu_k + K[y_k - C\hat{x}_k]
$$

The control signal $u_k$ is calculated using the state estimate

$$
u_k = g_1 R\hat{x}_k + g_2 u_{k-1} - g_1 M u_{k-1}
$$

Since the optimization is done in the least-squares sense, the separation principle allows us to design the estimator and control matrices ($K$, $R$, and $M$) independently and still provide the minimum least-squares error.

The theory behind the Kalman filter was introduced in 1960 in a paper by Rudolf E. Kalman. Subsequent developments by Richard S. Bucy have resulted in this filter being commonly referred to as the Kalman–Bucy filter. The extended Kalman filter was developed to apply the theory to nonlinear systems and is the state estimator most commonly used today for GPS and navigation systems.
**Disturbance Injection**

**Disturbance injection (DI)** allows us to determine the system response for specified inputs by injecting an artificial, controlled disturbance to the system through software. The DI inputs can be in either sensor space \( \mathbf{d}_{i1} \) or actuator space \( \mathbf{d}_{i2} \), as shown in the figure.

For closed-loop performance assessment, the DI inputs should be injected in sensor space \( \mathbf{d}_{i1} \), as this directly measures the sensitivity function or disturbance rejection properties. For open-loop performance assessment (actuator step responses), the DI inputs should be injected in actuator space \( \mathbf{d}_{i2} \). Injecting inputs in actuator space during closed-loop operation does not accurately capture a performance metric and can be additionally complicated by saturation and by limiting in the controller.

Given the multivariable nature of adaptive optics systems, the DI inputs are vectors rather than single values. A general method for testing temporal response is therefore to input a particular mode and then vary the amplitude of that mode in frequency. This allows determination of the system response to specific modes.

DI as described here works to determine local loop performance. For formal testing and performance verification, an optical disturbance should be injected, and an external unbiased truth sensor used to assess performance.

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**Wavefront Sensor Calibration**

**Wavefront sensor calibration** is an important step to relate the local loop performance to the plane where the performance is characterized. A key issue is the presence of common-path (NCP) errors, which are errors in one path but not in another.

In some cases, NCP errors can be measured directly through the use of a test beam. In other cases, they can be estimated from analysis of system performance data.

A calibration file for a wavefront sensor consists of measurements offsets to remove the phase difference between the wavefront sensor and the reference plane. Shack–Hartmann-style sensors, this can be implemented by spot center shifts in each subaperture.

If a wavefront sensor is not properly calibrated to the reference plane, the local loop may be performing well while the observed performance at the reference plane is poor. This is part of the reason that performance characterization should be measured by an unbiased truth sensor that is separate from the system.

The figure provides an example system that shows how the output beam differs from the measured/corrected beam by the addition of the NCP errors. If the wavefront sensor is calibrated to offset the NCP errors, the compensated beam will be the desired clean beam.
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The figure provides an example system that shows that the output beam differs from the measured/compensated beam by the addition of the NCP errors. If the wavefront sensor is calibrated to offset the NCP errors, the output beam will be the desired clean beam.