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First experimental validation of Fourier transform wave-front reconstruction at Palomar

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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 optics (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. Exactly this was done with the Palomar AO system on the 200-inch 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 FT method produced comparable performance to the PALAO least-squares matrix. The Fried-geometry method had a noticeable performance degradation of 0.043 Strehl in 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 last 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, speed and reasonable noise propagation to enable a large (~ 3000 actuator) system to be built with current computer technology. However, FTR has 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 PALAO system on the Hale 200-inch telescope at Palomar Mt., California. PALAO[5] has 241 active actuators with a subaperture size of $d = 31.75$cm. The control system records detailed telemetry, including wave-front sensor (WFS) centroids, flux and mirror residuals. The system normally runs with a least-squares reconstruction matrix, referred to as LS.

Matrices expressing FTR methods were generated for use in PALAO, with a few specific modifications. Tip and tilt were completely removed from the DM command vector and tip-tilt control was done with the standard PALAO method. The biggest hurdle in adapting the algorithms was dealing with the central obscuration. There are 21 actuators in the central obscuration that do not border 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 FT methods, our approach was to set this region to be as flat as possible. In the end, simply leaving all the slopes from the un-illuminated subapertures at zero (and not fixing any loop continuity) produced the most stable behavior.

Several varieties of FTR methods were produced, namely Hudgin- and Fried-geometry with various filtering options.[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 on bright stars, but only a few remained stable and had good correction on 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 of 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 constant as possible, with the same tip/tilt control, a fixed WFS gain, control loop parameters and control rate of 500 Hz. In the early morning of 24 September 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 PHARO observations in K-band with a Bracket γ filter (2.166 μm) were taken for all reconstructor trials. Exposure lengths varied from 10 to 30 sec, depending on the star's brightness. This procedure was used to produce a data set of sufficient size for each star such that variable effects like 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 amongst the methods by characterizing and comparing performance as a function of guide-star brightness. The most important criterion is point-spread-function (PSF) performance at the science camera. Analysis of the science images provides the Strehl ratio, a commonly used metric for PSF quality. The PHARO images were properly reduced and compared to the theoretical diffraction-limited PSF of the system to determine Strehl ratios. Strehl is related to residual wave-front error via the Marechal approximation.

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

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

where k_1 depends on the reconstructor and WFS. We assumed a bright-star Strehl 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 is 0.61. The average performance of FT-Fri-lw is 0.59 Strehl. 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] the confidence interval for the difference between the means can be determined. 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 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 impact.

The second important area is the bottom end of the performance curve with a very dim star. As shown in Fig. 1, the flux range from 80 to 300 photons spans 0.4 Strehl. 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 minute period in a very regular fashion, as clearly shown in Fig. 3. The regular drop-off of flux and the very high correlations between flux and Strehl 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 over 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 fit to the data from each reconstructor for star BD +25 51 only. Fig. 4 shows the data points and the best-fit curves for each reconstructor. The average difference between the best-fit curves of LS and FT-Hud-fil is 0.013 Strehl across the range of 80 to 130 photons. However, the data for both methods are almost fully overlapping and cover a broad range (about 0.075 Strehl at higher flux), resulting is large error margins on the fit. Given this, 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 significantly better fit to the FT-Fri-lw data. The best-fit curve is worse by an average of 0.043 Strehl (average of 165 nm additional rms wave-front error added in quadrature) in this flux range, compared to LS. Both these facts indicate that FT-Fri-lw actually has worse performance on this dim source.

This experiment of FTR at Palomar 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] the FLOPs required can be determined and compared to the VMM. For a circular aperture with 354 subapertures, FT-Hud-fil uses 4.5 times less computation than the VMM. For a 3024 subaperture system, this result is 82.7 times less. Since FT-Hud-fil can provide equivalent reconstruction quality, it enables the design of AO systems at faster control rates and with more subapertures than is currently possible.

This experiment would not have been possible without the generous donation of telescope time by the JPL Palomar AO team. Thanks go to F. Shi, R. Burruss, J. Hickey, V. Viswanathan and J. Muller for their help before and during the run. Observations at the Palomar Observatory were made as part of a continuing collaborative agreement between Palomar Observatory and the Jet Propulsion Laboratory. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. The document number is UCRL-JC-150605. This work has been supported by the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement No. AST - 9876783. Contact author L. Poyneer at poyneer1@llnl.gov.

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Fig. 4. Differences in method performance are visible on 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 performance (by 0.045) versus flux than the other two methods.

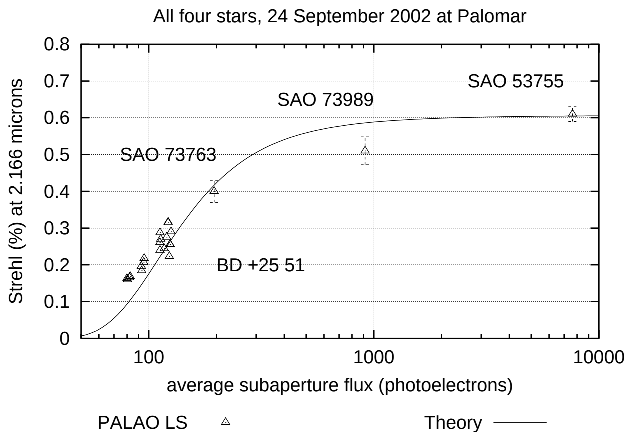

Figure 1, L.A. Poyneer et. al.

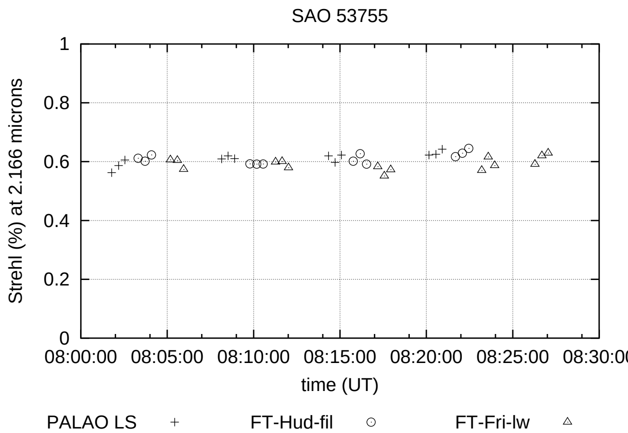

Figure 2, L.A. Poyneer et. al.

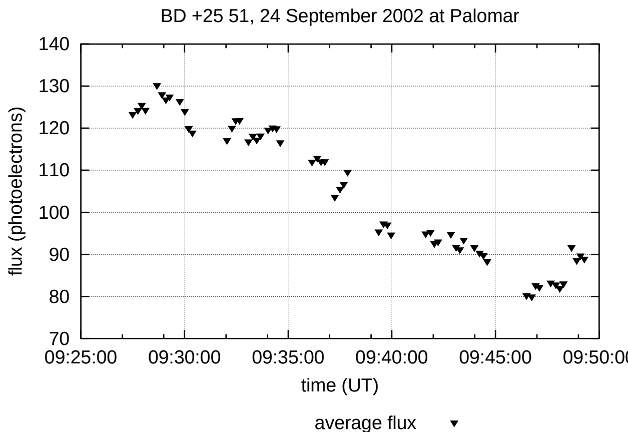

Figure 3, L.A. Poyneer et. al.

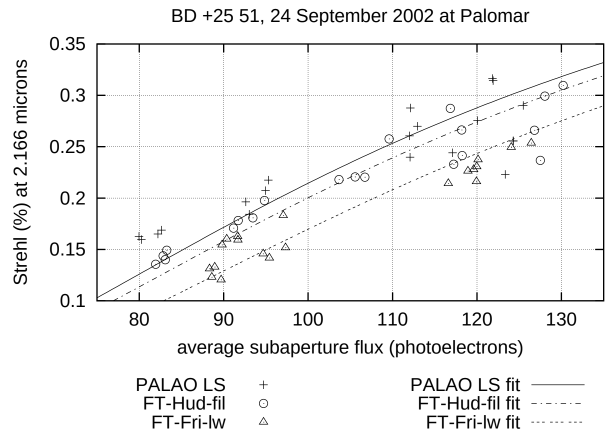

Figure 4, L.A. Poyneer et. al.