Experimental validation of Fourier-transform wave-front reconstruction at the Palomar Observatory

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Wave-front reconstruction with use of the Fourier transform has been validated through theory and simulation. This method provides a dramatic reduction in computational costs for large adaptive (AO) systems. Because such a reconstructor can be expressed as a matrix, it can be used as an alternative in a matrix-based AO control system. This was done with the Palomar Observatory AO system on the 200-in. Hale telescope. Results of these tests indicate that Fourier-transform wave-front reconstruction works in a real system. For both bright and dim stars, a Hudgin-geometry Fourier-transform method produced performance comparable to that of the Palomar Adaptive Optics least squares. The Fried-geometry method had a noticeable Strehl ratio performance degradation of 0.043 in the K band (165-nm rms wave-front error added in quadrature) on a dim star.

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Research into new and significantly faster methods of wave-front reconstruction for large adaptive optics (AO) systems has proceeded briskly in the past few years. Theoretical approaches such sparse matrix methods,[1] conjugate-gradient approaches,[2] and Fourier-transform filtering[3,4] have been analyzed. Of these, the sparse matrix approach is the only one to have been experimentally validated on an astronomical AO system.[1] Fourier-transform reconstruction (FTR) has been shown, through theory and simulation, to have sufficient accuracy and speed and reasonable noise propagation to enable a large (~3000-actuator) system to be built with current computer technology. However, FTR had not been experimentally validated until now. Such experimental validation is a key step in justifying the design of any large AO system that utilizes this new wave-front reconstruction algorithm.

Because all the steps of FTR are linear operations, the entire process can be expressed equivalently in matrix form.[3] This matrix formulation will of course not take advantage of the speed-up of the algorithm, but it does allow us to test the reconstructor's performance on current AO systems, which are configured to use reconstruction matrices. The AO system used for this test is the Palomar Adaptive Optics (PALAO) system on the Hale 200-in. telescope at Palomar Mountain, California. The PALAO system[5] has 241 active actuators, with a subaperture size of $d = 31.75$ cm. The control system records detailed telemetry, including wave-front sensor centroids, flux, and mirror residuals. The system normally runs with a least-squares reconstruction matrix (LS).

Matrices that express FTR methods were generated for use in the PALAO system, with a few specific modifications. Tip and tilt were completely removed from the deformable mirror command vector and tip–tilt control was done with the standard PALAO method. The biggest hurdle to overcome in adapting the algorithms was dealing with the central obscuration. There are 21 actuators in the central obscuration that do not border on an active subaperture. Instead of being fixed or slaved, these actuators are set by the matrix based on centroid data in the aperture. For the Fourier-transform methods our approach was to set this region to be as flat as possible. In the end, simply leaving all the slopes from the unilluminated subapertures at zero (and not fixing any loop continuity) produced the most stable behavior.

Several varieties of FTR methods, namely, Hudgin and Fried geometries with various filtering options, were produced.[4] From the set of possible reconstructors, the two best FTR methods were selected for rigorous on-sky testing, based on initial tests with calibration sources and a few stars. Many methods worked well with bright stars, but only a few remained stable and had good correction for dim sources. The two methods selected were a Hudgin-geometry method with shift filtering and a Fried-geometry method with local waffle removed by filtering; these methods are named FT-Hud-fil and FT-Fri-lw, respectively. Based on previous theoretical analysis, these two methods were predicted to have the best performance among the filtering options.[4]

For the actual test, the three matrices (LS and the two FTR matrices mentioned above) were used in an interleaved fashion on stars with a range of brightnesses. The test setup was kept as nearly constant as possible, with the same tip–tilt control, a fixed wave-front sensor gain, control loop parameters, and a control rate of 500 Hz. In the early morning of

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September 24, 2002 (UT 07:45-10:15), four stars near zenith were observed: SAO 53755 ($K5, m_v = 6.6$), SAO 73989 ($K0$, $m_v = 9.3$), BD + 25 51 ($K2$, $m_v = 10.5$), and SAO 73763 ($K0$, $m_v = 8.5$). Multiple Palomar High Resolution Observer (PHARO) observations in the K band with a Bracket γ filter (2.166 μm) were taken for all reconstructor trials. Exposure lengths varied from the 10 to 30 s, depending on the star's brightness. This procedure was used to produce a data set of sufficient size for each star that variable effects such as seeing would not dominate the results.

The goals of this experiment were to demonstrate that FTR works and to illuminate any significant differences in performance among the methods by characterizing and comparing performance as a function of guide-star brightness. The most important criterion is point-spread function performance at the science camera. Analysis of the science images provides the Strehl ratio, a commonly used metric for quality of the point-spread function. We reduced the PHARO images appropriately and compared them to the theoretical diffraction-limited point-spread function of the system to determine Strehl ratios. The Strehl ratio is related to residual wave-front error by means of the Marechal approximation.

The system Strehl ratio can be expressed as a function of average photon flux N_p, assuming that all other system factors are constant[6]:

$$S(N_p) = \exp\left[-0.5 - k_1 \frac{N_p + 16(5.7)^2}{{N_p}^2}\right], \qquad (1)$$

where k_1 depends on the reconstructor and the wave-front sensor. We assumed a bright-star Strehl ratio of 0.6, which is consistent with subaperture spacing and seeing conditions during this experiment. The other factors are from PALAO specifications of 16 pixels per subaperture and a read noise of $5.7e^-$. The AO system telemetry provides the total number of photoelectrons in each subaperture, recorded at 100 Hz. These data were analyzed to produce the average subaperture flux (for fully illuminated subapertures) for each PHARO image. As shown in Fig. 1, the system performance for the entire run fits this model well. These results are consistent with established PALAO performance.[5]

Two performance regimes are of special interest. First, on bright stars the AO system should correct down to internal system error. Any alternative reconstructor must perform at least as well in this mode. Bright star SAO 53755 provides data for this regime. As shown in Fig. 2, the Strehl ratios of the three matrices are scattered across the same range of values. For LS and FT-Hud-fil, the average Strehl ratio is 0.61. The average performance of FT-Fri-lw yields a 0.59 Strehl ratio. This difference corresponds to an additional wave-front error of 63 nm rms added in quadrature. Using the appropriate analysis for small data sets,[7] one can determine the confidence interval for the difference between the means. For 95% confidence, the interval for the difference between LS and FT-Fri-lw is $[-0.0003, 0.0365]$, indicating that FT-Fri-lw will show slight Strehl ratio degradation. For this star the flux was ignored in the analysis because the flux measurements were poorly correlated with the Strehl measurements, and, based on Eq. (1), the small changes in flux on this star should have virtually no effect.

The second important area is the bottom end of the performance curve with a dim star. As shown in Fig. 1, the flux range from 80 to 300 photons spans a Strehl ratio of 0.4. The trial on star BD + 25 51 proved ideal for exploring this part of the curve, as there was a large range of flux. Furthermore, the flux declined during the trial over a 25-min period in a regular fashion, as clearly shown in Fig. 3. The regular drop-off of flux and the high correlations between flux and Strehl ratio for all three reconstructors (which varied from 0.88 to 0.96) indicate that a phenomenon such as high cirrus clouds gradually reduced flux and dominated other effects such as significant changes in r_0. This fortuitous occurrence allowed us to analyze performance versus flux with most other conditions constant.

The same equation [Eq. (1)] was fitted to the data from each reconstructor for star BD + 25 51 only. Figure 4 shows the data points and the best-fit curves

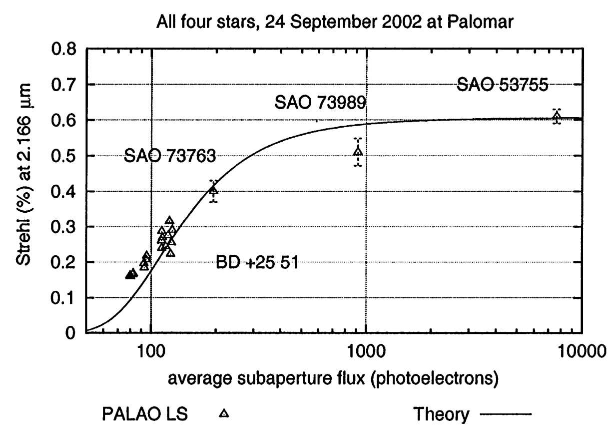

Fig. 1. Strehl ratios for the four stars tested versus average subaperture flux (as obtained from telemetry). Averages with σ error bars for PALAO LS only are plotted for clarity for the brighter stars, which have a narrow range of flux. The theoretical performance curve for an AO system under varying flux is best-fitted to the data.

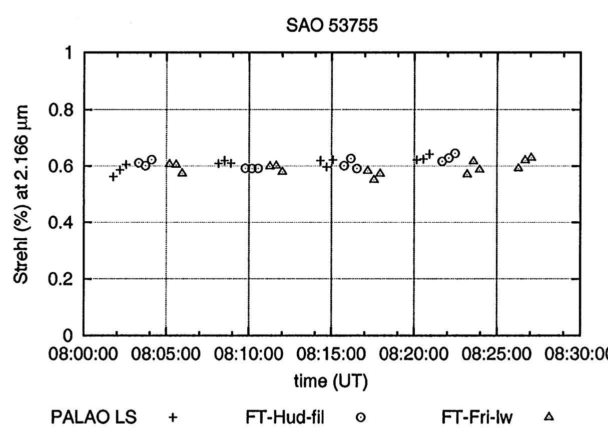

Fig. 2. Strehl ratios through time for bright star SAO 53755 ($m_v = 6.6$). FT-Hud-fil achieved the same average Strehl ratio as LS (0.61) FT-Fri-lw came in slightly below, at 0.59.

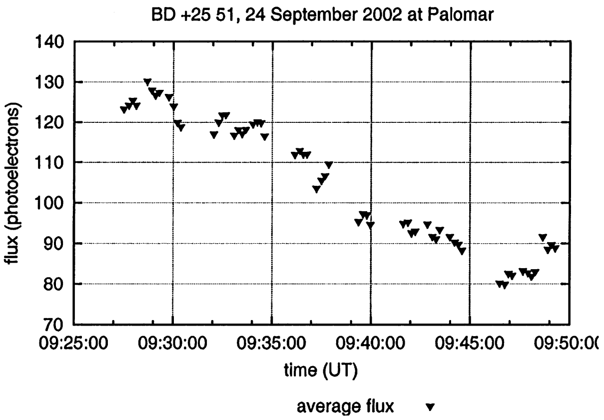

Fig. 3. Average subaperture flux versus time for observation of dim star BD + 25 51 ($m_v = 10.5$). A reasonable explanation for this drop-off across the observation period is that high cirrus clouds were gradually reducing available guide-star light.

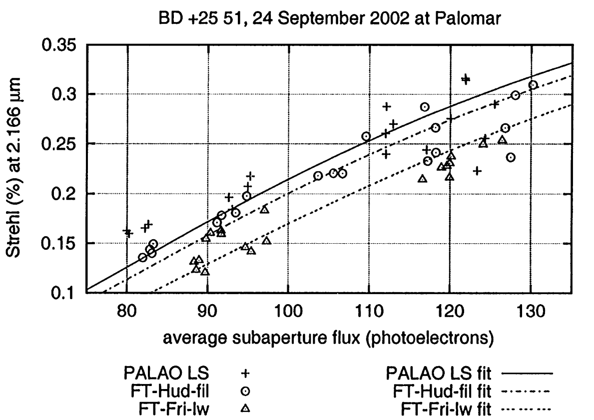

Fig. 4. Differences in method performance are visible for dim star BD + 25 51 ($m_v = 10.5$). The statistical correlations between Strehl and flux are very high: 0.88 for LS, 0.94 for FT-Hud-fil, and 0.96 got FT-Fri-lw. Based on best-fit curves of Eq. (1), FT-Fri-lw has clearly lower Strehl ratio performance (by 0.045) as a function of flux than the other two methods.

for each reconstructor. The average difference between the best-fit curves of LS and FT-Hud-fil shows a 0.013 Strehl ratio across the range of 80–130 photons. However, the data for both methods are almost fully overlapping and cover a broad range (a Strehl ratio of ~0.075) at higher flux, resulting is large error margins on the fit. Given these results, the data are not conclusive regarding any significant performance loss with FT-Hud-fil. However, the data for FT-Fri-lw are almost completely below those of the other two matrices: only 2 of the 40 LS and FT-Hud-fil points are below those of FT-Fri-lw for an equivalent flux. The performance equation has a significantly better fit to the FT-Fri-lw data. The best-fit curve is worse than the LS by a Strehl ratio average of 0.043 (average of 165 nm additional rms wave-front errors added in quadrature) in this flux range. Both of these facts indicate that FT-Fri-lw actually has worse performance on this dim source.

This experiment of FTR at Palomar Mountain has shown that FT-Hud-fil has equivalent Strehl ratio performance to the PALAO least-squares matrix over a wide range of star brightnesses. FT-Fri-lw performs nearly as well on brighter sources, but on dim stars there is a significant performance loss of an additional 165-nm rms error (added in quadrature). The big benefit for FTR comes through reduced computation. Using detailed analysis of total computation,[3] one can determine the FLOPs required and compare them to the vector-matrix-multiply. For a circular aperture with 354 subapertures, FT-Hud-fil requires 4.5 times less computation than the vector-matrix-multiply. For a 3024-subaperture system, this value is 82.7 times less. Because FT-Hud-fil can provide equivalent reconstruction quality, it permits the design of AO systems at faster control rates and with more subapertures than has been possible.

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