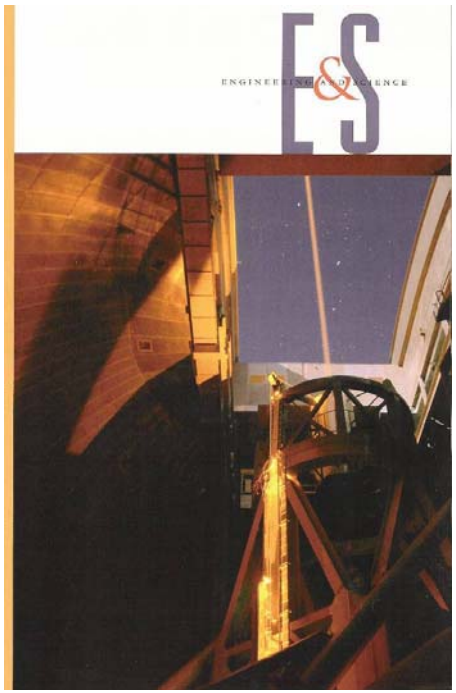
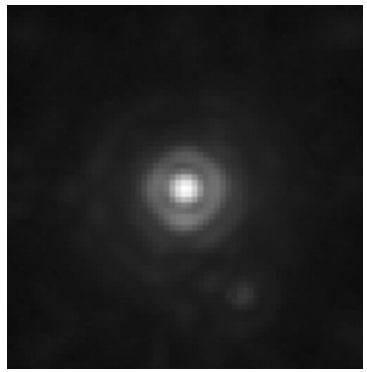
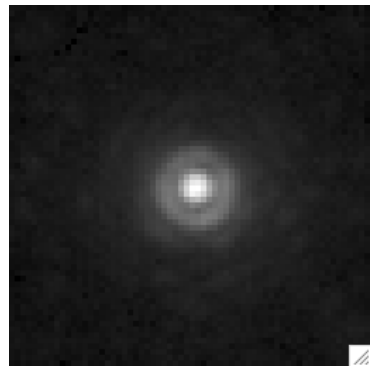






Faint Light Adaptive Optics

- Improving NGS and LGS AO -

CfAO Retreat

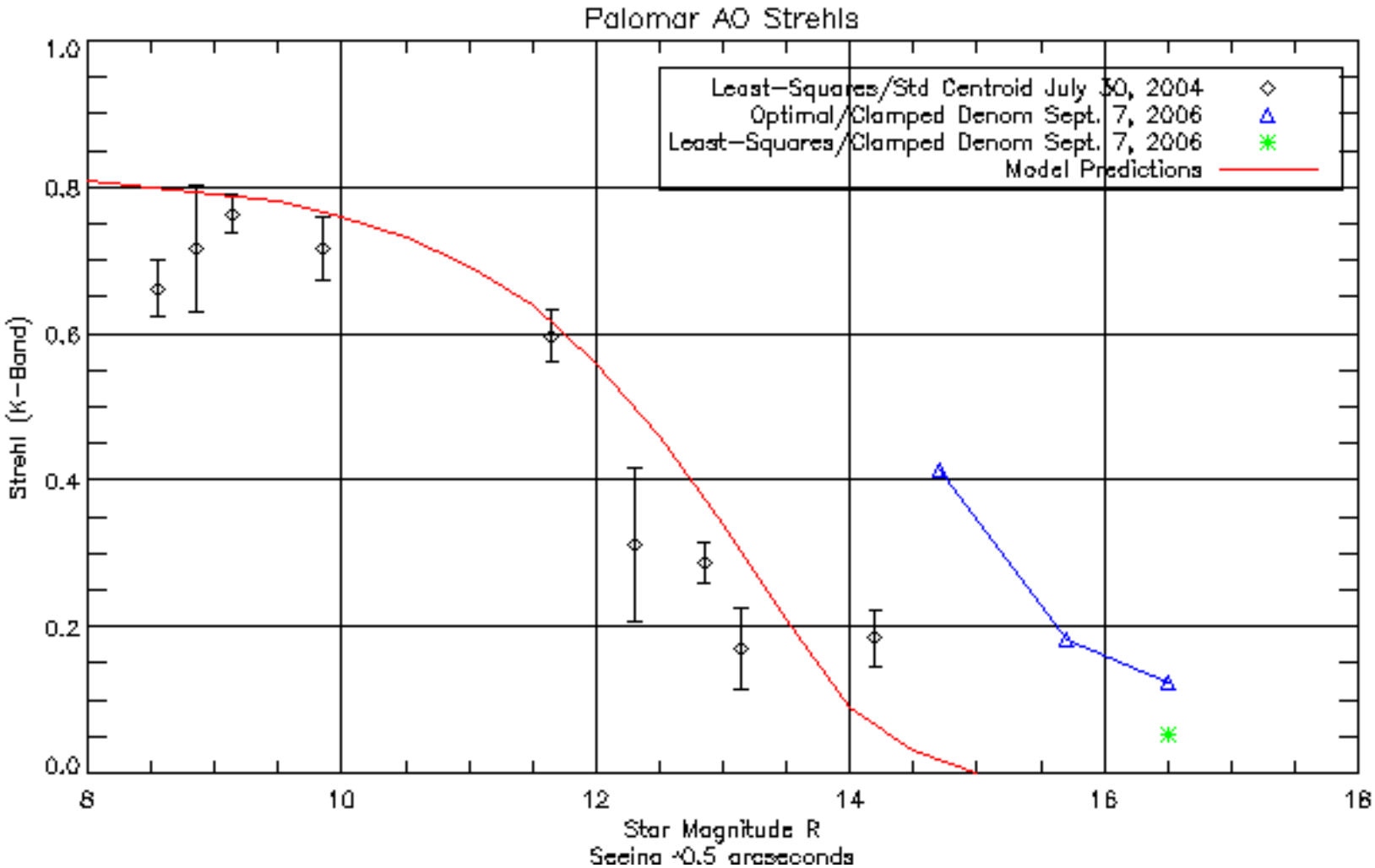
November 17, 2006

Chris Shelton, Mitchell Troy, Antonin Bouchez, Jennifer Roberts, Thang Trinh, Tuan Truong

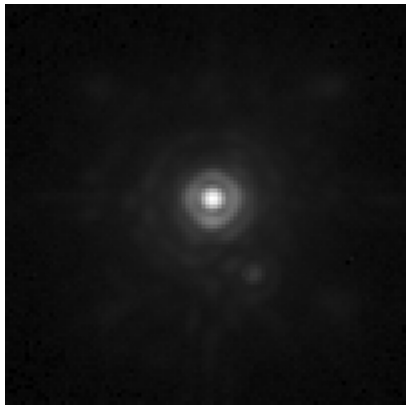
Innovations in AO Algorithms

- Changes to AO algorithms have been tested on the sky on the Palomar AO system and were found to improve the faint-light performance by about 2 magnitudes.
- The algorithm changes tested were
  - Clamped-centroid version of denominator-free algorithm (Shelton, J.C., Proc. SPIE, **3126**, 455-459 (1997))
  - Optimal estimator (baysian) control matrices , using Matlab routines graciously supplied by Marcos van Dam. (Wild, W.J., Opt. Lett, 21, **1433** (1996))
  - Null-vector suppression
  - Correctly handling obscuration
- Null vector suppression was added in November 2005.
- The denominator-free algorithm, optimal estimator and obscuration changes were tested on the sky on 7 September, 2006.
- The AO system was configured for LGS operation, with a 589nm narrow band dichroic feeding the high-order WFS. The measured attenuation for NGS operation was 3.3 magnitudes. Tabulated V magnitudes were offset by this amount to give a “Veff” magnitude in the following charts.

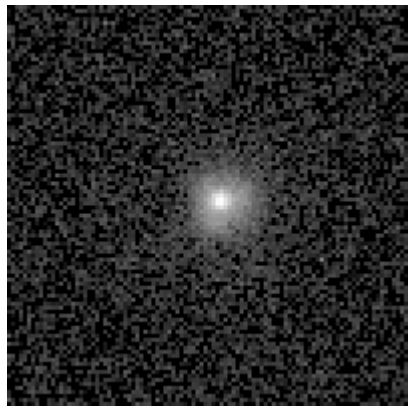
Measured NGS Strehl Improvement



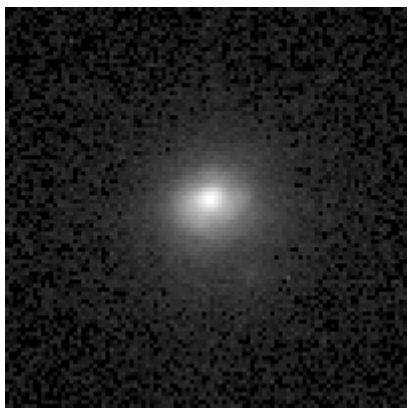
NGS Images, 2006 Sep 7



Veff 14.7
Landolt 111-1965
Optimal estimator
Clamped denominator
K Strehl 41.5%
K FWHM 94 masec

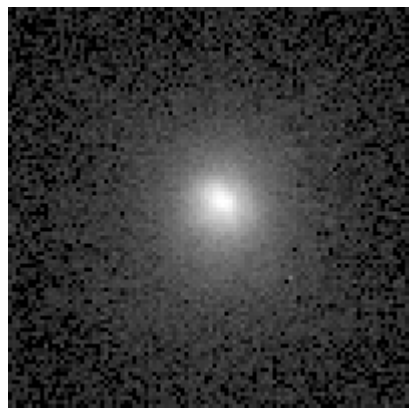


Veff 15.7
Landolt 111-1925
Optimal-estimator
Clamped denominator
K Strehl 18.1%
K FWHM 119 masec



Veff 16.5
Landolt 111-2088

Optimal-estimator
Clamped denominator
K Strehl 12.4%
K FWHM 152 masec



Veff 16.5
Landolt 111-2088

Least-squares
Clamped denominator
K Strehl 5.4%
K FWHM 209 masec

Denominator-Free Algorithm

- True “Denomintor-Free” algorithm uses “gradient” (A-B) rather than “centroid” (A-B)/(A+B) as input to reconstructor.
- The benefit is particularly great with scintillation, as the technique gives weight to bright regions of the pupil instead of dark regions.
- A theoretical underpinning can be derived from equations for optimal estimator, letting object intensity approach zero.
  - An optimal estimator faint light asymptote exists, just as a bright light asymptote exists.
  - Object brightness ends up in both numerator and denominator – so why bother with division?
- Operating at S/N less than one becomes possible, giving theoretically optimum performance through cloud fades, etc. Note that atmospheric transmission in LGS is round-trip, and is the square of the NGS one-way transmission.
- Operating with large background becomes possible – companions of bright objects, cores of comets, daytime operation, LGS low-order WFS.
- Technique requires restructuring of real-time code

Faint-limit Optimal Estimator

- The faint-limit optimal estimator can be seen easily using A++ or the like.
- Once alpha becomes bigger than a few hundred, the reconstructor stops changing.
- More formally:

$$M = \tilde{X}_{\varphi} A^T X_n^{-1}$$

$$M_{i,j} = 3.44 \left(\frac{d}{r_0} \right)^{\frac{3}{5}} \left(\frac{1}{\sigma^2} \right) \left| x_i - x_k \right|^{\frac{5}{3}} A^T_{k,j}$$

Clamped-Denominator Centroids

How to test theory without major edits to real-time code?

Instead of

C_x = ((A+B)-(C+D)) / Sum, use

C_x = ((A+B)-(C+D)) * K

If (Sum > Thresh) then

K = 1/Sum else

K = 1/Thresh

Threshold is uniquely defined by theory

This is called “clamped-denominator”

“Sum” can also have temporal or spatial averaging to improve faint-light performance without impacting system speed

What About Centroid Offsets?

Replace centroid offsets with algebraically equivalent pixel weights –

Call centroid offsets c_x, c_y

Then pixel weights become

$W_a = (1 + c_x)(1 - c_y)$

$W_b = (1 – c_x)(1 – c_y)$

$W_c = (1 + c_x)(1 + c_y)$

$W_d = (1 – c_x)(1 + c_y)$

The goal is a completely linear system, valid to S/N = 0.

Test this by operating on blank sky – should see DM and TT wandering around with zero mean.

Acquisition and AO lock onto objects slightly outside the field stop should become possible.

The Future

- The Palomar real-time code has been modified to allow selection of different algorithms on the fly. We plan further NGS testing with this.
- We plan on simplifying, documenting, and eventually automating, the AO optimization procedures for the benefit of AO operators.
- We plan on applying these techniques to the LGS low-order WFS, and testing on the sky.
- I plan further work to improve the theoretical underpinning and to publish these results.
- Those responsible for modeling and simulation software are encouraged to correctly include centroid denominator statistics.

A Testimonial

Hey, Very good news.

Short story, we had a target of opportunity tonight to test some new NGS AO capabilities. There has been a sudden brightening in a ~15th mag galaxy (guesstimate based on companion) so close to the nucleus that it was not known if the sudden brightening was an active nucleus or supernova.

Using "clamped-denominator centroiding" and a new Baysian reconstructor we successfully locked on the bright companion (~14.5mag from email) and separated the supernova from the galaxy nucleus. This was not possible with the AO default settings. The cores are now easily defined for astrometry with a separation of 1.04". Congrats and thanks to Chris, Jenny, Antonin, and Mitch, for instituting this and helping us understand what needed to be done.

I'm so excited I'm off to Harrah's to make last call.

Cheers,
Jeff Hickey