Application of “blind” deconvolution to Adaptive Optics Imaging

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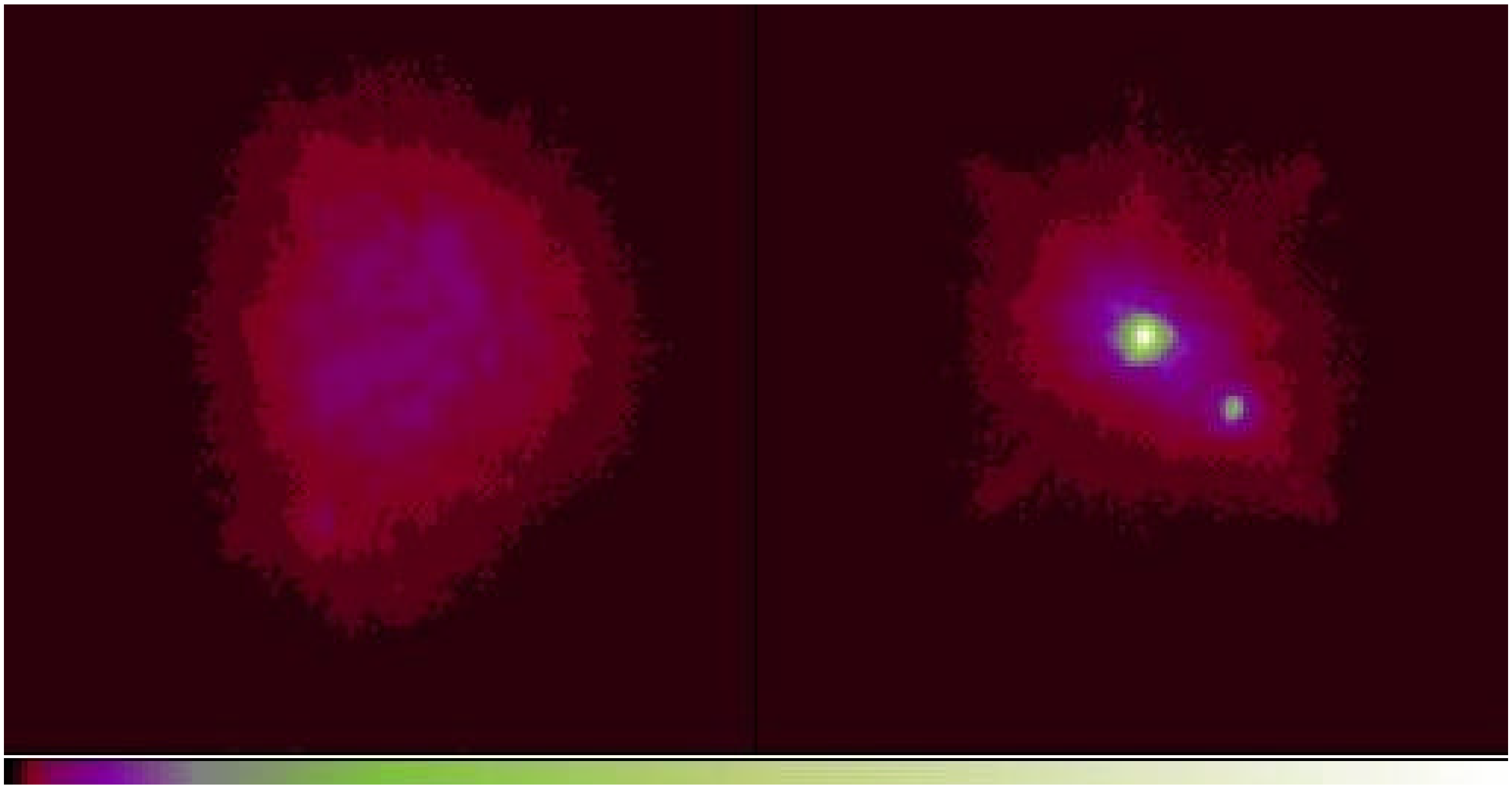
Adaptive Optics Imaging

- Quality of compensation depends upon:
  - Wavefront sensor
  - Signal strength & signal stability
  - Speckle noise ($\boldsymbol{d / r_0}$)
  - Duty cycle ($\boldsymbol{t / t_0}$)
  - Sensing & observing **ë**
  - Wavefront reconstructor & geometry
  - Object extent
  - Anisoplanatism (off-axis)

Adaptive Optics Imaging



Uncompensated image
(200 msec)

Poorly compensated image
(SR ~ 5%) (200 msec)

Adaptive Optics
Point Spread Function Variability

- Differences in Target & Reference compensation due to:
  - Temporal variability (changing $\boldsymbol{r_0}$ & $\boldsymbol{t_0}$).
  - Object dependency (extent and brightness)
    - full & sub-aperture tilt measurements
  - Spatial variability

- Adaptive Optics PSFs are poorly determined.

The Imaging Equation

Shift invariant imaging equation

(Image & Fourier Domains)

$$g(r) = f(r) * h(r) + n(r)$$

$$G(f) = F(f) \bullet H(f) + N(f)$$

***g(r)* –** measurement

***h(r)* –** Point Spread Function (blur)

***f(r)* –** Target

Physically Constrained Iterative Deconvolution

- "Blind" deconvolution solves for both **object *f(r)*** and **PSF *h(r)*** simultaneously.
  - Ill-posed inverse problem.
  - Under – determined: 1 measurement, 2 unknowns

- Uses Physical Constraints.
  - ***f(r)*** & ***h(r)*** are positive, real & have finite support.
    - Finite support reduces # of variables (symmetry breaking)
  - ***h(r)*** is band-limited – symmetry breaking

- *a priori* information - further symmetry breaking.
  - Noise statistics
  - PSF knowledge
  - Object & PSF parameterization
  - Multiple Frames:
    - Same object, different PSFs.
    - ***N*** measurements, ***N+1*** unknowns.

idac – iterative deconvolution algorithm in c

- Developed at Steward Observatory
  - Authors – Keith Hege, Matt Chesalka
  - Collaborators - Stuart Jefferies & Julian Christou
- Available to download from SO & CfAO
  - http://babcock.ucsd.edu/cfao_ucsd/idac/idac_package/idac_index.html
  - http://bach.as.arizona.edu/~hege/docs/idac.html
- “blind” and fixed PSF multi-frame deconvolution

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PSF Calibration using "idac"

- Introduction
- The Algorithm
- User's Guide
- Example
- Downloads
- Editing the FITS Header

Point Spread Function Calibration using Iterative "Blind" Deconvolution

Blind Deconvolution

Blind deconvolution estimates both the **object** and **PSF** from a set of observations. It is able to do this by making use of physical constraints which serve to break the symmetry of what appears to be an untractable problem. These constraints include multiple observations of the same **object** such that there is one common object with each observation having a different **PSF**, that each **PSF** is band-limited due to the finite size of the aperture used for the observations and both **object** and **PSF** have to be positive. Prior information about the average structure of the **PSF** may also be used. Further details about the procedure is given in the references below.

The Code

This code was based upon the FORTRAN code developed by Stuart Jefferies & Julian Christou (*Astrophys. J.* **415**, 682, 1993) and developed further in collaboration with Keith Hege with major programming support by Matt Cheselka. It is a non-linear, iterative scheme using a conjugate gradient minimization algorithm applied to an error metric derived from the data.

Support

This code has been developed at The Center for Astronomical Adaptive Optics (CAAO). It has been been tested and used by reseachers at the European Southern Observatory (ESO) and at the Starfire Optical Range.

Distribution

It is being made available for distribution via The Center for Adaptive Optics (CfAO).

Copyright

Julian Christou, Keith Hege
17 December, 2000

idac – iterative deconvolution algorithm in c

- Conjugate Gradient Error Metric Minimization

$$E = E_{\mathrm{conv}} + E_{\mathrm{bl}} + \alpha E_{\mathrm{SAA}}$$

  – Convolution Error

$$E_{\mathrm{conv}} = \sum_{ik} [g_{ik} - (f'_i * h'_{ik})]^2$$

  – Band-limit Error

$$E_{\mathrm{bl}} = \Sigma_k \Sigma_{u > u_c} |H'_{uk}|^2$$

  – Non-negativity

$$f'_i = \alpha^2 \qquad \& \qquad h'_{ik} = \beta^2$$

  – PSF Constraint

$$E_{\mathrm{SAA}} = \Sigma_i |h_i^{\mathrm{SAA}} - h'^{\mathrm{SAA}}_i|^2$$

idac – iterative deconvolution algorithm in c

- Regularization via Truncated Iterations

$$E_{\mathrm{conv}} = \sum_{ik}[(g_{ik} + n_{ik}) - (f'_i * h'_{ik})]^2$$
$$= \sum_{ik} |n_{ik}|^2 = k\sigma_n^2$$

- SNR Regularization (Fourier Domain)

$$E_{\mathrm{conv}} = \sum_{uk}[G_{uk} - (F'_u \bullet H'_{uk})]^2 F_u$$
$$F_u = (\langle |G_u|^2 \rangle - |N_u|^2) / \langle |G_u|^2 \rangle$$

Applications of “*idac*” to AO Data

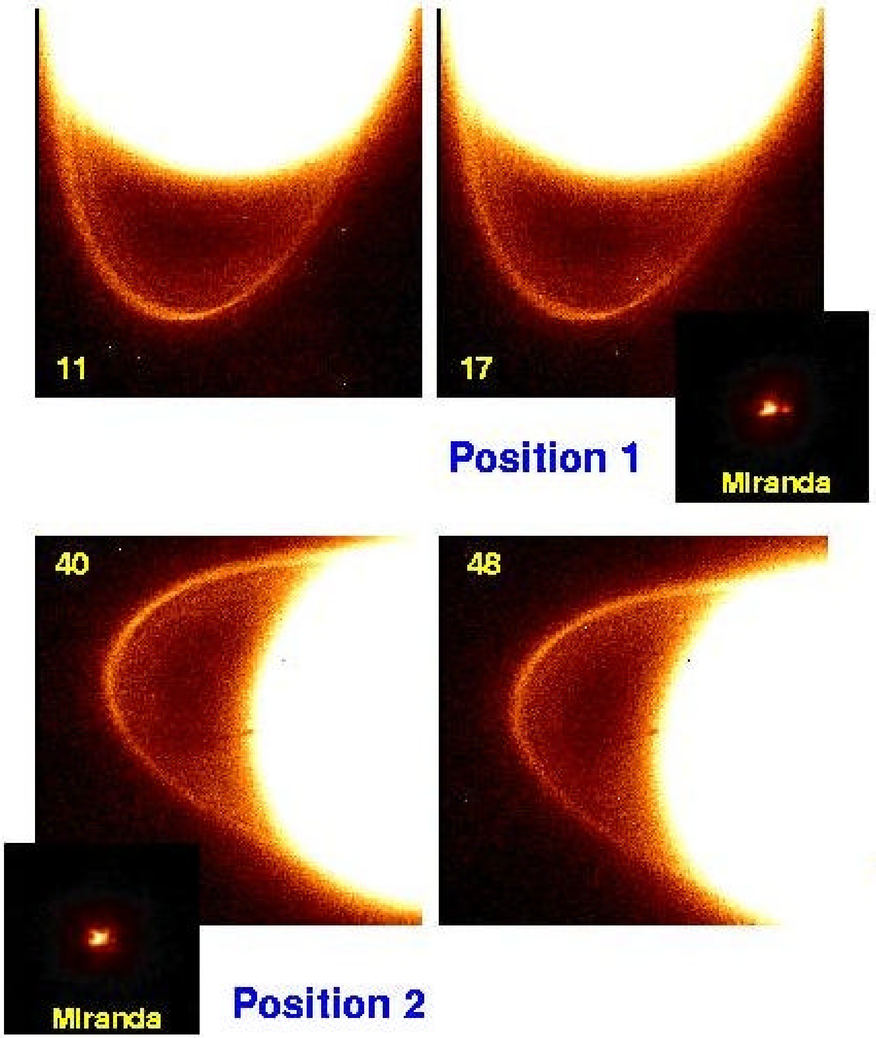
1. Solar System Objects
   - Keck AO imaging of Uranus’ Rings
   - ADONIS Imaging of Io

2. Starfire Optical Range
   - Artificial Satellite
   - Close Binary Stars

3. Gemini/Hokupa’a Imaging of the Galactic Center

   Using Starfinder for Photometry and Astrometry

Keck AO Imaging of Uranus



Observations

(Imke de Pater - UCB)

Keck II AO

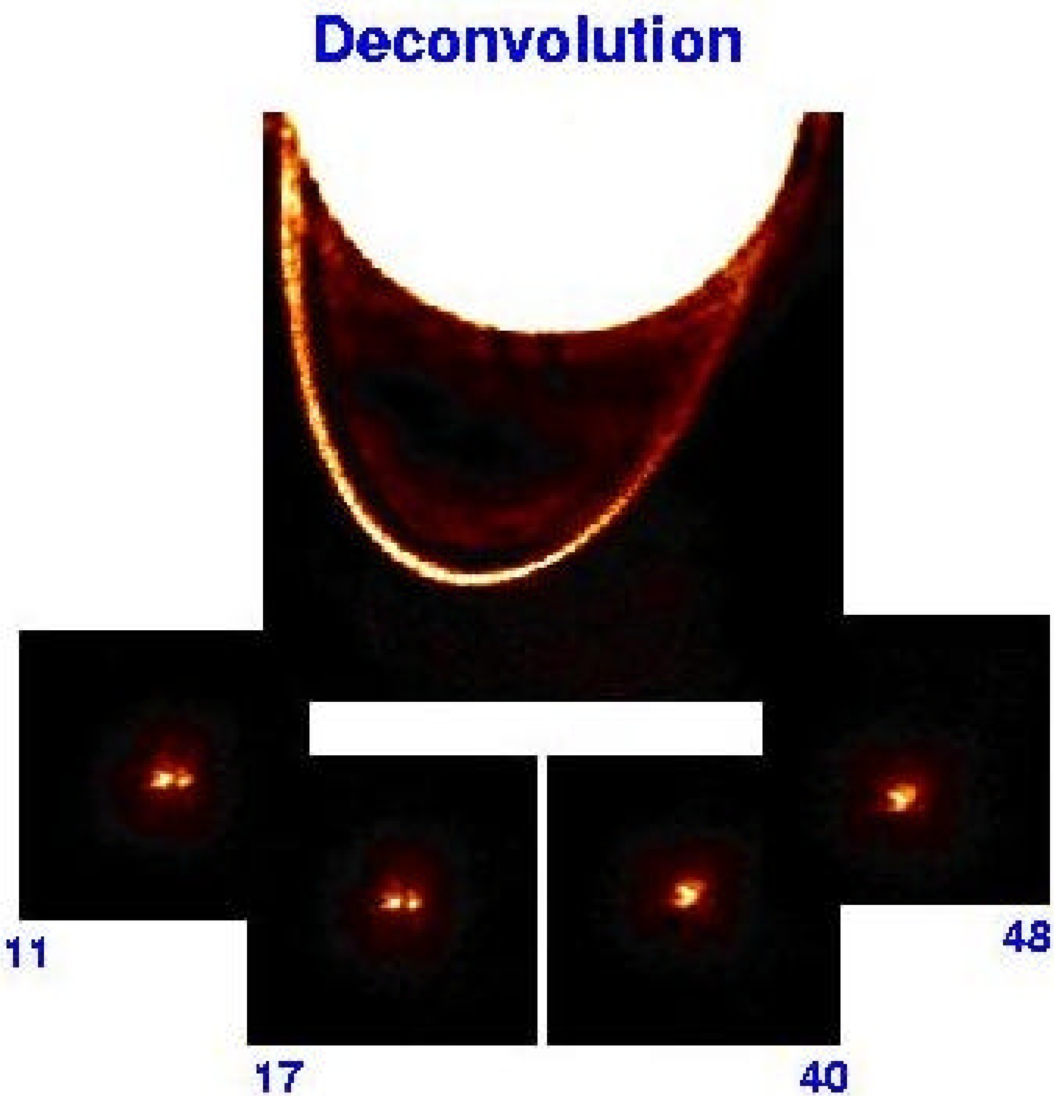
λ = 2.2 µm

Loop closed on Uranus

3 frames/data set

90° rotation between 11,17 and 40,48

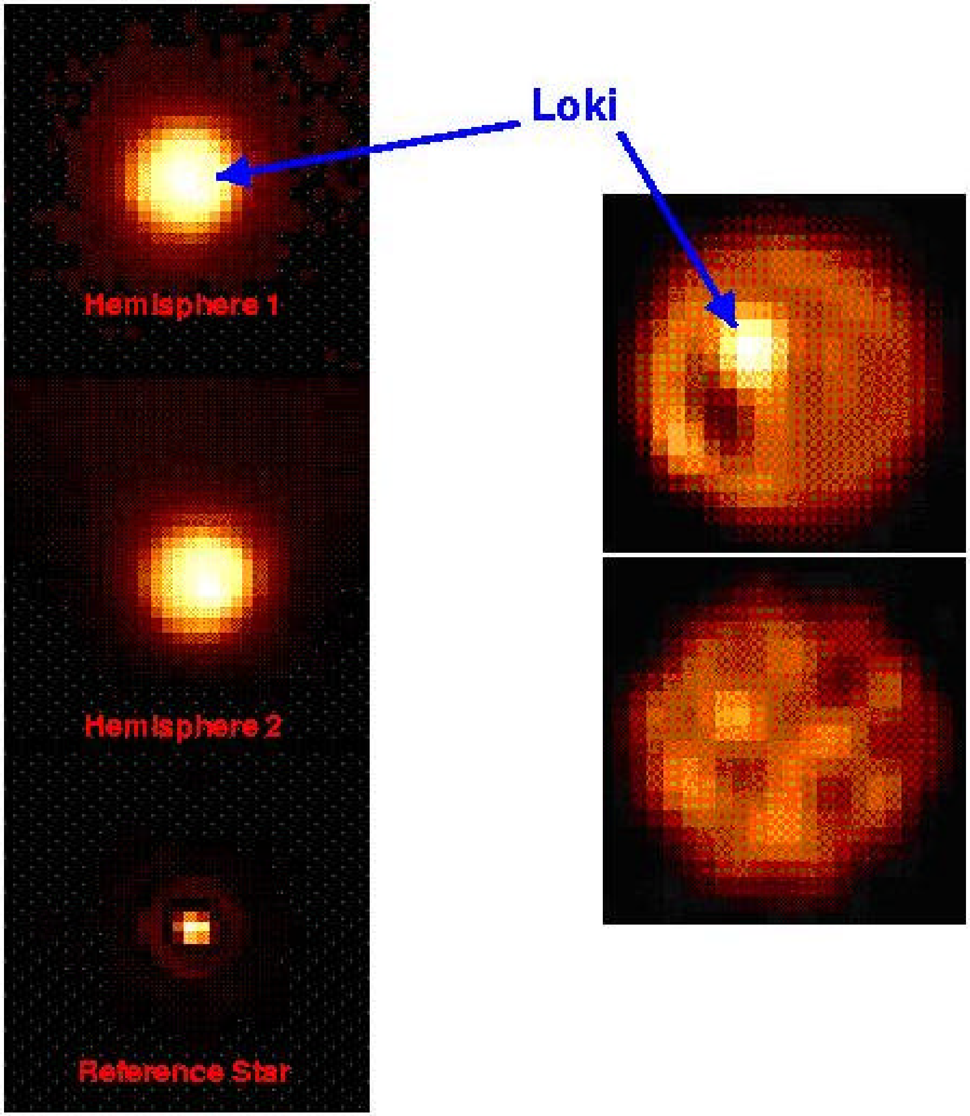
Keck AO Imaging of Uranus



Target & PSF Reconstructions

4 frames - same orientation
(256 x 256 embedded in 512 x 512)
Miranda images - initial PSF
Co-added Uranus – initial object
Brightness variation along Ring
Inner ring structure
PSF recovery

ADONIS Imaging of Io



λ = 3.8 μm

Two distinct hemispheres
~ 11 frames/hemisphere

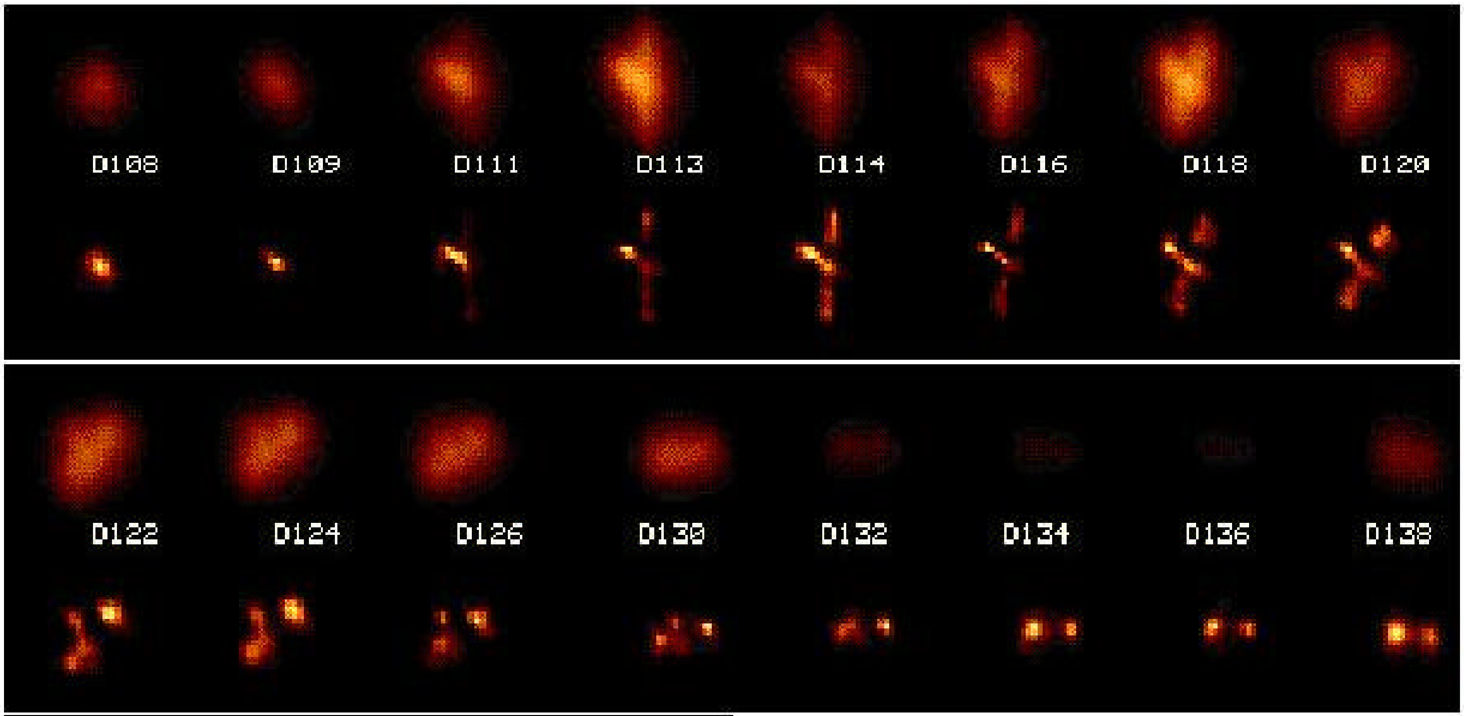
Co-added initial object

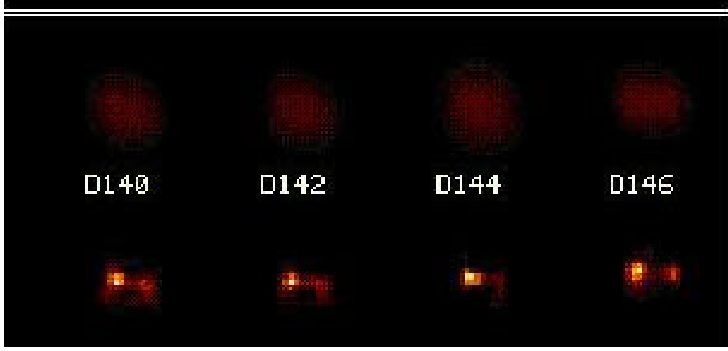
PSF reference as initial PSF

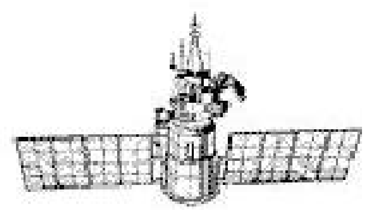
Surface structure visible
showing volcanoes.

(Marchis *et. al.*, Icarus, 148, 384-396, 2000.)

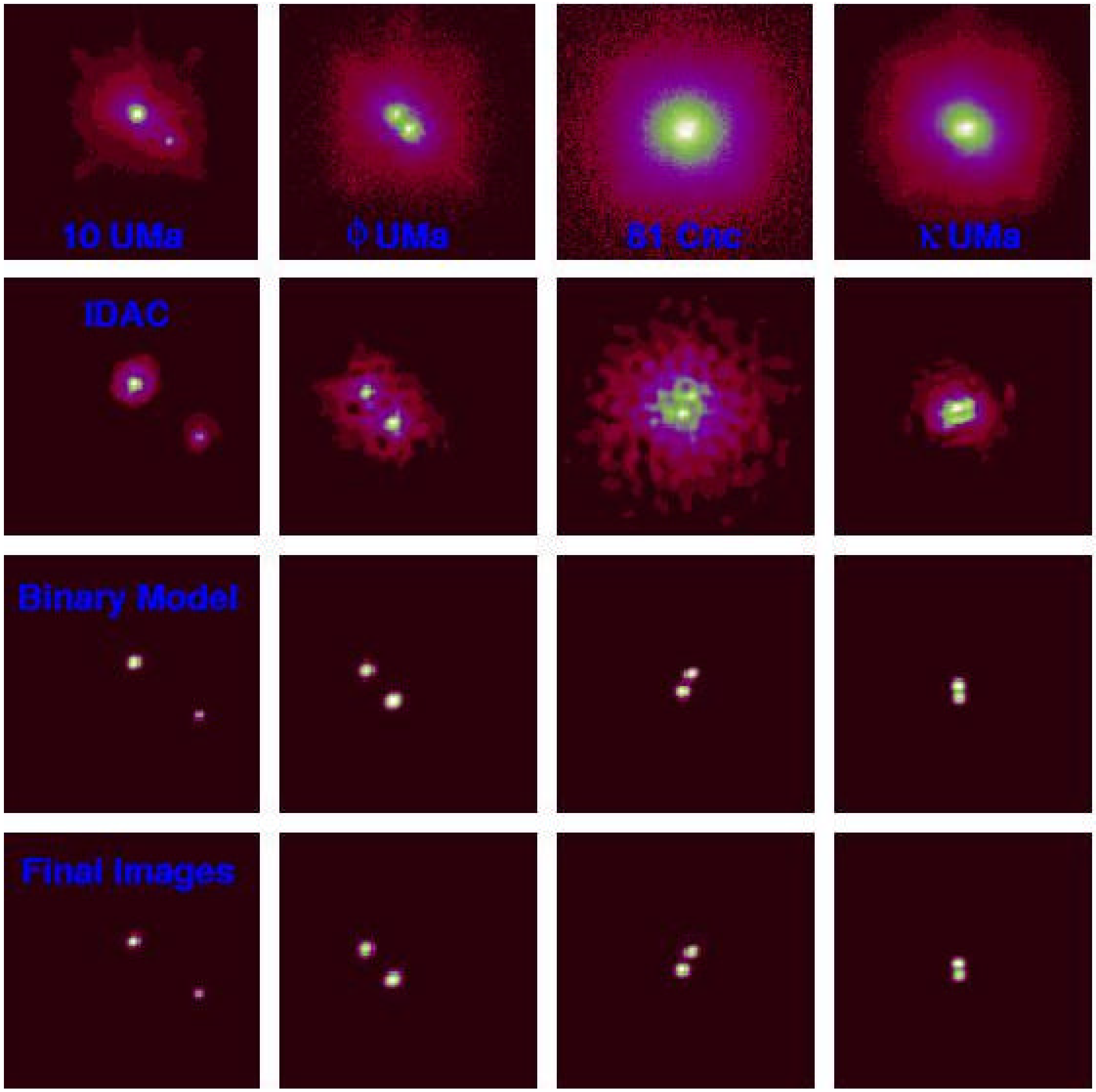
Artificial Satellite Imaging







SOR Binary Star Imaging



Observations:

3.5m

λ= 0.65/0.10 μm

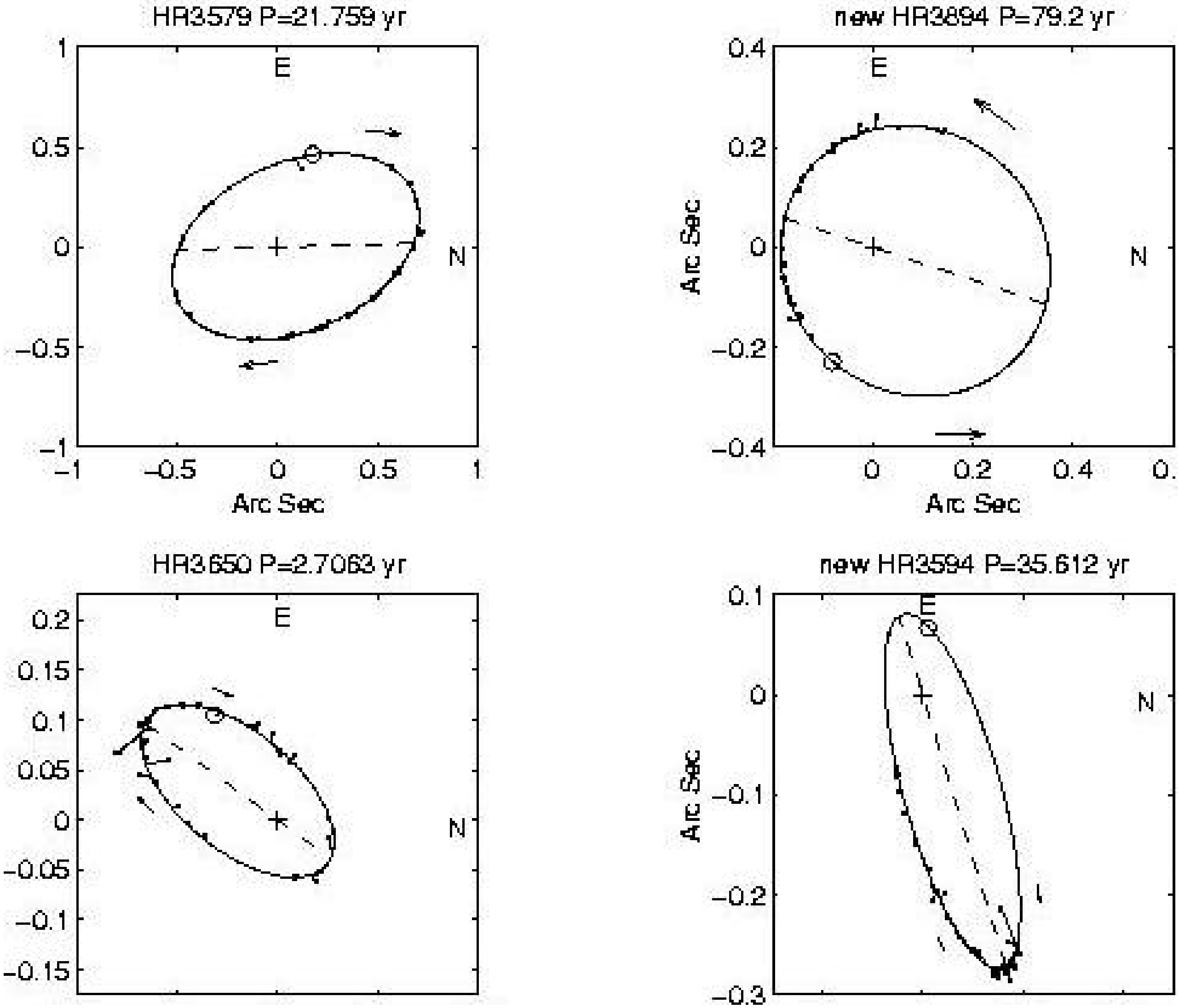
Multiple observations
(10 – 12 frames)

t_{exp} = 100 – 500 msec

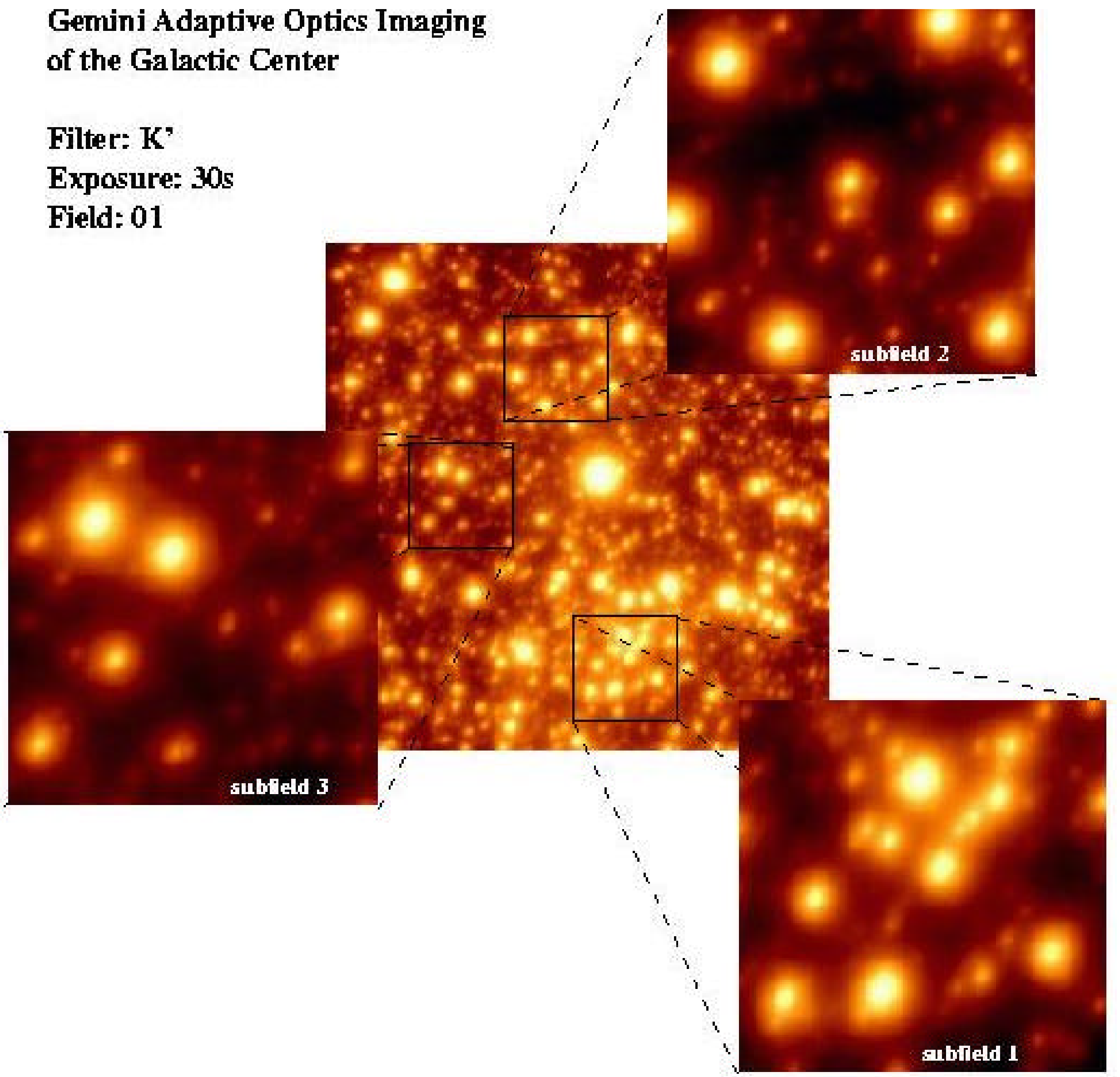
Strehls – 4% - 9%

Δx = 0.026"/pixel
(Nyquist Sampled)

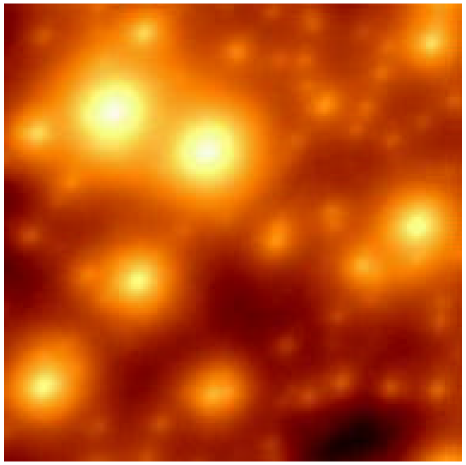
SOR Binary Star Imaging - Orbits



Gemini Imaging of the Galactic Center



Gemini Imaging of the Galactic Center
"*idac*" application

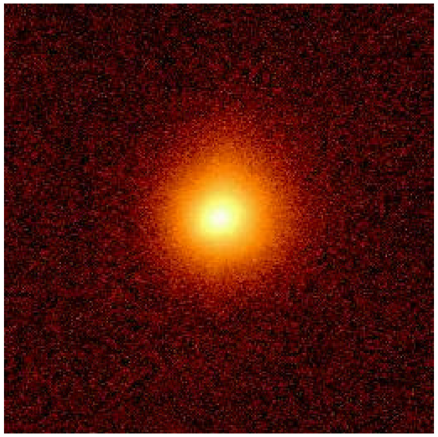


Initial Estimates:

Object – 4 frames co-added (top)

PSF – K' 20 sec reference (bottom)

(FWHM = 0.2")

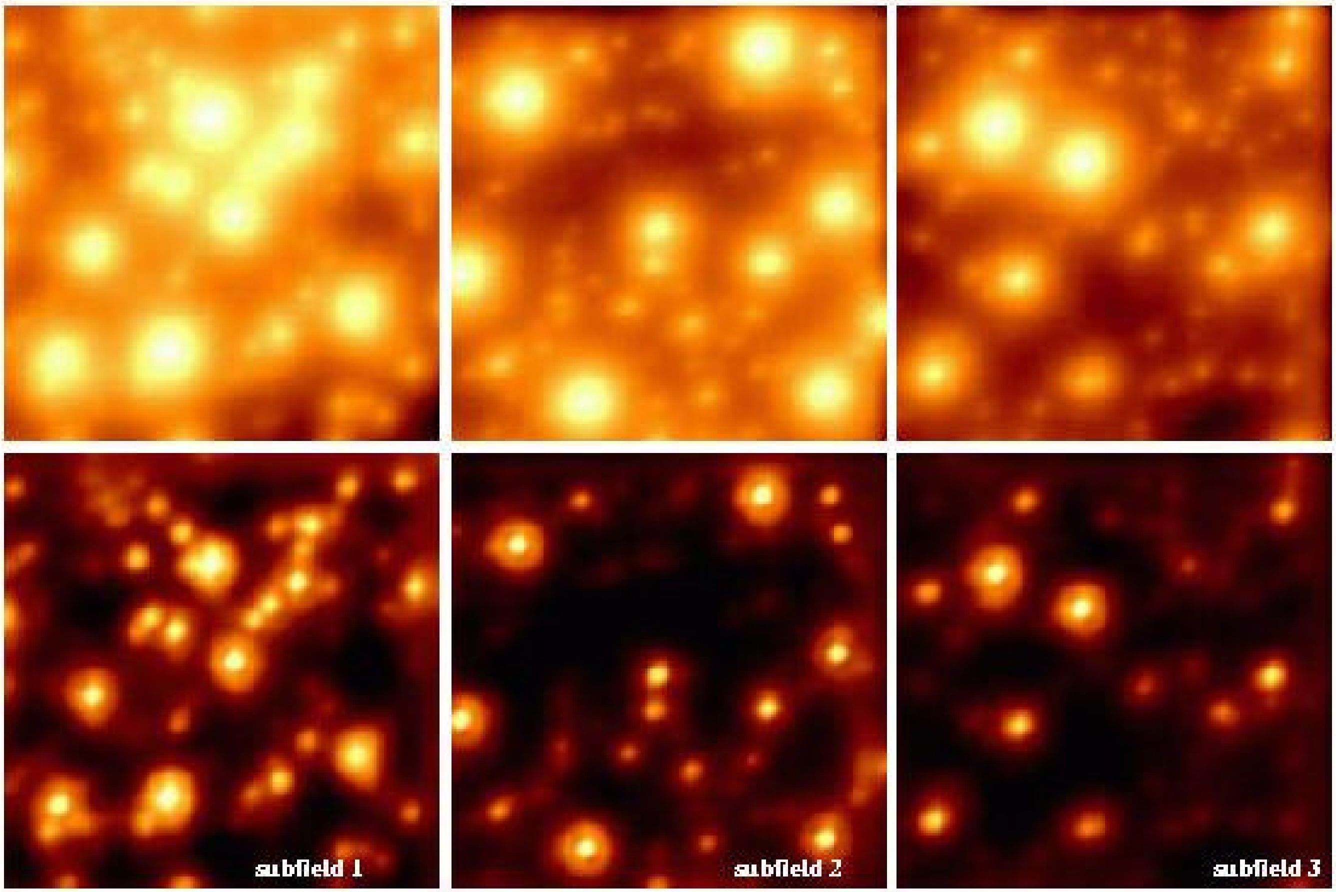


4.8 arcsecond subfield

256 x 256 pixels

reduced to 3.8 arcsec with tapering

Gemini Imaging of the Galactic Center
“*idac*” reductions



Top:

4 frame average for each of the sub-fields.

Bottom:

“***idac***” reductions.

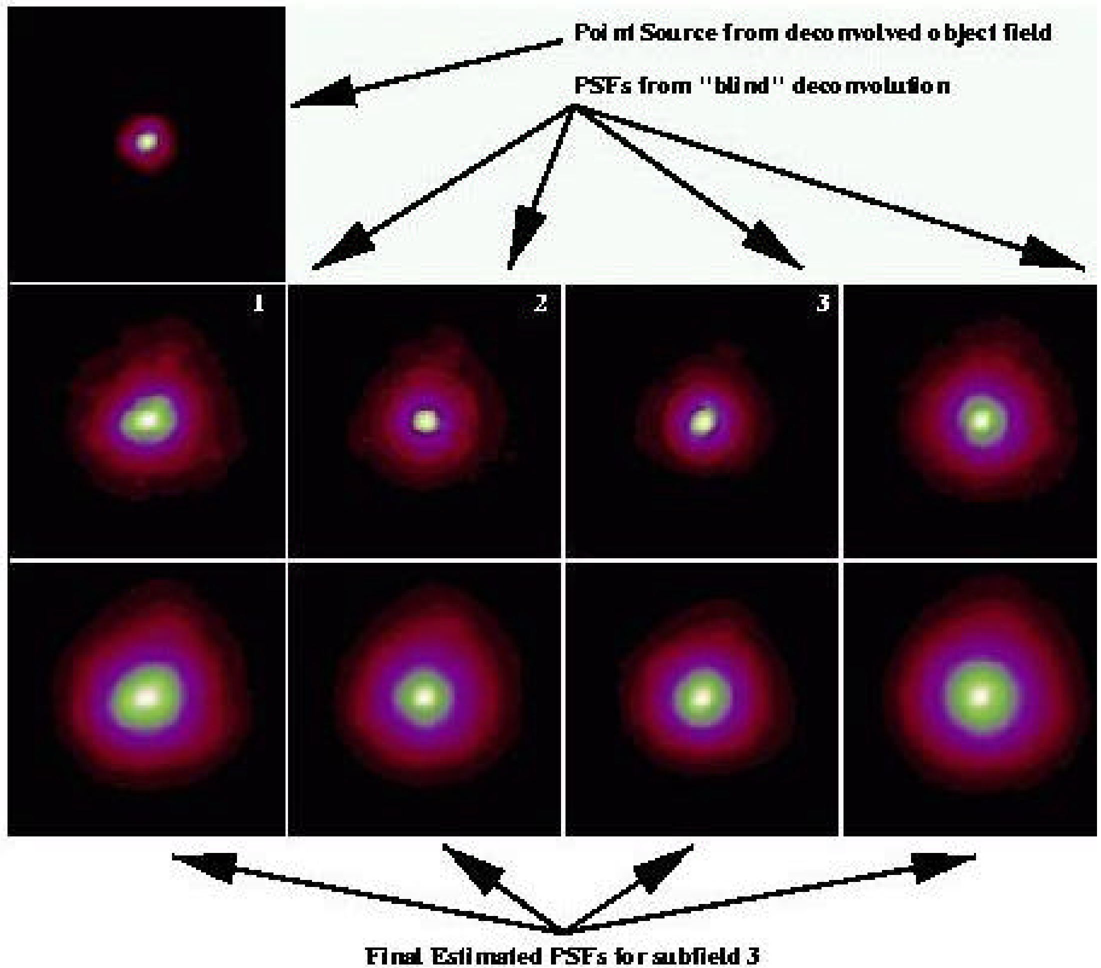
FWHM = 0.07"

Note residual PSF halo

Gemini Imaging of the Galactic Center
PSF Recovery

$$g(r) = f(r) * h(r)$$

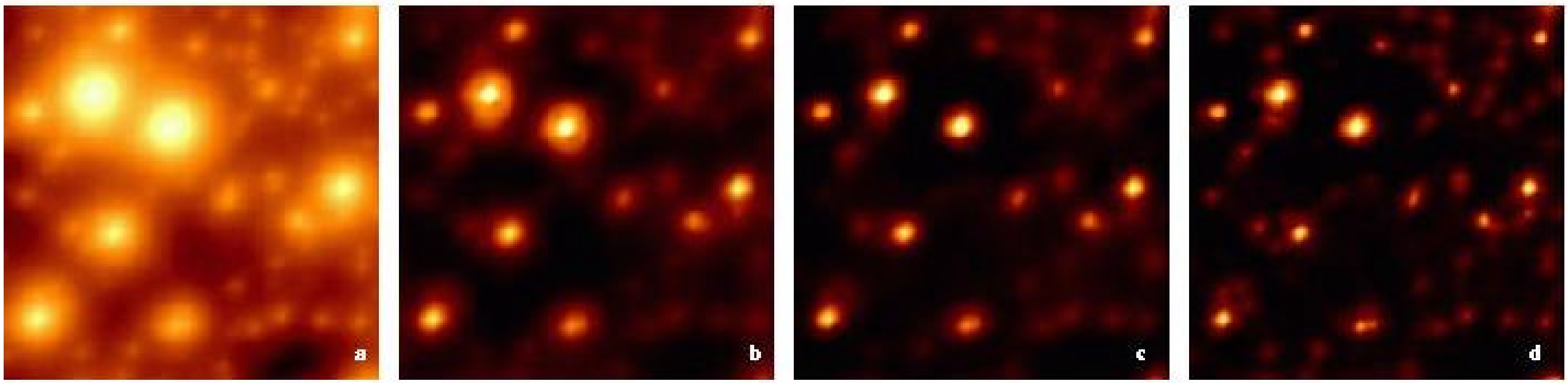
Frame PSF recovered by isolating individual star from ***f(r)*** and convolving with recovered PSFs, ***h(r)***.



Gemini Imaging of the Galactic Center
Further Object Recovery

- Data Reduction Outline
  - “Blind” Deconvolution to obtain target & PSF
  - Estimate PSF from isolated star and ***h(r)***
  - “Known” Deconvolution using estimated PSF
  - “Blind” Deconvolution to relax PSF estimates

Gemini Imaging of the Galactic Center Object Recovery



Average observation,

initial “***idac***” result,

fixed PSF result,

final “***idac***” result

Gemini Imaging of the Galactic Center
Image Sharpening

FWHM

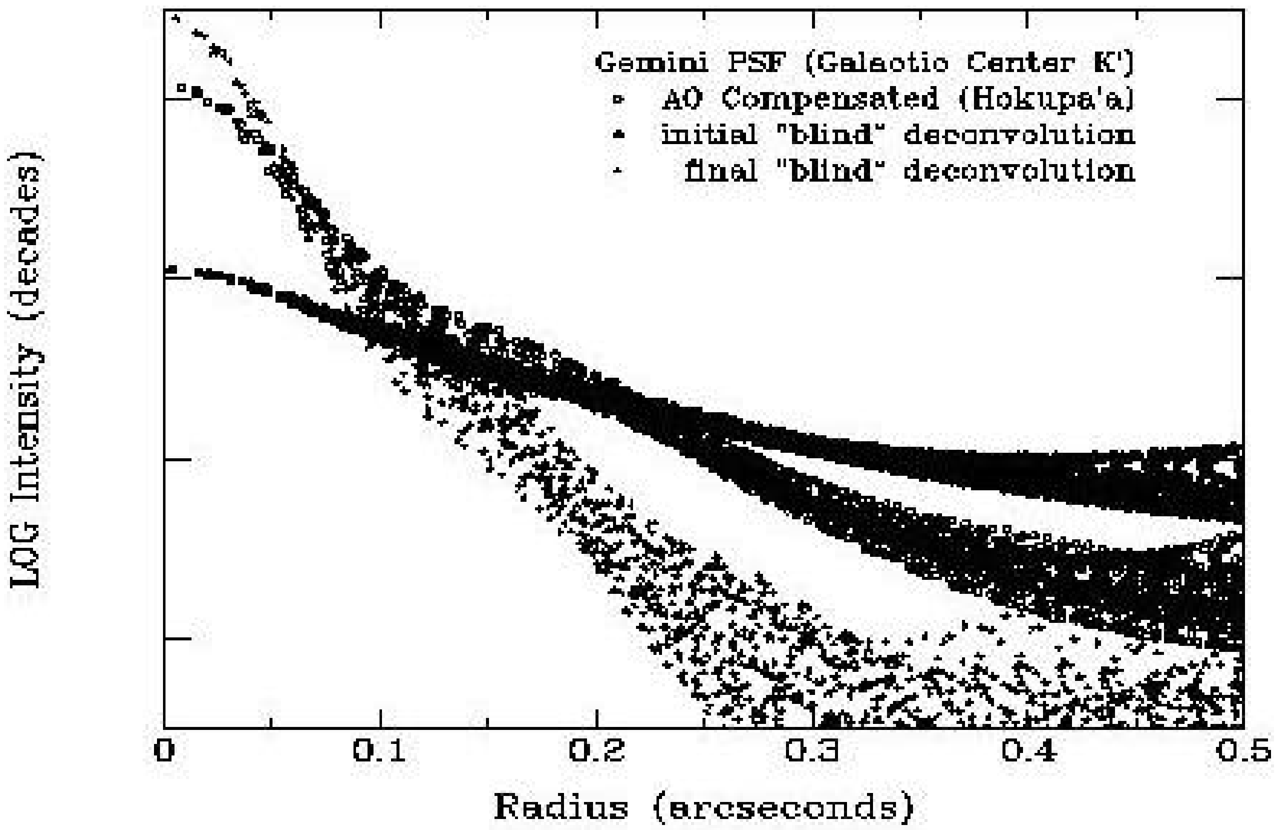
Compensated –

0.20 arcsec

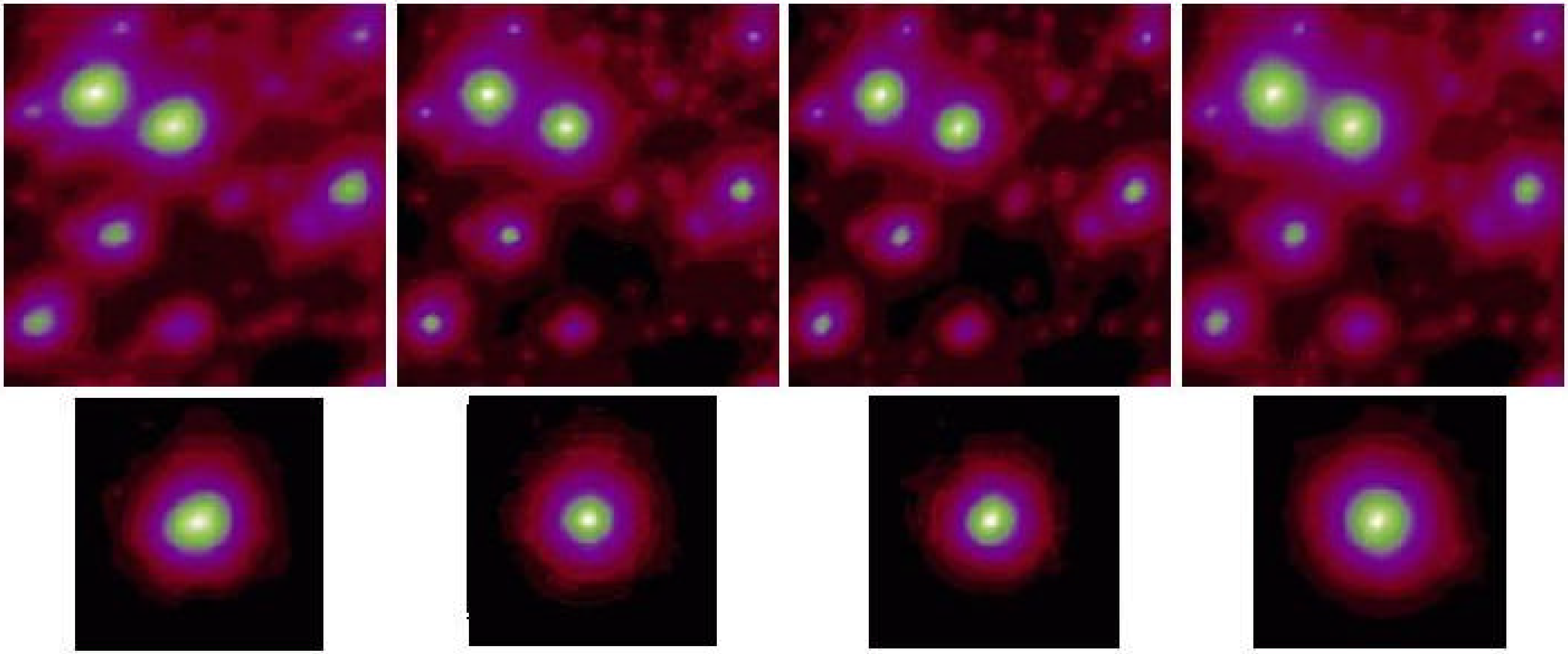
Initial - 0.07 arcsec

Final - 0.05 arcsec

á = 0.06 arcsec

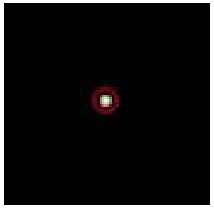


Gemini Imaging of the Galactic Center
Crowded Field Reconstructed PSFs



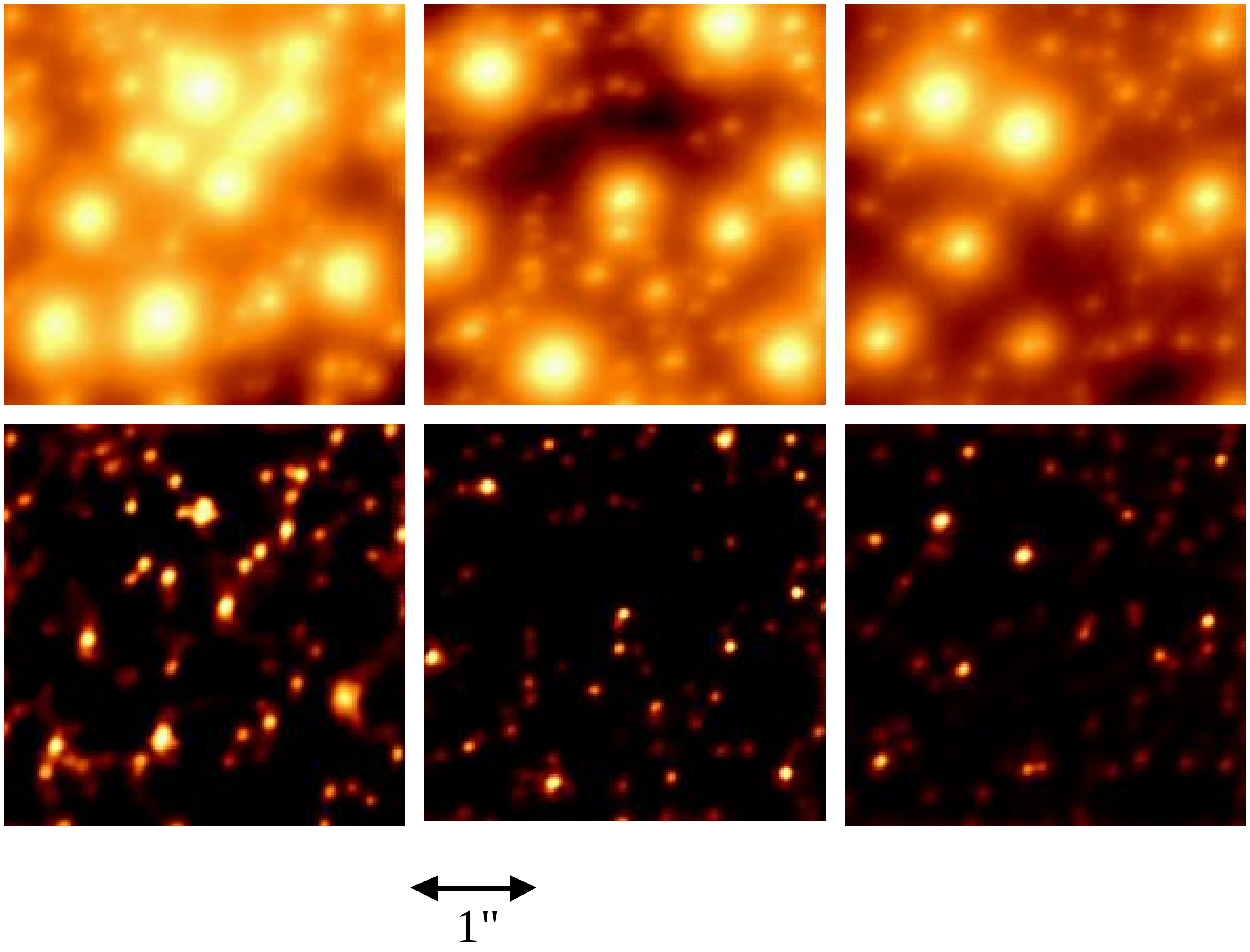
FWHM:	0.22"	0.15"	0.15"	0.18"
Strehl:	2.5%	3.5%	4.1%	2.4%

Top: Observations of the subfield 3



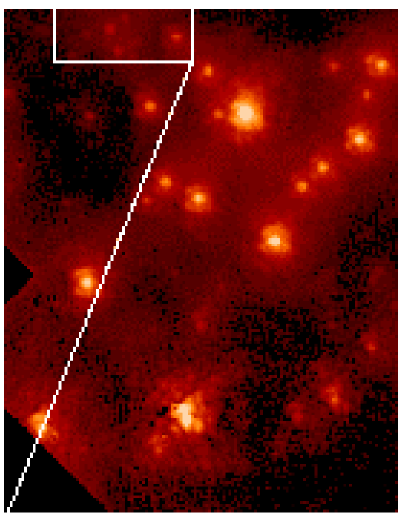
Bottom: Reconstructed PSFs

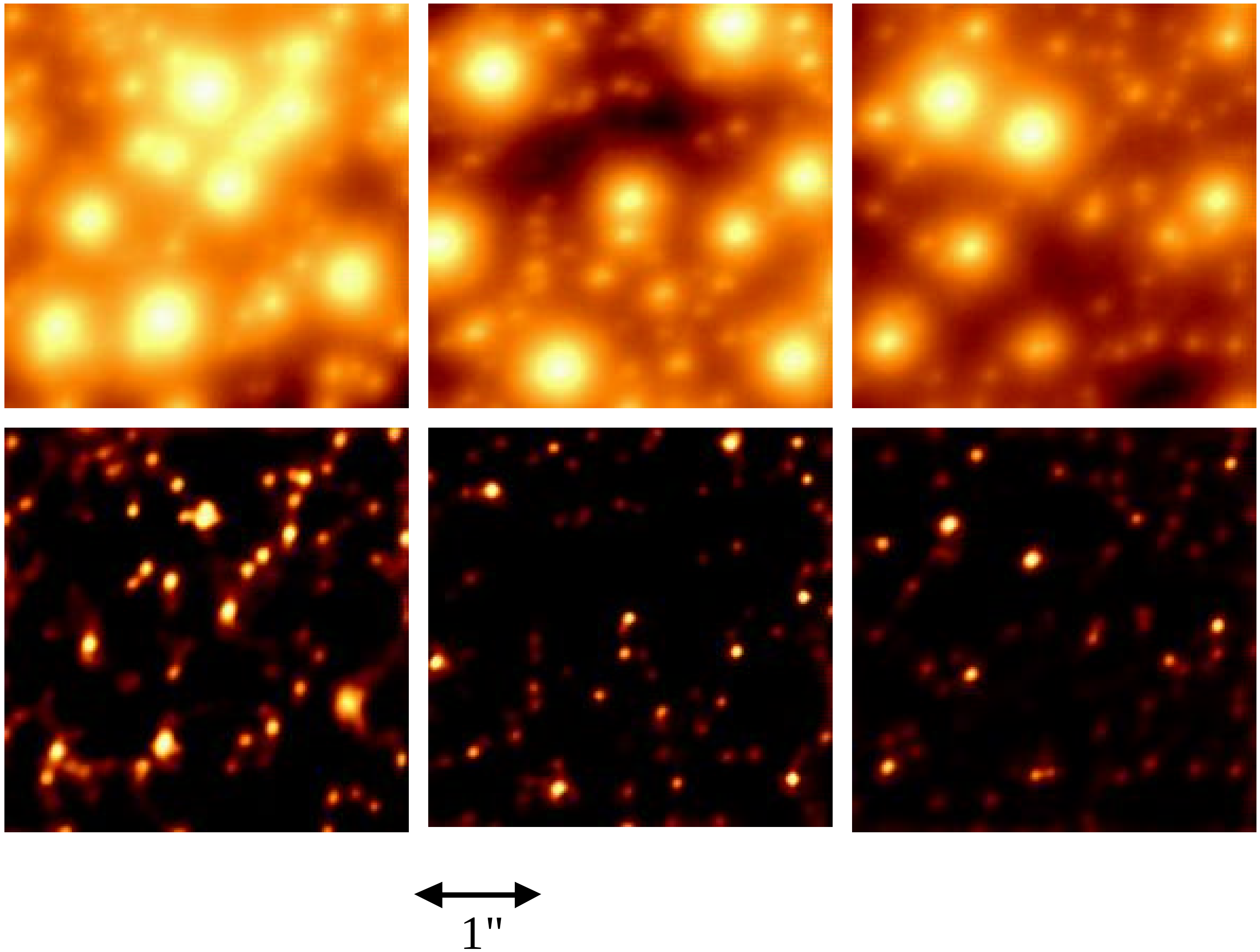
Gemini Imaging of the Galactic Center
Final Reconstructions



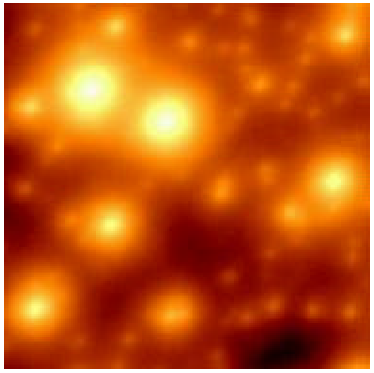
Gemini Imaging of the Galactic Center
Final Reconstructions

Keck Image
(A. Ghez)





Gemini Imaging of the Galactic Center Photometry & Astrometry

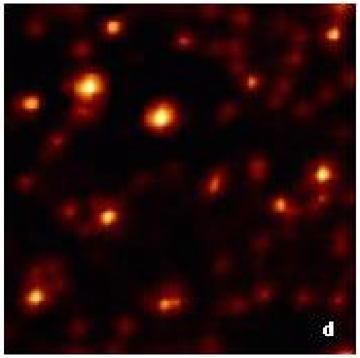


- "***Starfinder***" – without deconvolution on the four frames of Subfield 3

  - Let "Starfinder" generate it's own PSF
  - Use PSFs generated from "***idac***"

  - Generate mean photometry and astrometry

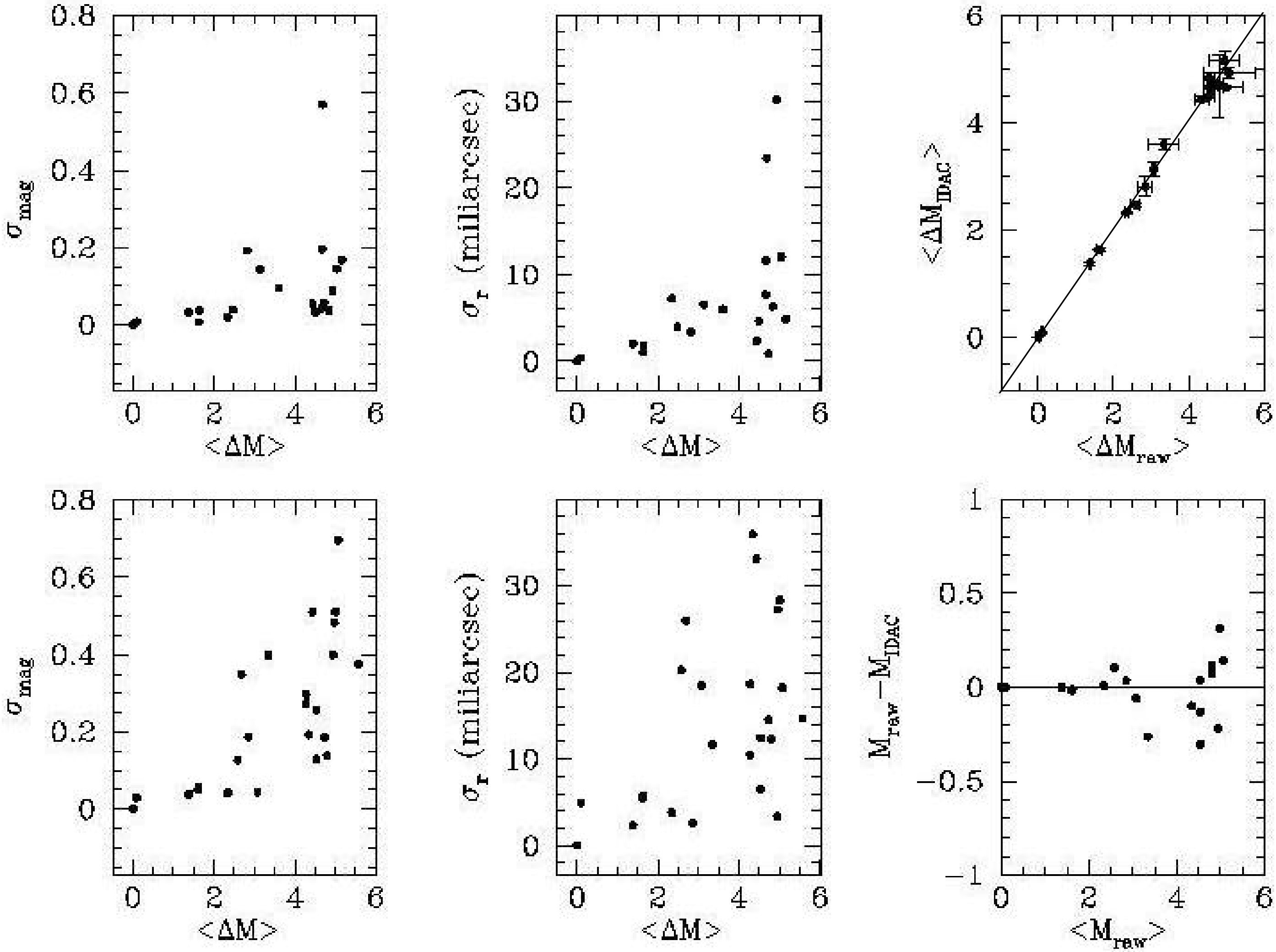
All analysis Sasha Hinkley (UCSC/CfAO)



Gemini Imaging of the Galactic Center
Photometry & Astrometry

“***idac***” PSFs

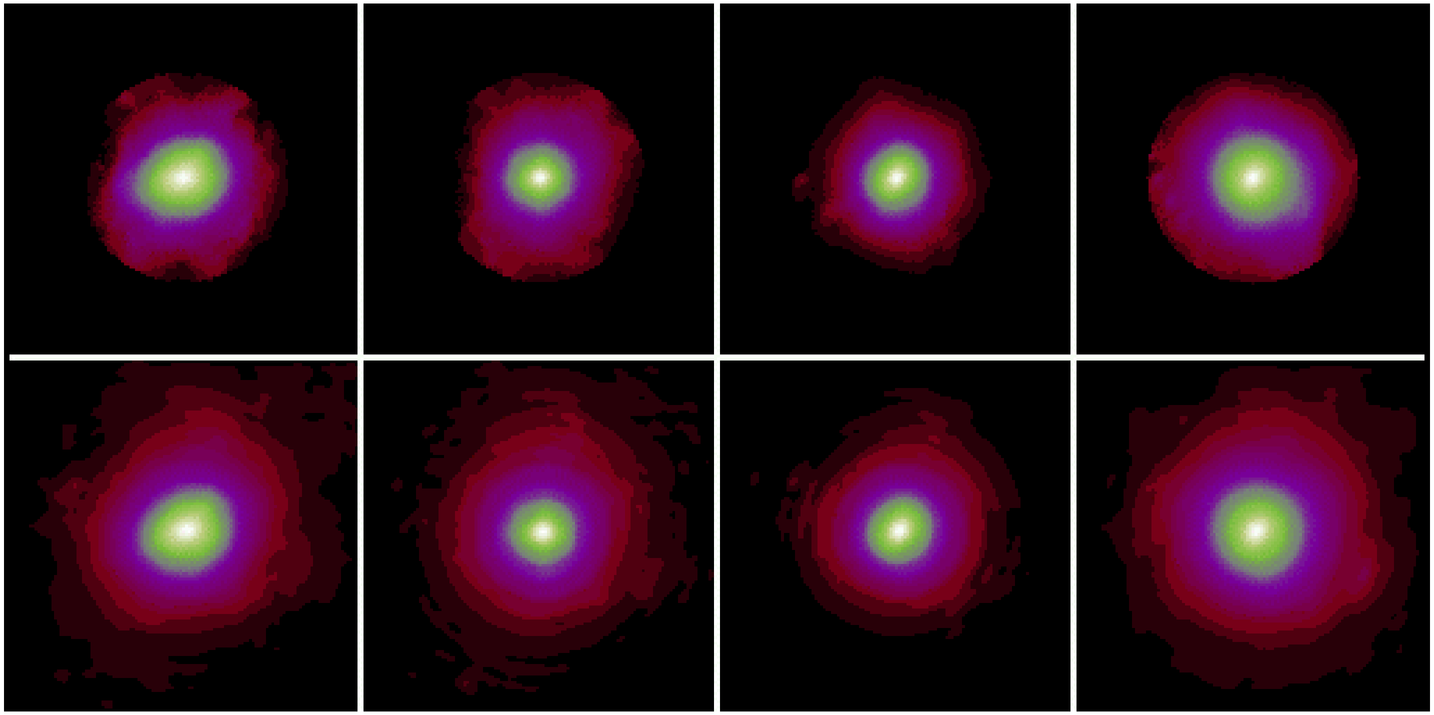
“***Starfinder***” PSFs



Gemini Imaging of the Galactic Center
Point Spread Functions

"***Starfinder***" PSFs

"***idac***" PSFs



Gemini Imaging of the Galactic Center
Photometry & Astrometry

Summary:

- The "***idac***" PSFs produce smaller uncertainties of astrometry ~ 10 mas cf. ~ 20 mas especially for the fainter sources.

- The "***idac***" PSFs produce smaller uncertainties of photometry ≤ 0.2 mag cf. ≤ 0.6 mag especially for the fainter sources.

Summary

idac **–** Successfully applied for object and PSF recovery from AO data.

- Caveat – Forward modeling of the imaging process is necessary for obtaining good photometry. This includes flat-fielding and background subtraction.

– Future developments

Symmetry Breaking

- Pupil Constraint (PSF is power spectrum of complex pupil)

  incorporate ***psfcal*** into ***idac***

- Object Modeling

  Multiple Point source field - $\Sigma A_i \delta(x-x_i, y-y_i)$

  Asteroid ellipsoidal figure

Noise Regularization

- Autocorrelation Function metric – looks at structure of residuals

$$E_{\mathrm{ACF}} = \Sigma_{ik} \mathrm{ACF}^2[g_{ik} - (f'_i * h'_{ik})]$$

- Object regularization

  Pixon based schemes

  object smoothing - $f'_i = a^2 * k$