PALAO/PHARO Observer's Workshop

February 12, 2002

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Presented by

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Workshop goals

- Improve science for PALAO/PHARO
- Share observing wisdom and 'best practices'
  - Participants input essential
- Disseminate PALAO/PHARO capabilities to a wider audience
- Improve proposal quality and provide resources for proposers

Workshop agenda

• Adaptive optics science	Dekany
• Basic PALAO operation	Burruss
• Basic PHARO operation	Burruss
• Factors affecting AO performance	Troy
• Break	
• Imaging	Troy
• Spectroscopy	Bouchez
• Coronagraphy	Dekany
• Future directions	Dekany

Adaptive optics science

Richard Dekany
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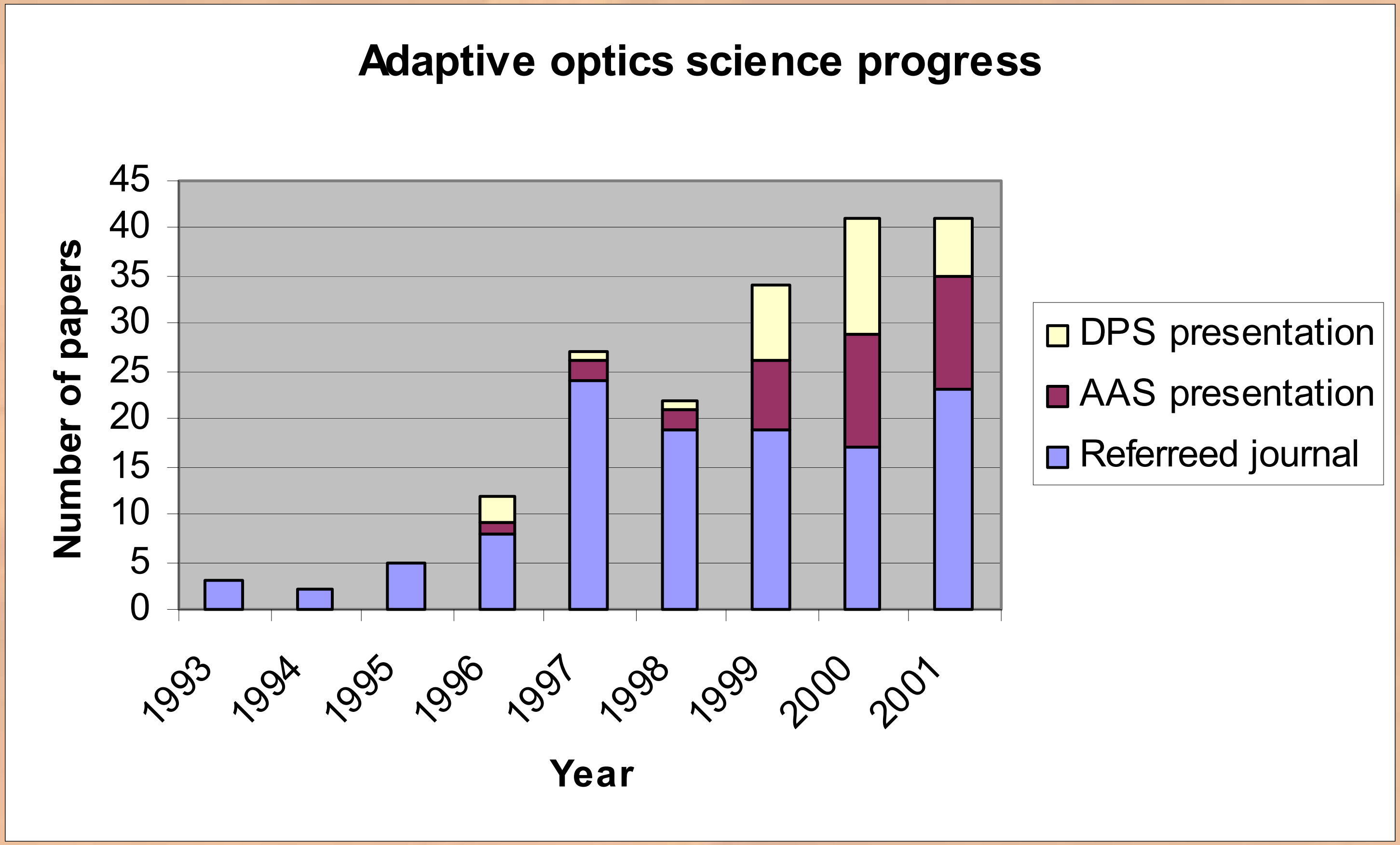
AO Science Outline

- Science opportunities
- AO advantages
- AO limitations
- Caltech AO program
- PALAO/PHARO status
- AO Observation Preparation



- 1993 – 1999 Journal statistics compiled by Wizinowich and Ridgeway
- 2000 – 2001 Journal statistics estimated by Dekany
  - Specific AO science results in ApJ, A&A, AJ, Icarus, PASP
- 1996 – 2001 AAS and DPS meeting statistics estimated by Dekany

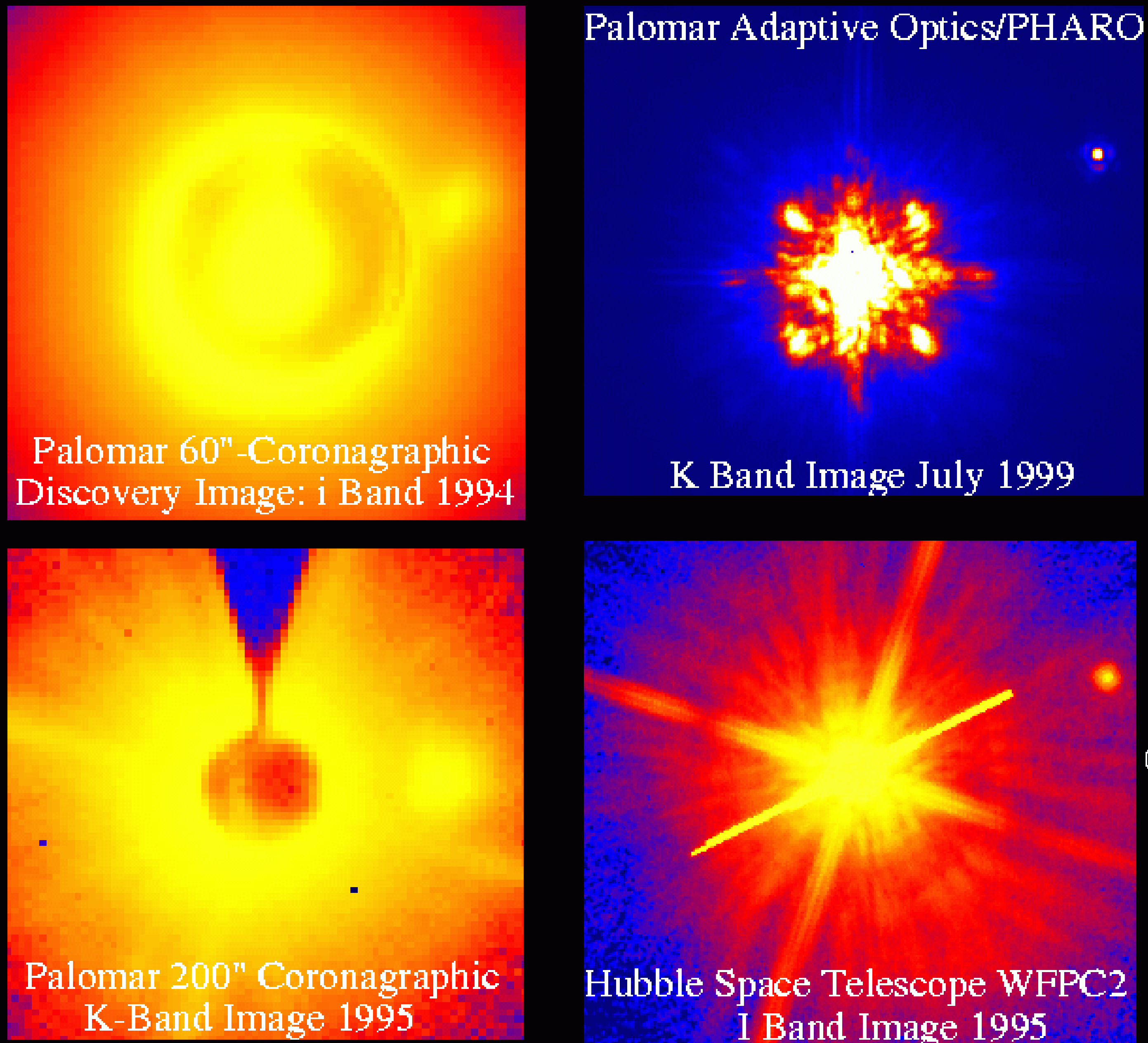
Example PALAO/PHARO solar system observations*

Object	Diameter or Separation (arcsec)	K-band Resolution (km)	J-band Resolution (km)	Reference Source**	mV	Distance (arcsec)
1 Ceres	0.8	101	58	Ceres	7.4	
2 Pallas	0.65	75	43	Pallas	7.3	
4 Vesta	0.6	84	48	Vesta	5.9	
216 Kleopatra	0.2? (sep.)	132	75	Kleopatra	10.2	
624 Hector	0.1 (sep.)	264	150	Hektor	14.2	
Venus	55	22	13	Hot spots?	mK~4	
Mars	20	29	16	I (Phobos)	11.3	< 25
				II (Deimos)	12.4	< 65
Jupiter	49.5	264	150	I, II, III, or IV	4.5-5.6	< 140 (I)
Io	1.2	264	150	Io or other sat.	5	
Saturn	20.5	528	300	I to VI & VIII	8.3-12.9	< 30 (I)
Titan	0.85	528	300	Titan	8.3	
Uranus	4.3	1056	600	Uranus	5.9	
				III (Titania)	13.7	< 17
Neptune	2.9	1496	850	Neptune	7.7	
		1496	850	I (Triton)	13.5	< 17
Pluto/Charon	0.7 (sep.)	2464	1400	Pluto	~14	
KBO's, TNO's, etc.	?	?	?	Conjunctions / LGS only		

* Ring systems not included

** Stellar and asteroid conjuctions are also possible

Images of the Gliese 105AC System

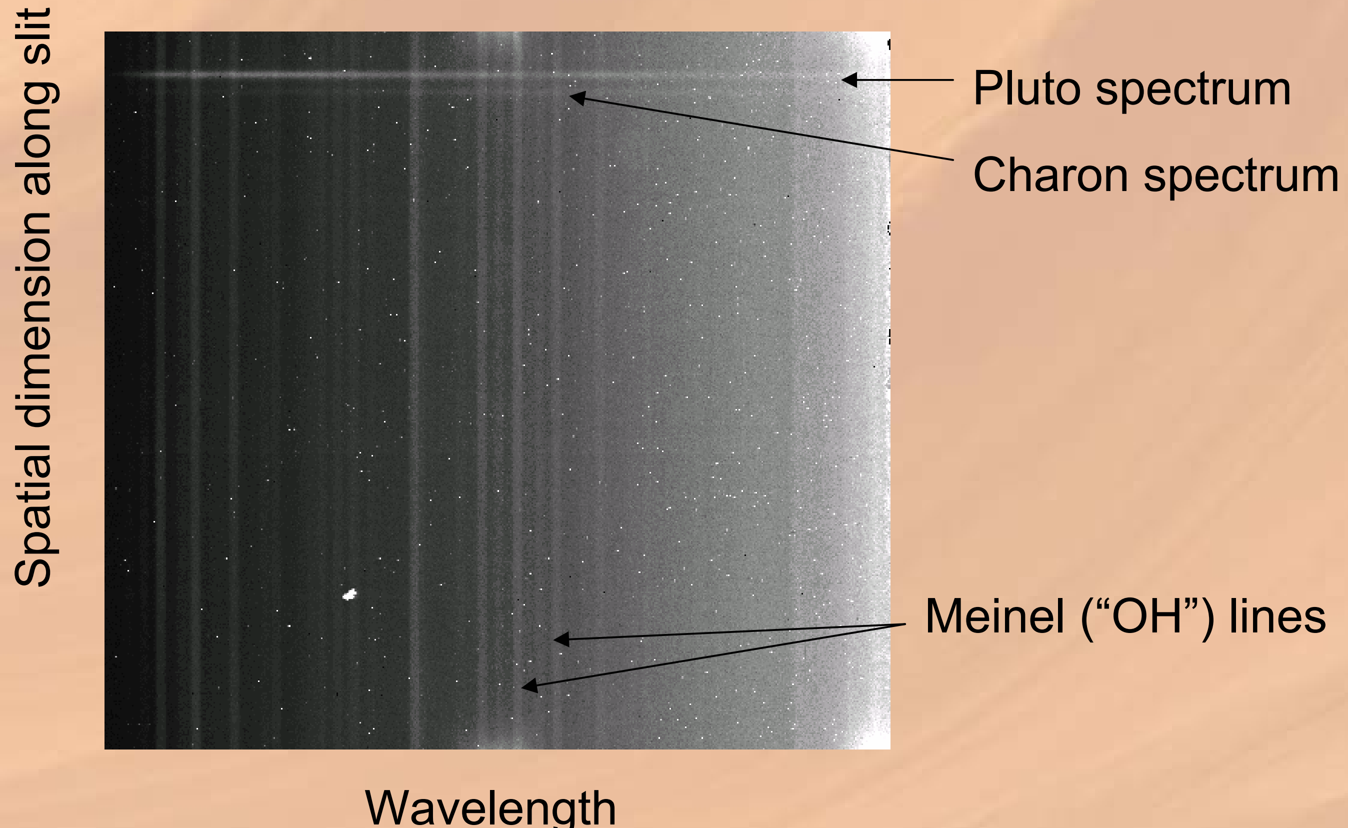


Pluto/Charon

Raw spectra taken using an mV=7 guide star during a chance 75” conjunction

Pluto K-band FWHM measured at 0.25” in 1” seeing (for on-axis Strehl ~50%)

(0.8” planet separation clearly resolved)



Adaptive optics benefits

- Improved angular resolution (✪ D/r_0)
  - Resolves nearby bodies
  - Reduces confusion in crowded fields
  - Improves astrometric precision (to the order of a few mas)
- Improved sensitivity
  - SNR change (pixel size matched to image size):

	Signal noise limited	Read-out limited	Background limited
Unresolved target	Even	Even	Gain as $S^*(D/r_0)$
Resolved target	Even	Lose as $S^{2*}(D/r_0)^2$	Lose as $S^*(D/r_0)$

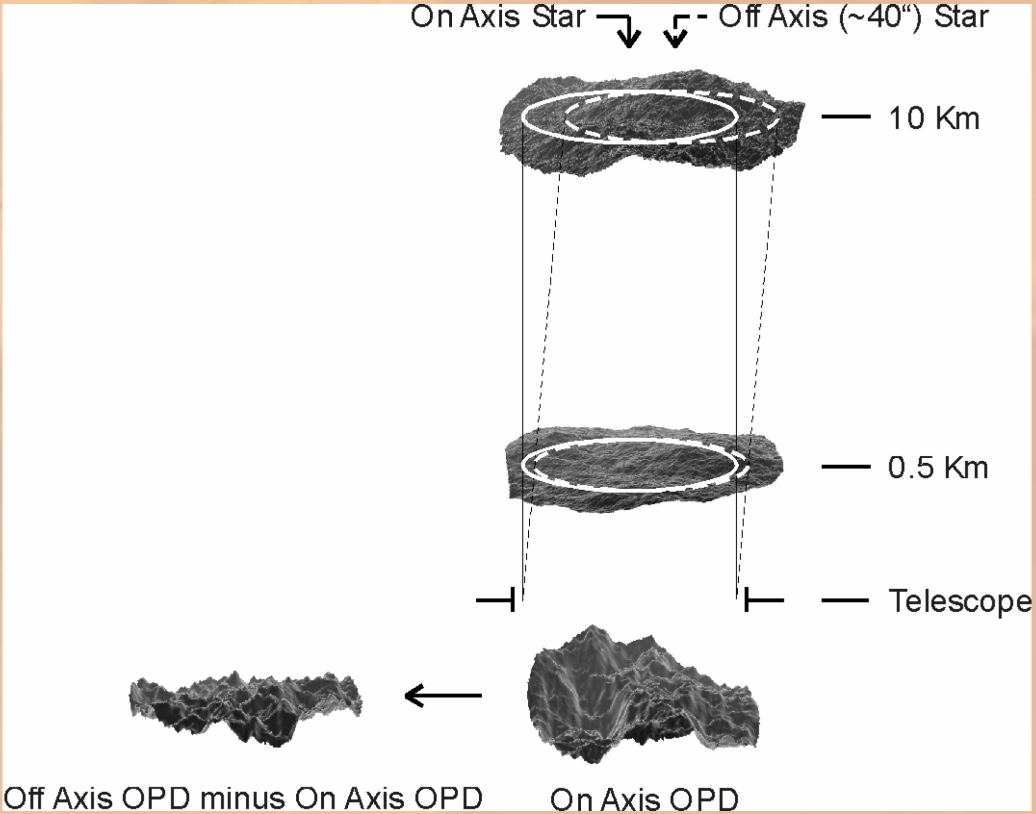
Adaptive optics benefits (cont.)

- Improved contrast
  - For primary star Strehl ratio, S
  - Reduce stellar halo flux / $asec^2$ by factor ~ 1 / (1-S)
  - SNR of companion detection:
    - Unresolved target signal gain (previous slide) is S* (D/r_0)
    - Stellar halo photon noise reduction is sqrt (1/(1-S))
    - Contrast SNR improves as (D/r_0) * sqrt $(S^2/(1\text{-}S))$
      - Good ground detection needs: big scope, good site, and **high Strehl**
    - Practical contrast limits usually dominated by primary figure errors and halo speckle noise before the halo photon noise limit is reached
      - So we also want a high spatial bandwidth, low temporal bandwidth primary corrector
- Improved coherence
  - Reconstruction of coherence core allows efficient coupling to single mode fibers
  - Enables deconstructive interferometry (e.g. nulling)

Adaptive optics costs

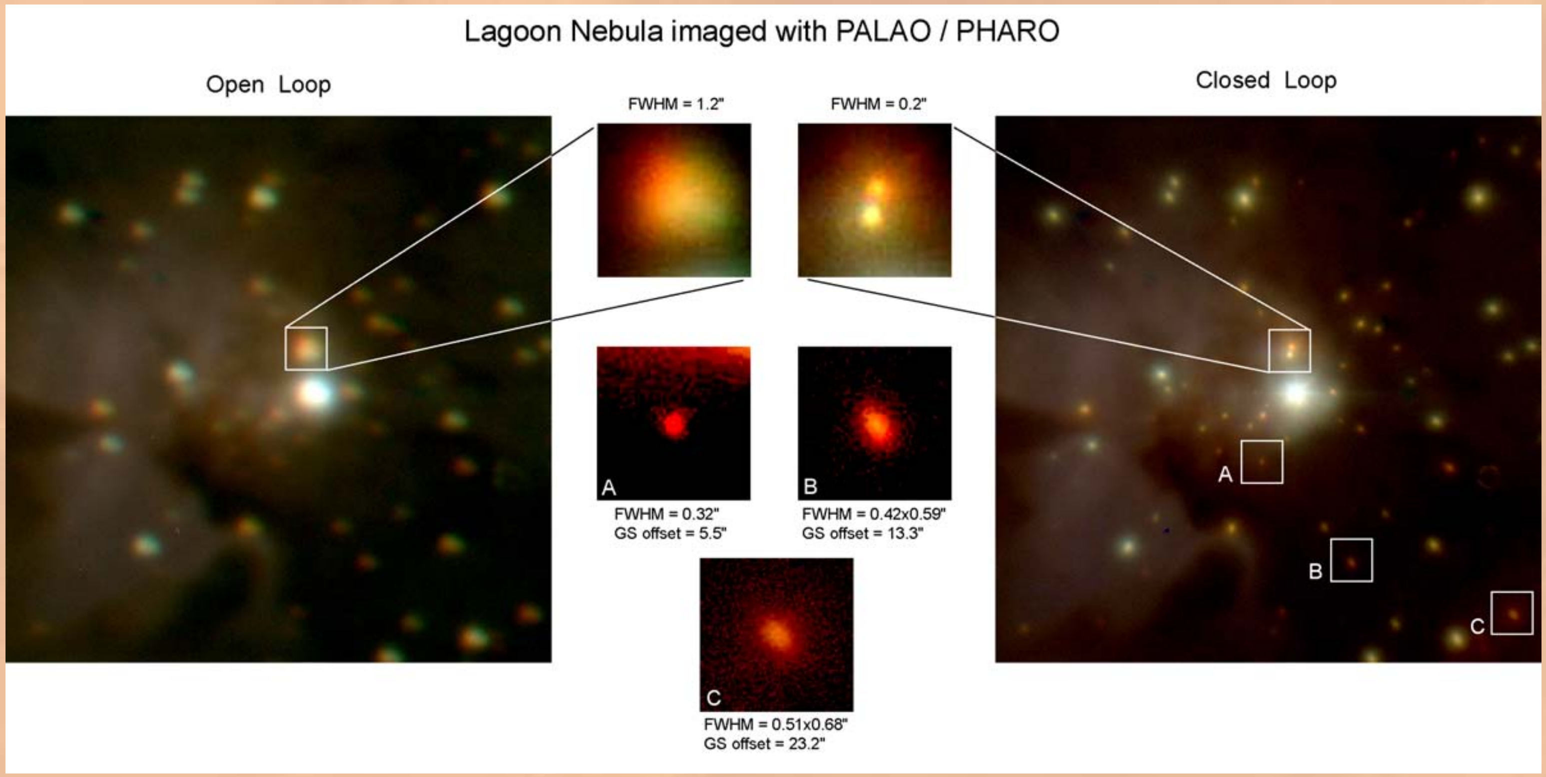
- Requires a sufficiently bright guide star
  - Guide star of mV = 11 or brighter needed for median seeing
    - For excellent (0.5” K-band) seeing, partial correction has been achieved with mV = 13.5 at 50Hz operation
- Correction is not constant over wide fields-of-view
  - Strehl degrades ~ $(\theta/\theta^*)^{-5/3}$ where θ is distance from the guide star and θ^* is a function of λ and seeing (typ. 50” for K-band)
    - Partial correction possible at large offsets (limited by acquisition range (40” radius) and AO relay vignetting (begins at 45” radius))
  - Complicates crowded field photometry and deconvolutions
- Reduced transmission
  - PALAO/PHARO science transmission (incl. telescope) ~ 45% (per T. Hayward)
- Increased emissivity
- Increased observing overheads
- Increased preparation and post-processing effort

Anisoplanatism



- Wavefront corrections measured for one direction in the sky are not applicable some angular distance away (the isoplanatic angle)

Example of anisoplanatism with AO



- Composite J, H, K band image, 30 second exposure in each band
- Field of view is 40”x40” (at 40 mas/pix)
- On-axis K-band Strehl ~ 40%, falling to 25% at field corner

Caltech/JPL AO program goals

- Improved optical/IR science at Palomar
  - Increase observing efficiency, particularly for spectroscopy
    - SNR per unit time of observation
  - Enable new observations
    - Increased spatial resolution and contrast
- Develop AO technologies required for CELT
  - Demonstrate make-or-break technologies prior to start of major CELT construction
  - Reduce technical and financial risk by prototyping systems in low-cost environment
- Develop a mature science/technology community to guide AO/instrumentation program direction

Caltech Adaptive Optics Group

(February 2002)

- Baranec
- Beichman
- Bouchez
- *Brack*
- Britton
- Brown
- Dekany
- Eisner
- Ellis
- Hillenbrand
- *Koresko*
- Kulkarni
- *Levine*
- *Lowrance*
- MacMartin
- Murray
- Osario
- Petrie
- *Serabyn*
- *Shi*
- Taylor
- Thrasher
- *Troy*
- Trujillo
- *Truong*
- *Trinh*
- *Wallace*

Science / Technology / *JPL*

PALAO Status

- Current AO performance
    - Visible seeing of 1 arcsec, v_{wind} = 13 m/s, bright guide star (mV < 8)
        - Band / Strehl / Diffraction limited FWHM (~λ/D)

Band	Strehl	Diffraction limited FWHM (~λ/D)
K	~50%	0.091 arcsec
H	~25%	0.068 arcsec
J	5-10%	0.052 arcsec

    - Best Strehl to date ~70% K-band
  - Lock achieved on mV ~ 13.5 at slow correction rate
    - Partial correction from 0.7 arcsec to < 0.2 arcsec $FWHM_K$
  - Routine static correction of telescope aberrations
    - Image quality improved from 0.7 arcsec to 0.4 arcsec $FWHM_K$
    - Available for any target, no SNR penalty if background limited, but suffers from transmission losses and increased emissivity

PALAO Status (cont.)

- Current Strehl limitations and activities
  - Calibration of PSF limits max K band Strehl at ~92% (+-5%)
  - In fast winds, high order correction bandwidth is the limitation
    - Dominated by computer latency
      - Computer upgrade is planned during FY02
  - For long exposures, image drift due to internal flexure is the limitation
    - Error is approximately 5 mas/min, depending on position in sky
      - Metrology system is designed, but awaiting tests on repeatability of image motion due to flexure
  - In poorest seeing, total stroke available sets limit for operation
    - System not operable in worse than ~ 2 arcsec $FWHM_K$
    - Currently, about 1/4 of available deformable mirror stroke used to correct static telescope aberrations

AO Observation Planning

- Guide stars catalog searches
- Understanding the PSF
- Proposal checklist

Star catalogs for guide star search

(After B. MacIntosh, CfAO 2001 Summer School)

Catalog	Mag Limit	Spectral information	Notes
SAO/PPM	9	Types	Old, bright stars Good for quick PSFs
Hipparcos	9	Colors	Very accurate, available as IDL file
Tycho 2	11-12	Colors	Very accurate
HST Guide Star	15	None	Unreliable but good near bright stars, locally searchable in IRAF – B. Macintosh willing to provide scripts
USNO A2.0	20	Colors	Incomplete near bright stars; Vizier limits large searches

AO planning tools

- VizieR
  - Has the ability to do constrained searches – limited in position, magnitude, etc. – from a list of input targets
    - Results can be read into IDL or spreadsheet for sorting and processing
    - http://vizier.u-strasbg.fr/viz-bin/VizieR
- Horizons
  - Generates ephemeredes of many solar system objects
    - http://ssd.jpl.nasa.gov/horizons.html
    - Additional information (close-approach tables) available via email or telnet (not via web interface)
- Stellar occultations
  - Predictions up to 2050 available
    - http://tdc-www.harvard.edu/occultations/
- TNO appulse events (conjunctions)
    - http://astron.berkeley.edu/~fmarchis/Science/TNOs_Appulse/
- AO community is still (2/02) missing a general small-body guide star solver (i.e., when is *any* object near a faint science target)

Proposal checklist

- Before submitting a PALAO/PHARO proposal, ask:
  - Expected image quality
    - What image quality is required for my science?
      - What is the minimum Strehl ratio, Strehl stability FWHM, and/or encircled energy?
      - Is this consistent with my guide star brightness, offset, airmass, and expected (hoped for) seeing?
  - Guide star
    - Is the guide star magnitude sufficient for the image quality expected (brighter than mV = 11 (median seeing) or mV = 13.5 (exceptional seeing))?
    - Is the guide star offset consistent with the image quality expected (max offset ~ 80 arcsec (corner-to-corner), effective isoplanatic angle (K-band, typ.) θ^* ~ 50 arcsec.
    - Will I need to offset beyond ~50 arcsec? (This may require special Cass ring rotation.)
    - Is the guide star an extended object or of spectral type O, B, or A? (Requires special wavefront sensor settings)

Proposal checklist (cont.)

- PSF calibrations
  - What is my PSF calibration strategy (Cass ring rotation, reference star, telemetry, other?)
  - What is the impact an anisoplanatism on the photometry? The morphology?
  - What are my postprocessing steps for PSF halo suppression?
- Observing time
  - Have I accurately estimated the overhead for my particular observing strategy?
  - Have I requested the correct telescope operator hours (particularly for sky flats?)
- Misc
  - How will I calibrate the sky fluxes (offset skies, dithering, other?)
  - How will I calibrate detector response variations?
  - What plate scale is required?

Basic PALAO Operation

Rick Burruss
rsb@bigeye.palomar.caltech.edu

PALAO/PHARO Adaptive Optics

- Mounted at the 200” Cassegrain focus (f/16)
- Consists of AO optical bench and IR camera
- Palomar staff operates Adaptive Optics
- Observer operates the IR camera (PHARO)
- Palomar engineers support / assist operators and observers
- JPL engineers assist as needed

Palomar Staff

- Jean Mueller / Senior Telescope Operator
- Karl Dunscombe / Telescope Operator

- Rick Burruss / Instrument Engineer
  rsb@bigeye.palomar.caltech.edu

- Jeff Hickey / Instrument Engineer
  jhickey@astro.caltech.edu

Telescope Operators Responsibility

- Telescope / instrument safety, telescope pointing, observer assistant

- All Adaptive Optics operations
  - Guide star acquisition
  - AO tuning

Observer Responsibility

- IR camera operation (PHARO)
- Help telescope operator monitor AO performance
- Data backup

Palomar Engineer Responsibility

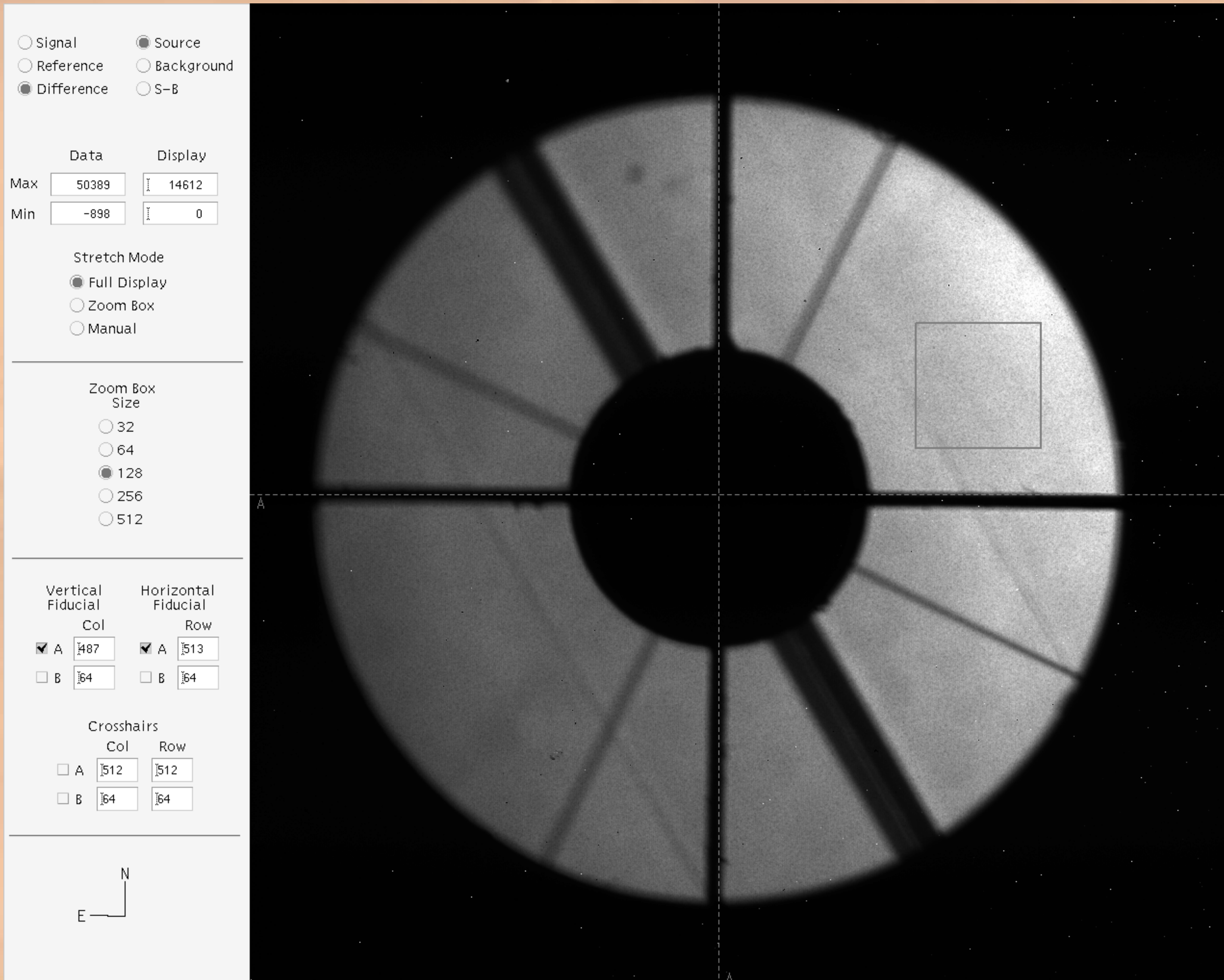
- Support / assist AO operator in adaptive optics operation and performance
- Support / assist observer in PHARO operation
- Available from noon until first half of night every day

AO Operations (brief description)

- First Day / Night of AO run
- Start of Each Night
- Nightly AO Tuning

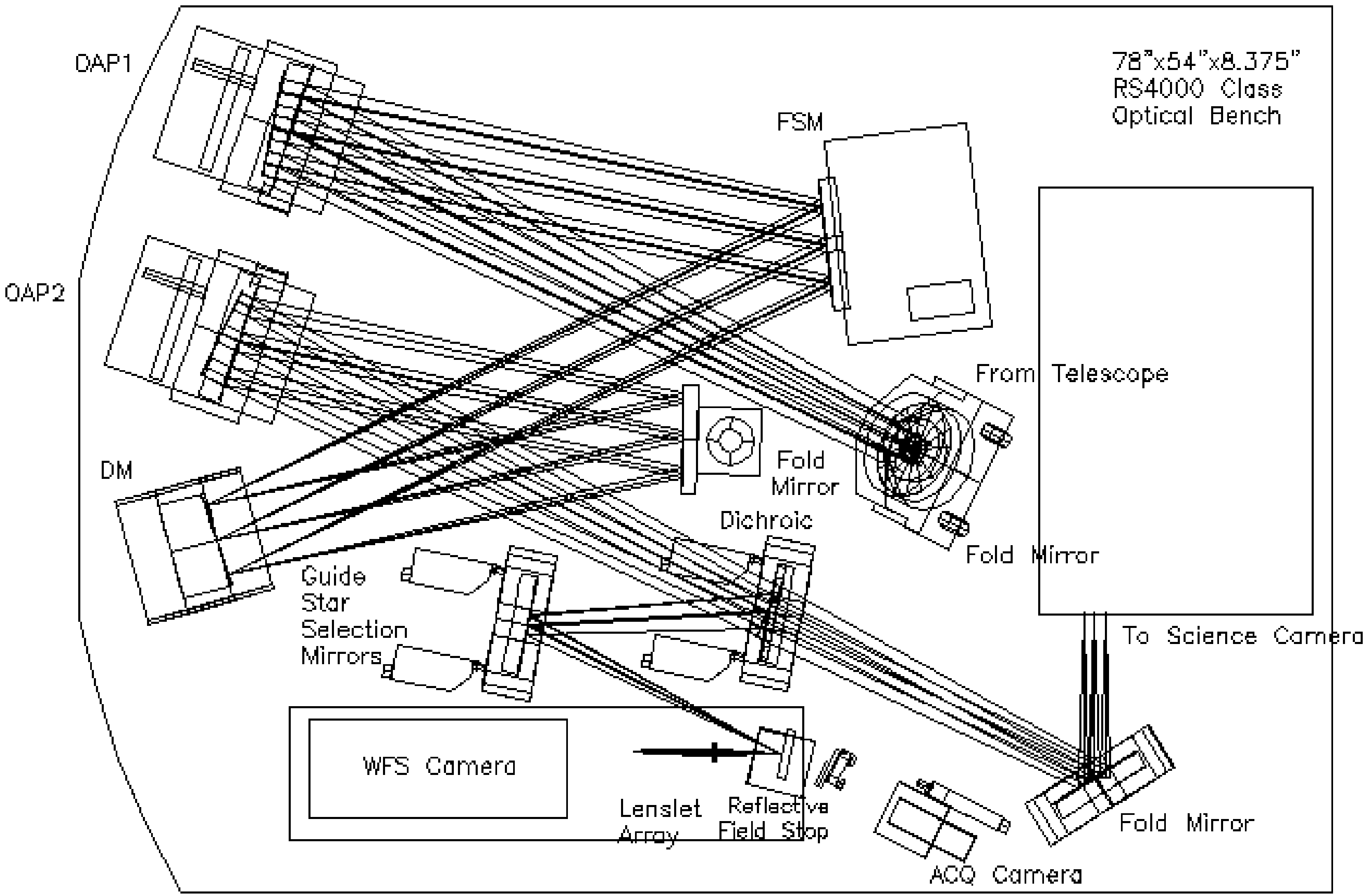
First Day / Night Of AO Run

- Telescope / AO / Pharo alignment
  - Translation and rotation between telescope spiders, prime focus cage, and Pharo Lyot stop
  - Cassegrain ring rotation away from nominal (north up / east left) may result in misalignment
  - Alignment done once per AO run
  - Alignment done by Palomar engineers


Signal
Source
Reference
Background
Difference
S-B
Data
Display
Max
50389
14612
Min
-898
0
Stretch Mode
Full Display
Zoom Box
Manual
Zoom Box Size
32
64
128
256
512
Vertical Fiducial
Horizontal Fiducial
Col
Row
A
487
A
513
B
64
B
64
Crosshairs
Col
Row
A
512
512
B
64
64
N
E
A
A

First Day / Night Of AO Run

- Sharpening AO Image
  - In perfect AO system, WFS centroids should be (0,0)
  - Non-common path errors between AO dichroic and Pharo array lead to non-zero centroids needed to produce best science image
  - We manually force zernikes on DM to improve Pharo science image to account for these non-common path errors
  - Centroid offset files are created this way for both J and K filters; either file is loaded by operator as needed to match filter in use by observer
  - Tuning done once per run by Palomar engineers



78"x54"x8.375"
RS4000 Class
Optical Bench
OAP1
OAP2
DM
FSM
From Telescope
Fold
Mirror
Dichroic
Fold Mirror
Guide
Star
Selection
Mirrors
To Science Camera
WFS Camera
Lenslet
Array
Reflective
Field Stop
Fold Mirror
ACQ Camera

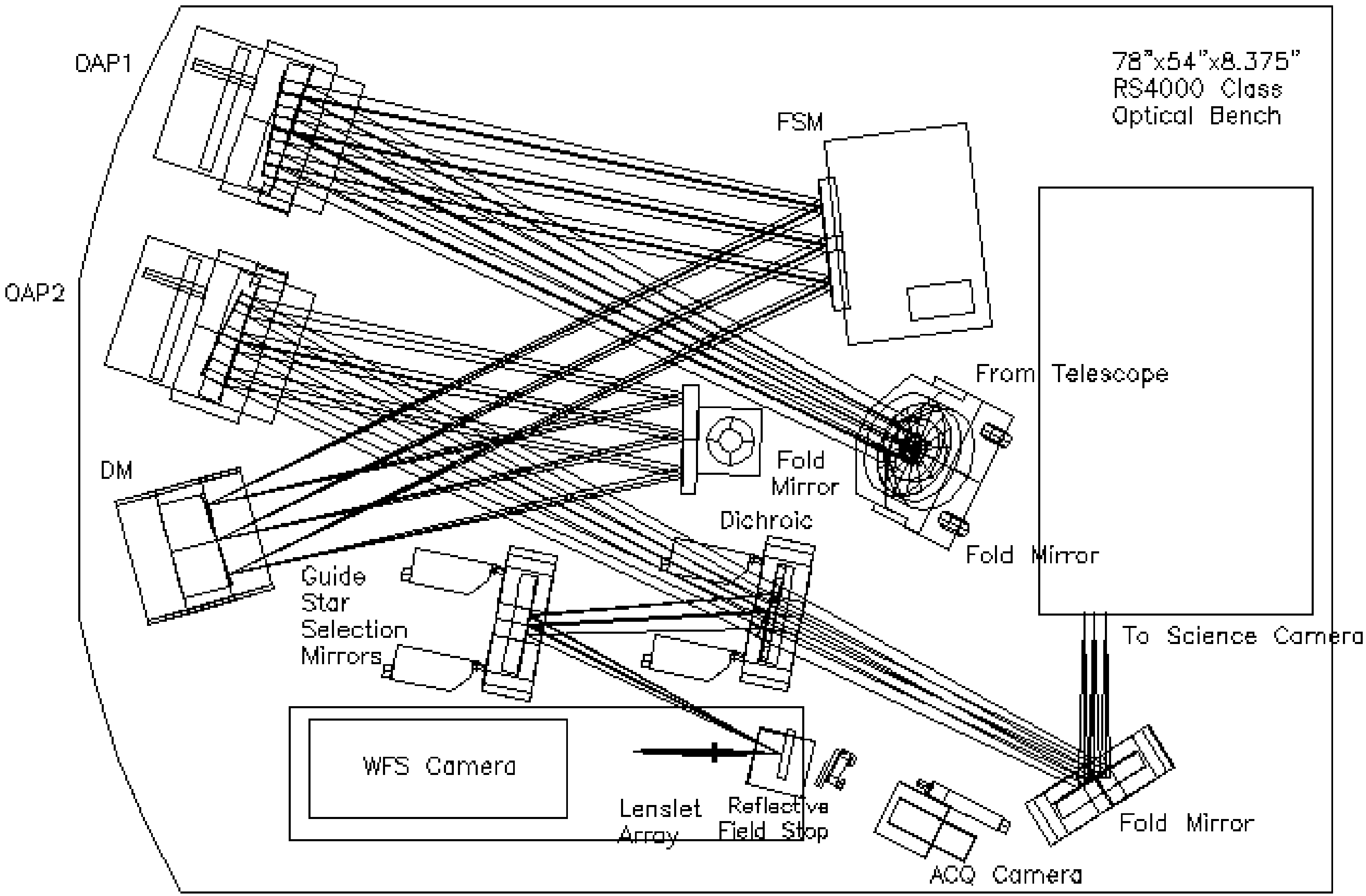
Start Of Each Night

- Sky Flats
  - Palomar staff starts AO program (5 minute start-up script)
  - Palomar staff clears path to IR camera

Start Of Each Night

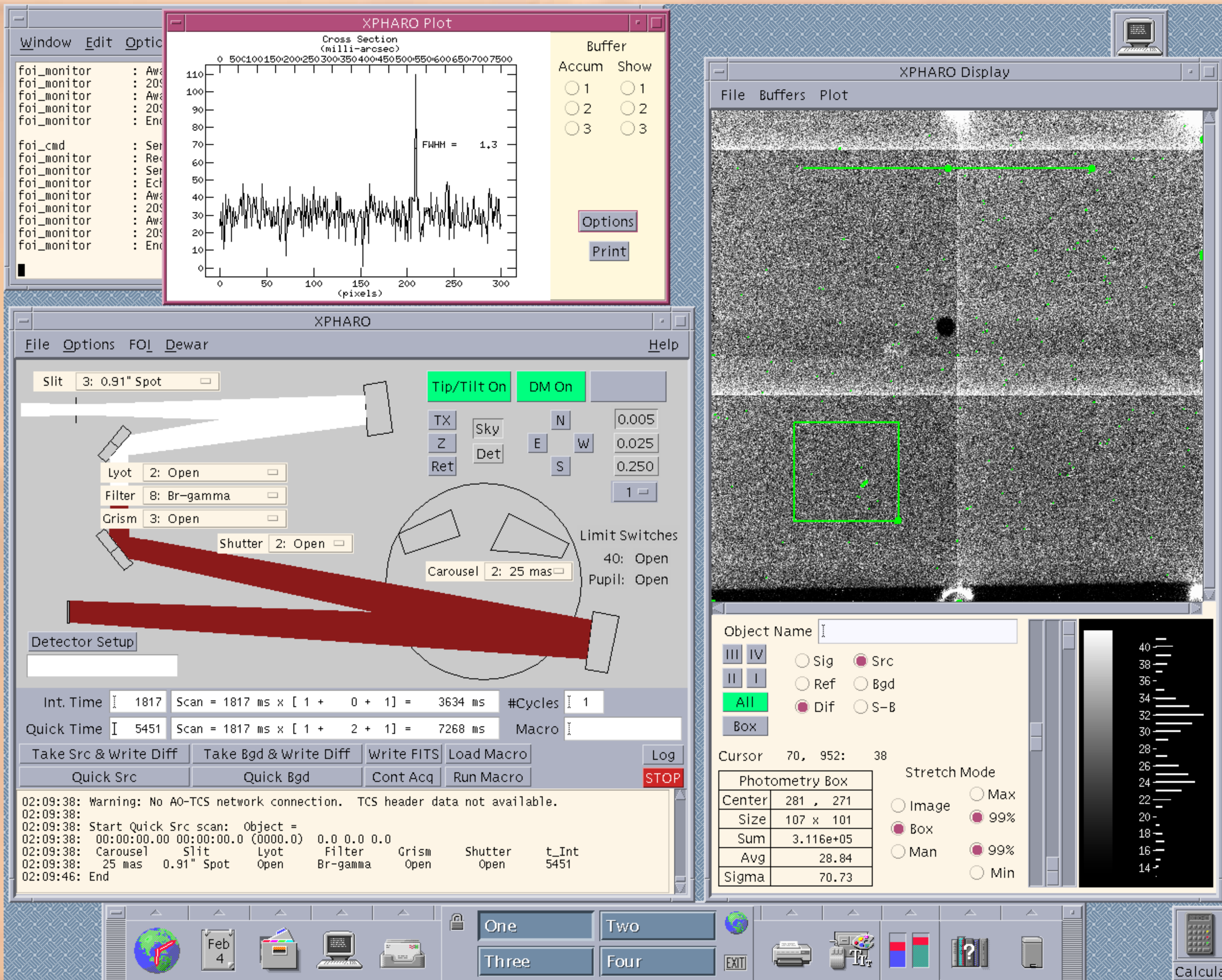
- Pointing / Initial Tuning
  - Operator points to 5th m_v G - K star
  - Operator sets telescope pointing to Field Stop
  - Operator tunes AO on this guide star
  - Telescope focus now under high order DM control
  - Science is now ready

- Total Process ~ 5 Minutes


78"x54"x8.375"
RS4000 Class
Optical Bench
OAP1
FSM
OAP2
From Telescope
DM
Fold
Mirror
Dichroic
Fold Mirror
Guide
Star
Selection
Mirrors
To Science Camera
WFS Camera
Lenslet
Array
Reflective
Field Stop
Fold Mirror
ACQ Camera

First Pointing Exposures (PHARO)

- By default, star appears in upper right quadrant
- Pointing location on array may be changed by observer
  - Must move with xpharo direction buttons while Tip Tilt and DM loops are locked (5” limit + a pause between)
- Operator can save observer’s new pointing, plus other current PALAO parameters to a file
- Movement while locked moves object on array
- Movement while unlocked moves guide star off of Field Stop


XPHARO Plot
Cross Section
(milli-arcsec)
(pixels)
FWHM = 1.3
Buffer
Accum
Show
Options
Print
XPHARO Display
File
Buffers
Plot
XPHARO
File
Options
FOI
Dewar
Help
Slit 3: 0.91" Spot
Tip/Tilt On
DM On
TX
Z
Ret
Sky
Det
N
E
W
S
0.005
0.025
0.250
Lyot 2: Open
Filter 8: Br-gamma
Grism 3: Open
Shutter 2: Open
Carousel 2: 25 mas
Limit Switches
40: Open
Pupil: Open
Detector Setup
Int. Time 1817
Scan = 1817 ms x [1 + 0 + 1] = 3634 ms
#Cycles 1
Quick Time 5451
Scan = 1817 ms x [1 + 2 + 1] = 7268 ms
Macro
Take Src & Write Diff
Take Bgd & Write Diff
Write FITS
Load Macro
Log
Quick Src
Quick Bgd
Cont Acq
Run Macro
STOP
02:09:38: Warning: No AO-TCS network connection. TCS header data not available.
02:09:38: Start Quick Src scan: Object =
02:09:38: 00:00:00.00 00:00:00.0 (0000.0) 0.0 0.0 0.0
02:09:38: Carousel Slit Lyot Filter Grism Shutter t_Int
02:09:38: 25 mas 0.91" Spot Open Br-gamma Open Open 5451
02:09:46: End
Object Name
Sig
Src
Ref
Bgd
Dif
S-B
All
Box
Cursor 70, 952: 38
Photometry Box
Center 281 , 271
Size 107 x 101
Sum 3.116e+05
Avg 28.84
Sigma 70.73
Stretch Mode
Image
Box
Man
Max
99%
99%
Min
Window
Edit
foi_monitor
foi_cmd
One
Two
Three
Four
Feb 4
EXIT
Calcula

Nightly AO Tuning

- Four Steps Of AO Tuning

  1. Guide star moved behind Field Stop
     - Telescope hand paddle or AO GUI direction buttons
  2. WFS camera rate and gain optimized
     - WFS Camera Rates = 500, 400, 250, …, 1 Hz
  3. WFS camera sky (background) taken
     - Telescope moved 60” away from guide star
  4. DM / WFS alignment registered
     - Automated procedure

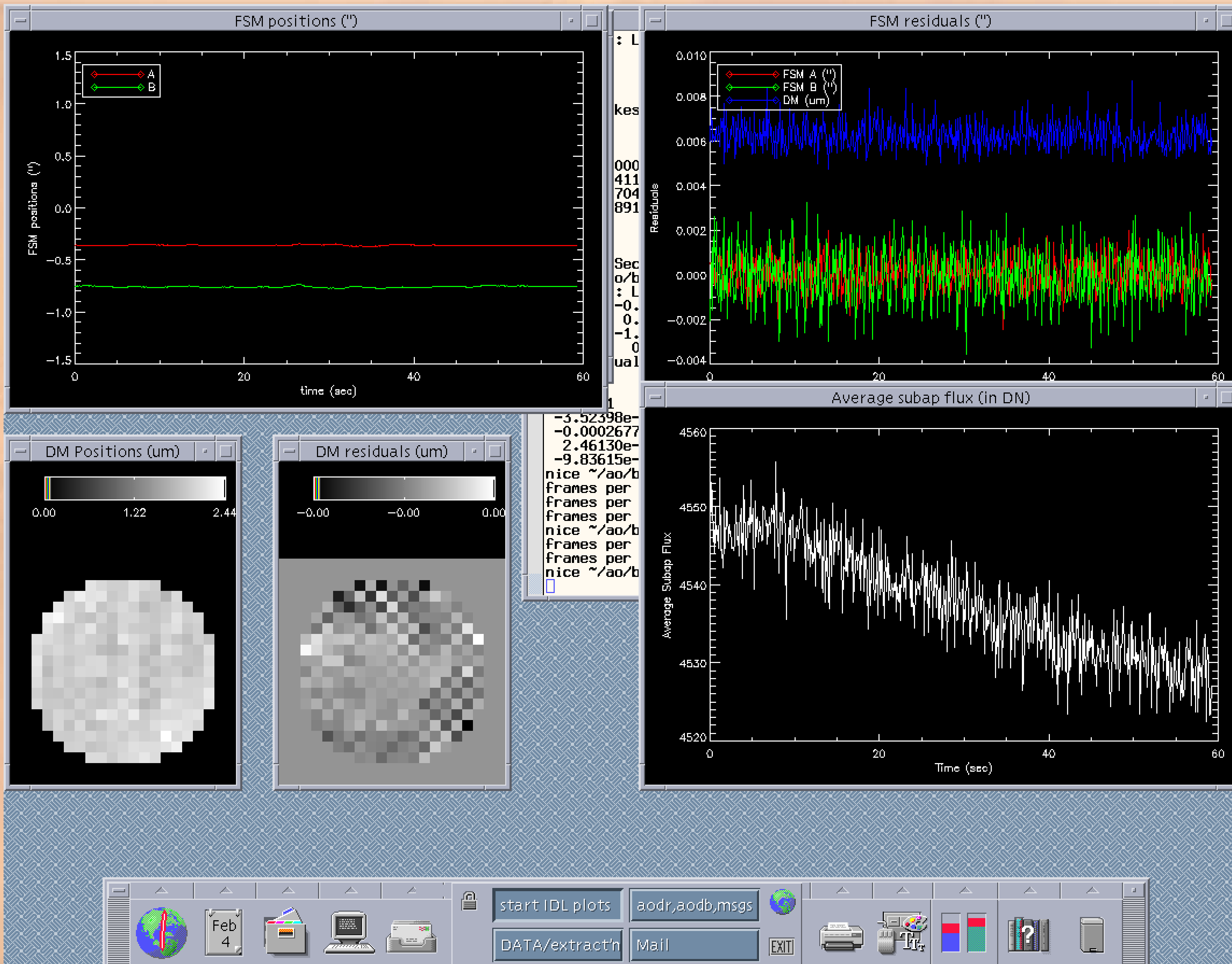
- TOTAL TIME ~ 1 – 2 minutes

Nightly AO Tuning

- When Does Operator Tune AO?
  - At each new telescope pointing
  - When background changes (clouds, moon)
  - When flexure changes (after slew, long integrations)
  - Whenever observer requests an updated tune
- AO operator is responsible for all AO tuning

AO Performance Plots

- FSM Positions
  - Shows current FSM X and Y position (arcseconds)
  - Telescope automatically commanded to offload FSM when either limit is approached
    - (Note for slow WFS rates (~ 50Hz or less) one should turn off the automatic offloading and manually watch for saturation on the FSM performance plots)
- Residuals
  - FSM residuals in arcseconds
  - DM residuals (blue) in microns (WFS wavefront error)
    - 0.05 - 0.1 microns indicate a good lock, good seeing
    - 0.1 - 0.2 microns is typical of poor seeing conditions
- Flux
  - > 200 DN average sub aperture flux needed for good lock



FSM positions (")
A
B
FSM positions (")
time (sec)
FSM residuals (")
FSM A (")
FSM B (")
DM (um)
Residuals
Average subap flux (in DN)
Average Subap Flux
Time (sec)
DM Positions (um)
0.00
1.22
2.44
DM residuals (um)
-0.00
-0.00
0.00
nice ~/ao/b
frames per
start IDL plots
aodr,aodb,msgs
DATA/extract'n
Mail
EXIT
Feb
4

AO Performance at PHARO

- Observer can calculate a rough Strehl ratio
- Communication between AO operator (plots) and PHARO observer (image / Strehl) is essential for good performance
- Details of PHARO operation to be given later

Basic PHARO Operation

Rick Burruss
rsb@bigeye.palomar.caltech.edu

PHARO

- Dewar mounted to AO bench at Cassegrain focus (f/16)
- Detector is 1024 x 1024 HgCdTe HAWAII array
- Array is optimized for wavelengths between 1 - 2.5 μm
- All reflecting optical system
- Provides diffraction limited images at 25 or 40 milliarcseconds / pixel plate scales
- Provides coronagraphic and long slit grism spectroscopic observing modes

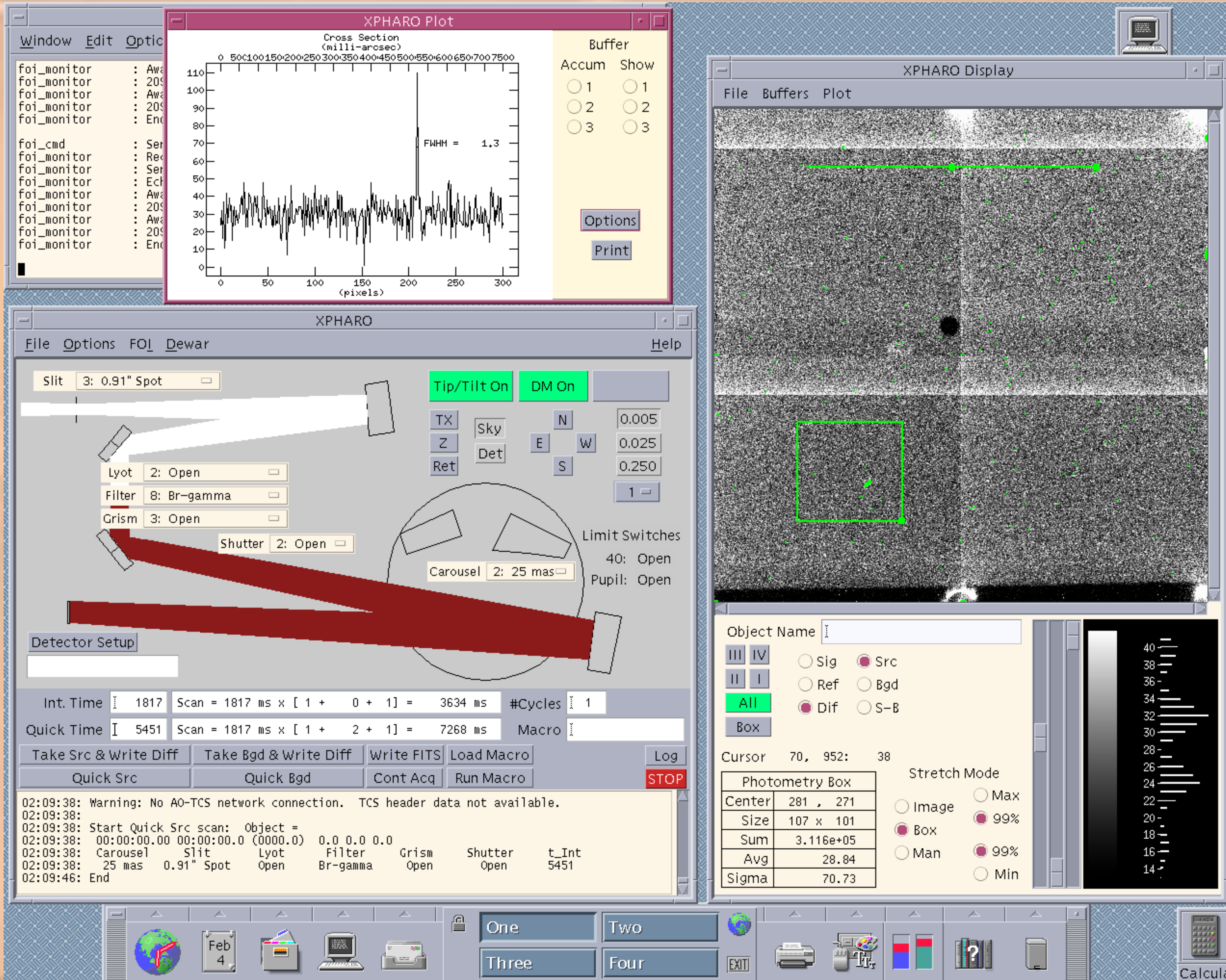
PHARO Computer

- User interface computer is a Sun Ultra 2 running CDE
- 40 Gigabytes of scratch disk space available
- Exabyte 8mm tape drive available
- Typical FITS image size ~ 4.2 Megabytes

- Bring plenty of tapes!

xpharo

- PHARO camera is operated entirely by Xwindows GUI (xpharo)
- At startup, xpharo prompts for user name (header) and data directory, which it will then create
- xpharo controls detector setup, exposures, wheel positions, image / telescope movements, and macros
- Exposures are automatically forwarded to xpharo display
- When written to disk, all exposures are standard 3-dimensional FITS files [x, y, quad#]
- Header info includes most PHARO, Telescope, and PALAO parameters
- xpharo creates and maintains a useful text log in the data directory


XPHARO Plot
Cross Section
(milli-arcsec)
FWHM = 1.3
(pixels)
Buffer
Accum
Show
Options
Print
XPHARO Display
File
Buffers
Plot
Object Name
Sig
Src
Ref
Bgd
Dif
S-B
All
Box
Cursor 70, 952: 38
Photometry Box
Center 281 , 271
Size 107 x 101
Sum 3.116e+05
Avg 28.84
Sigma 70.73
Stretch Mode
Image
Box
Man
Max
99%
99%
Min
XPHARO
File
Options
FOI
Dewar
Help
Slit 3: 0.91" Spot
Tip/Tilt On
DM On
TX
Z
Ret
Sky
Det
N
E
W
S
0.005
0.025
0.250
Lyot 2: Open
Filter 8: Br-gamma
Grism 3: Open
Shutter 2: Open
Carousel 2: 25 mas
Limit Switches
40: Open
Pupil: Open
Detector Setup
Int. Time 1817
Scan = 1817 ms x [1 + 0 + 1] = 3634 ms
#Cycles 1
Quick Time 5451
Scan = 1817 ms x [1 + 2 + 1] = 7268 ms
Macro
Take Src & Write Diff
Take Bgd & Write Diff
Write FITS
Load Macro
Log
Quick Src
Quick Bgd
Cont Acq
Run Macro
STOP
02:09:38: Warning: No AO-TCS network connection. TCS header data not available.
02:09:38:
02:09:38: Start Quick Src scan: Object =
02:09:38: 00:00:00.00 00:00:00.0 (0000.0) 0.0 0.0 0.0
02:09:38: Carousel Slit Lyot Filter Grism Shutter t_Int
02:09:38: 25 mas 0.91" Spot Open Br-gamma Open Open 5451
02:09:46: End
Window
Edit
foi_monitor
foi_cmd
One
Two
Three
Four
Feb 4
EXIT
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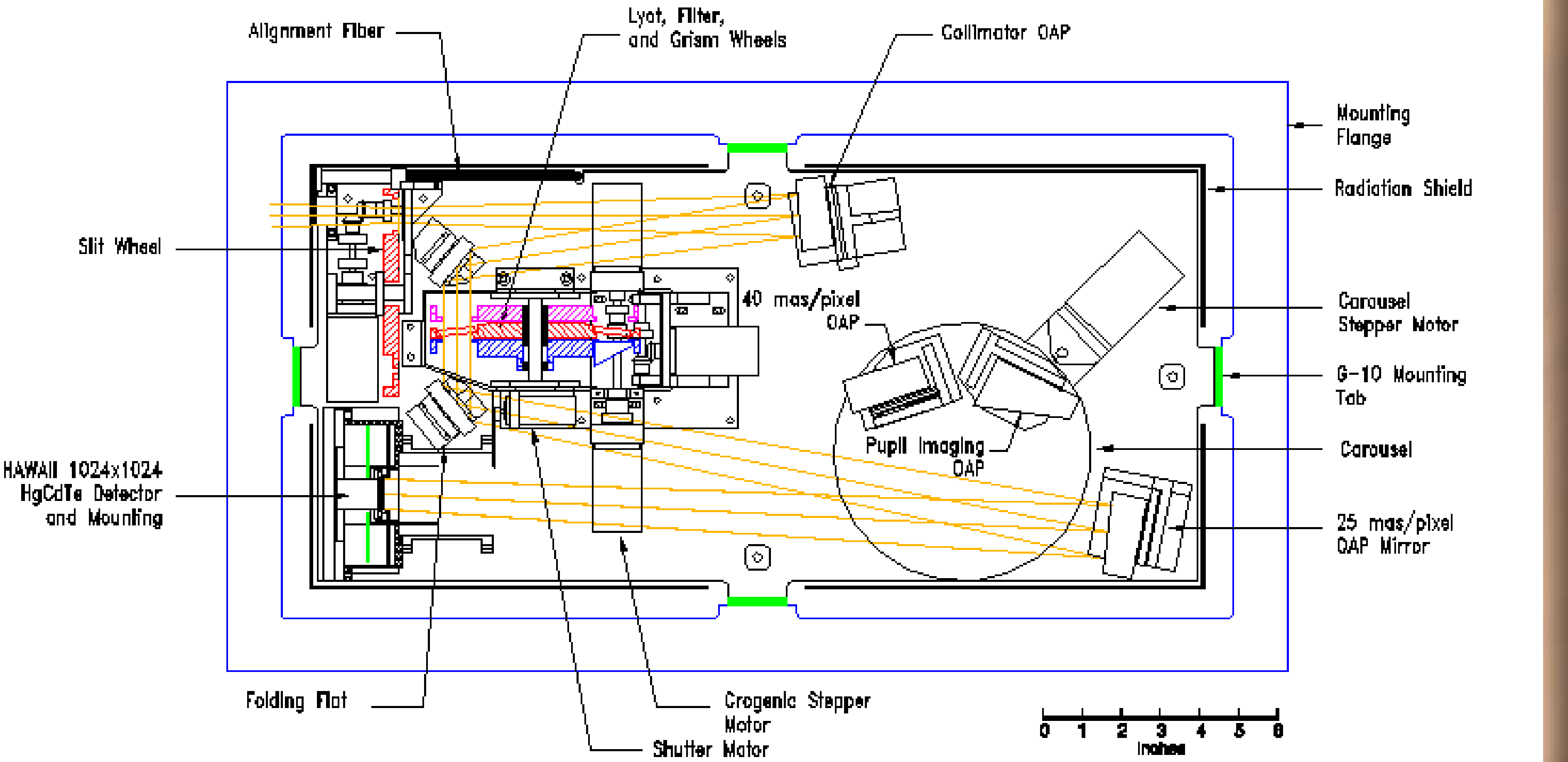
PHARO / Internal Moving Devices

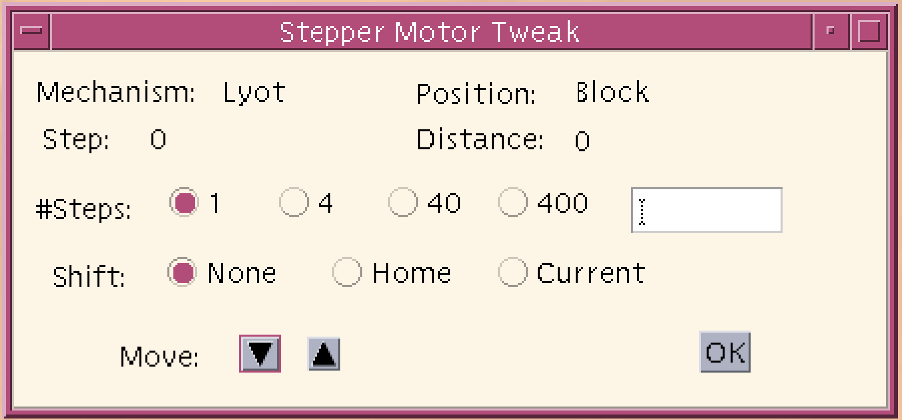
- Slit Wheel (10 position wheel)
  - Near entrance window; beam is in focus
  - Contains coronagraphic spots, slits, 25” field stop, 40” field stop
- Lyot Wheel (10 position wheel / pupil plane)
  - Contains cold block, various lyot stop masks (spiders, pf cage)
- Filter Wheel (10 position wheel / pupil plane)
  - Contains broad and narrow band filters
- Grism Wheel (10 position wheel / pupil plane)
  - Contains ND filters, grisms, filters
- Carousel (3 position wheel / pupil plane)
  - Contains 25 mas OAP, 40 mas OAP, and Pupil imaging OAP


Alignment Fiber
Lyot, Filter, and Grism Wheels
Collimator OAP
Mounting Flange
Radiation Shield
Slit Wheel
40 mas/pixel OAP
Carousel Stepper Motor
G-10 Mounting Tab
Pupil Imaging OAP
Carousel
HAWAII 1024x1024 HgCdTe Detector and Mounting
25 mas/pixel OAP Mirror
Folding Flat
Crogenic Stepper Motor
Shutter Motor
0 1 2 3 4 5 6
Inches

PHARO Devices / Encoding

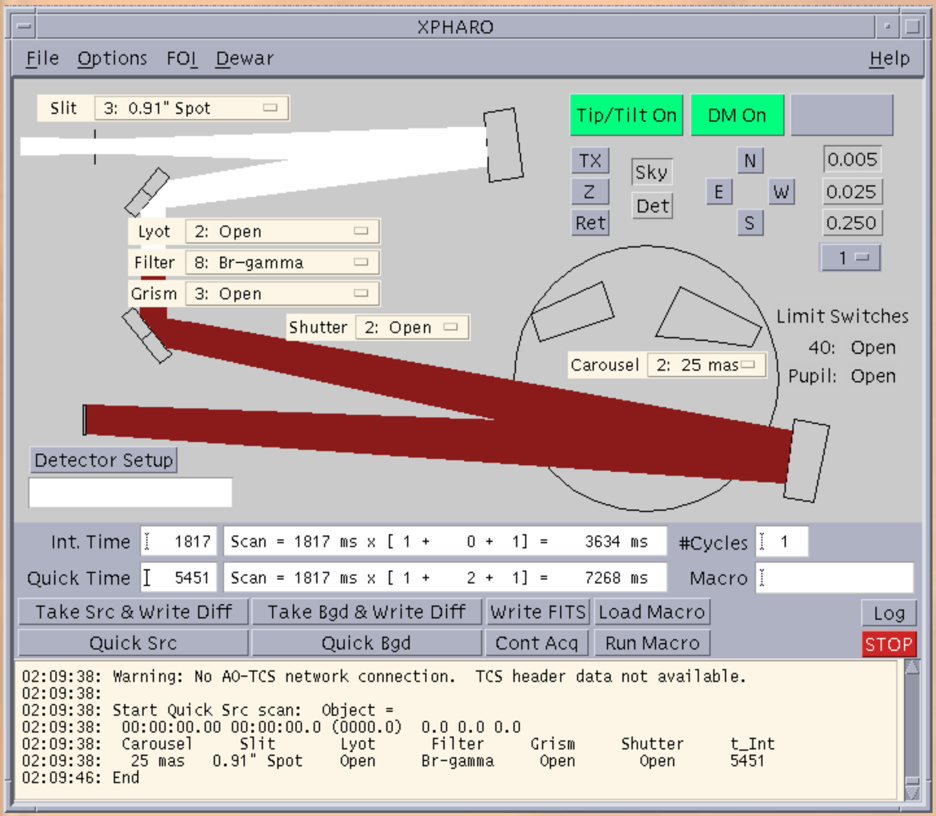
- 10 position wheels each have a unique location (magnet) defined as HOME
- Each GUI selector that controls a wheel has a HOME selection request
- Use the HOME selection request to remove any lost motor steps

PHARO Devices / Tweaking



- Each GUI selector has a TWEAK request that opens a popup window
- Steps of ~ 10 units are stable
- None = no change to encoder file
- Home = changes HOME location
  - Expert use only!
- Current = changes current position only

PHARO Devices / Carousel

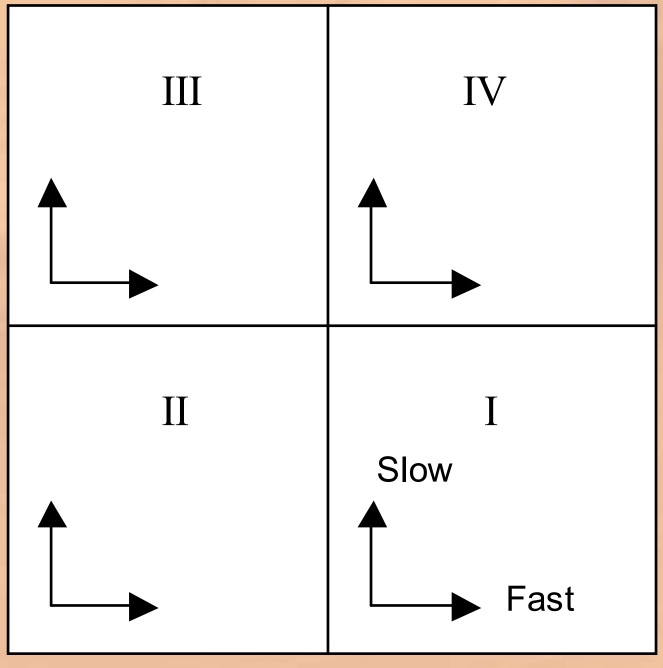


- Pupil / 40 mas positions settle against a limit switch and a hard stop
- Limit Switch must read “Trip” before observing
- Use TWEAK option to tweak Carousel into Trip limit position

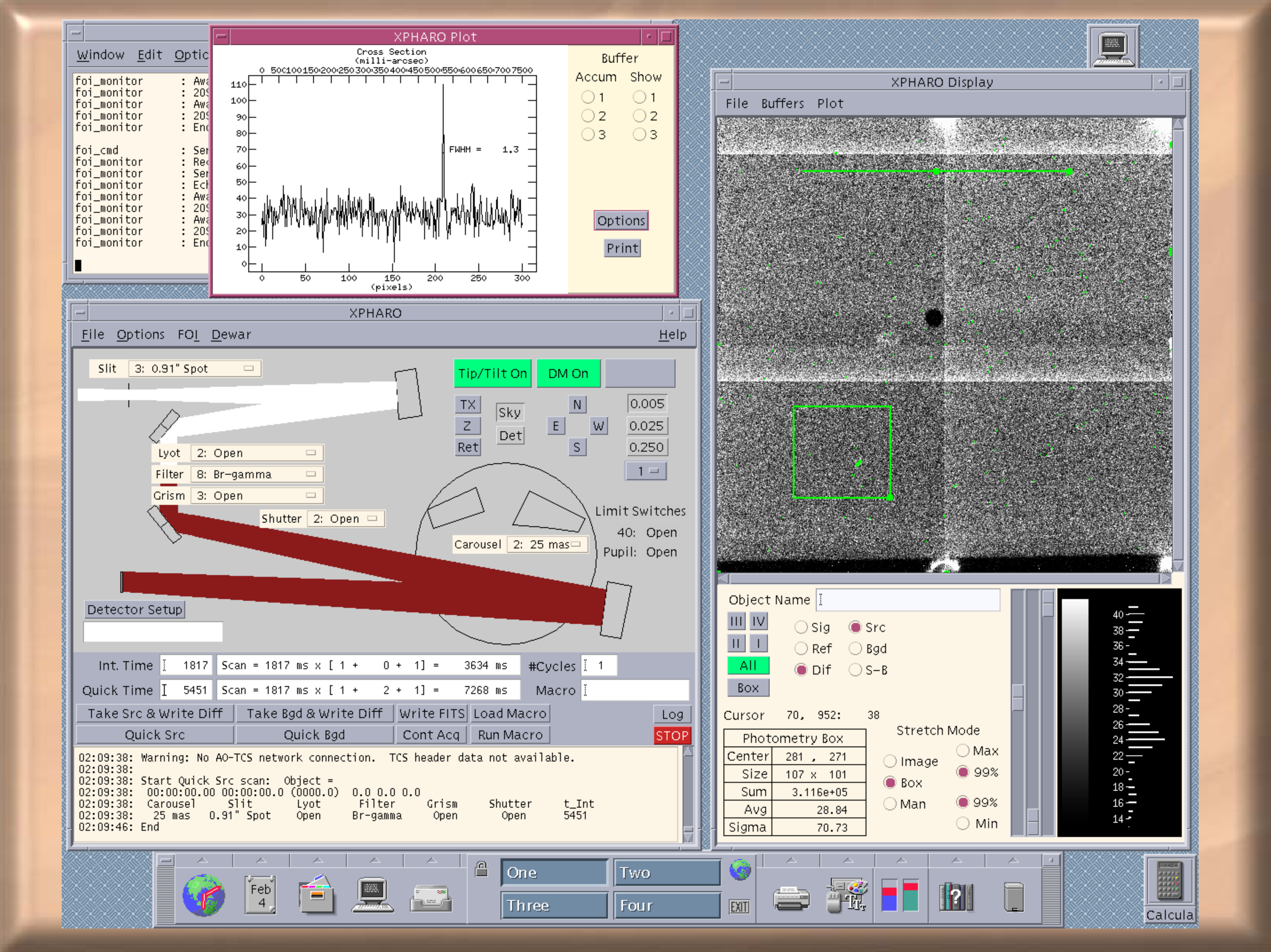
PHARO Array Specifications

Material	HgCdTe
Format	Four 512 x 512 quadrants
Pixel Pitch	18.5 μm
Q.E.	~ 0.4 @ J ~ 0.7 @ K
Well Depth	100,000 e^-
Saturation	Approx. linear to 2^{16} (65,536) DN (optimum linearity up to 40,000 DN)
Dark Current	~ 0.1 e^- / second
Read Noise	~ 9 e^-

PHARO Array Quadrants



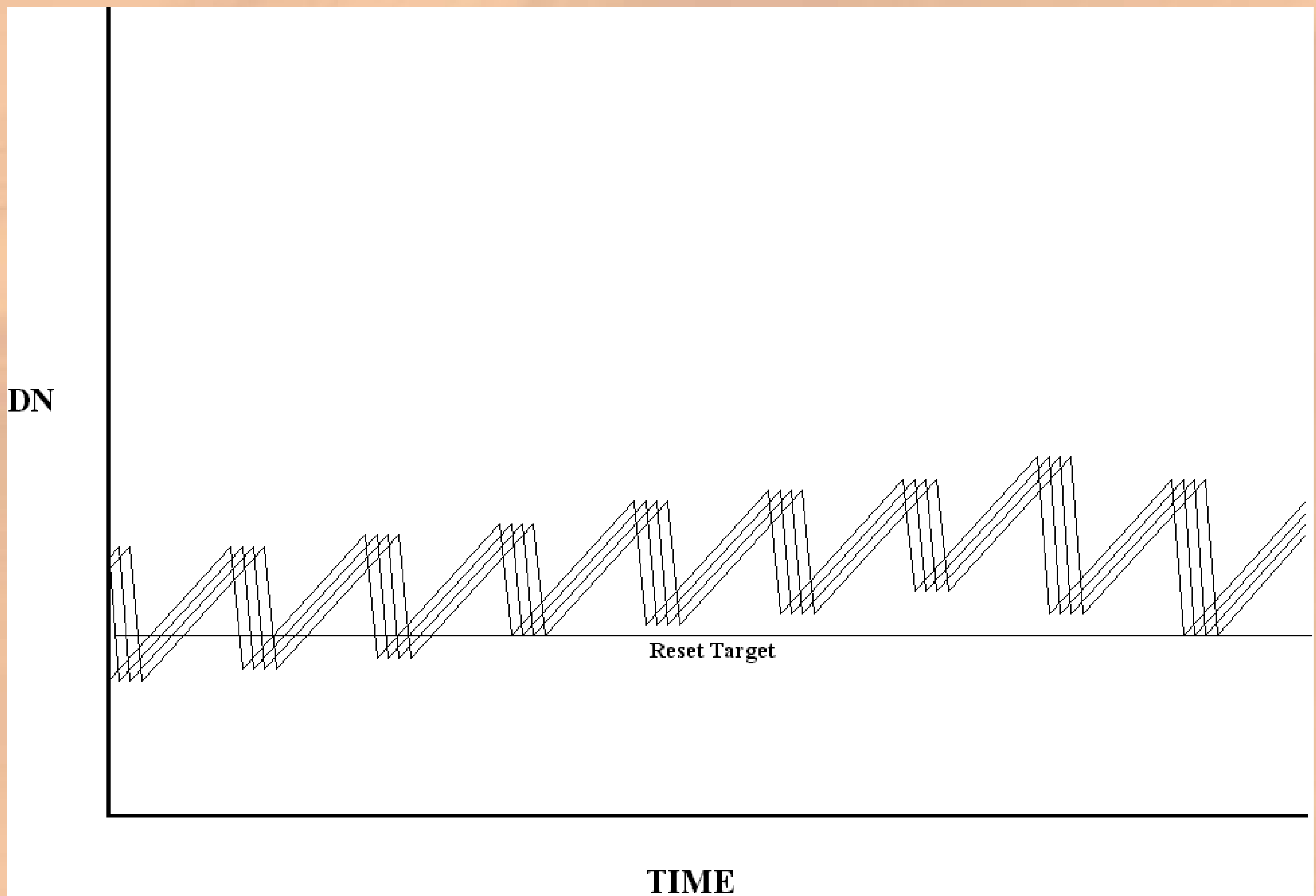
- Pixels are read one row at a time
- Reset is then applied to all pixels in the row
- Timing discontinuity exists over the quadrant borders
- Avoid placing objects on the borders
- Multiplexer FET glow apparent at 4 read points on array


XPHARO Plot
Window Edit Optic
foi_monitor
foi_cmd
Cross Section
(milli-arcsec)
(pixels)
FWHM = 1.3
Buffer
Accum Show
Options
Print
XPHARO Display
File Buffers Plot
XPHARO
File Options FOI Dewar Help
Slit 3: 0.91" Spot
Tip/Tilt On
DM On
TX Z Ret
Sky Det
N E W S
0.005
0.025
0.250
Lyot 2: Open
Filter 8: Br-gamma
Grism 3: Open
Shutter 2: Open
Carousel 2: 25 mas
Limit Switches
40: Open
Pupil: Open
Detector Setup
Int. Time 1817
Scan = 1817 ms x [1 + 0 + 1] = 3634 ms
#Cycles 1
Quick Time 5451
Scan = 1817 ms x [1 + 2 + 1] = 7268 ms
Macro
Take Src & Write Diff
Take Bgd & Write Diff
Write FITS
Load Macro
Log
Quick Src
Quick Bgd
Cont Acq
Run Macro
STOP
02:09:38: Warning: No AO-TCS network connection. TCS header data not available.
02:09:38:
02:09:38: Start Quick Src scan: Object =
02:09:38: 00:00:00.00 00:00:00.0 (0000.0) 0.0 0.0 0.0
02:09:38: Carousel Slit Lyot Filter Grism Shutter t_Int
02:09:38: 25 mas 0.91" Spot Open Br-gamma Open Open 5451
02:09:46: End
Object Name
III IV II I All Box
Sig Src Ref Bgd Dif S-B
Cursor 70, 952: 38
Photometry Box
Center 281 , 271
Size 107 x 101
Sum 3.116e+05
Avg 28.84
Sigma 70.73
Stretch Mode
Image Box Man
Max 99% 99% Min
One Two Three Four
Feb 4
EXIT
Calcula

PHARO Array / Idle

- When idle, the PHARO array is continuously reset to the preset bias level
- Bias level is carefully set above zero to avoid clipping
- This reset is very noisy (tens to hundreds of DN ± bias target level)
- Correlated Double Sampling used to remove reset noise

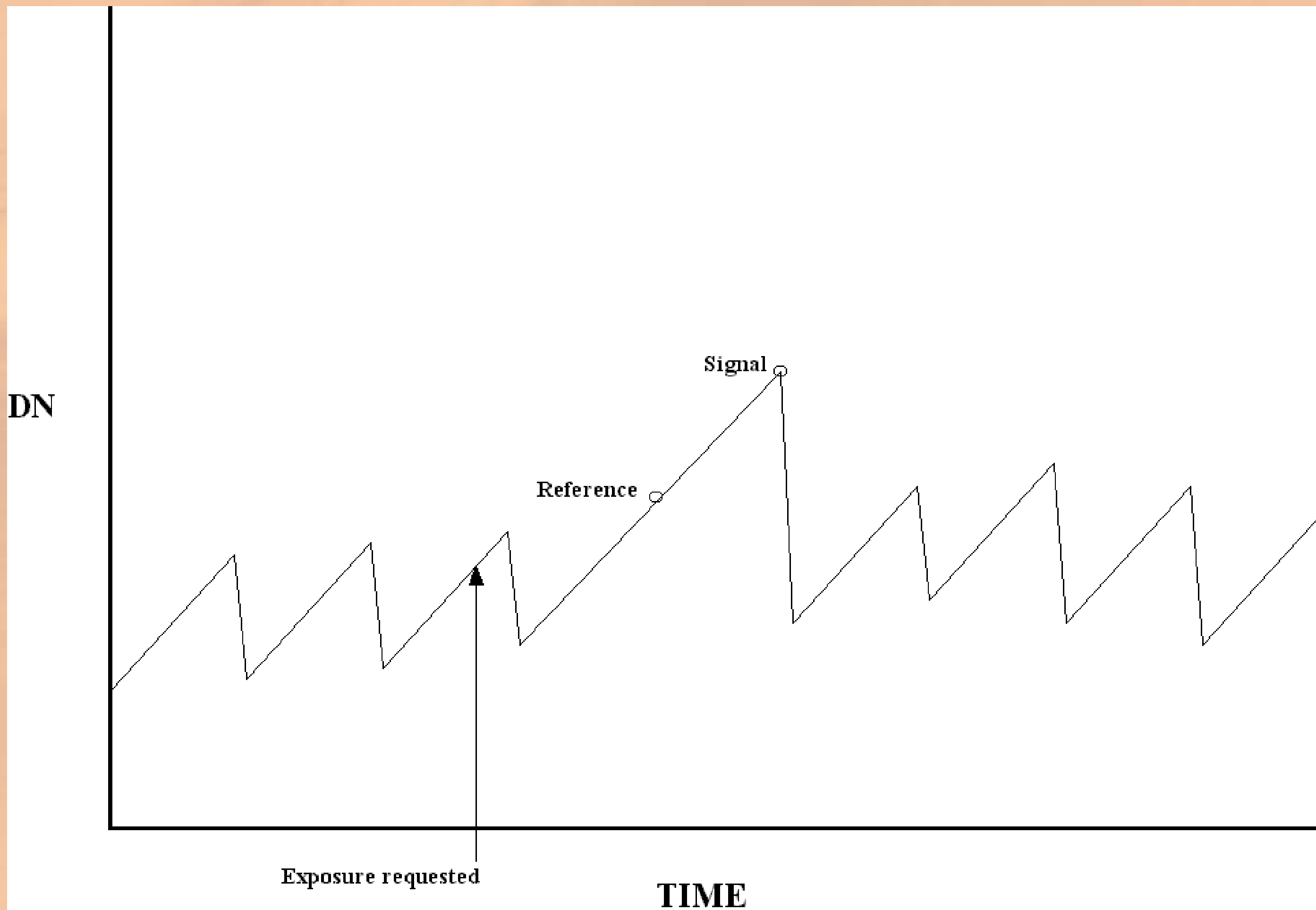
4 Pixels / Idle PHARO Array



PHARO Array / Default Exposure

- Default quadrant size = 512 x 512 pixels
- Default exposure time = 1817 ms
- Default End Points = 1
- Image sent to xpharo display is the difference of the signal image minus the reference image (Diff = Sig - Ref)
- Timestamp in header may not be exact exposure start time

Single Pixel / Default Exposure



Default Exposure Header

Int Time 1817 Scan = 1817 ms x [1 + 0 + 1] = 3634 ms

Header

T_SCAN = 3634 / Detector total scan time (msec)

T_INT = 1817 / Detector integration time (msec)

T_EFF = 1817 / Effective integration time (msec)

T_FRAME = 1717 / Frame clocking time

T_FRGAP = 100 / Pause time between frames

NENDPTFR= 1 / N End Pt. Frames

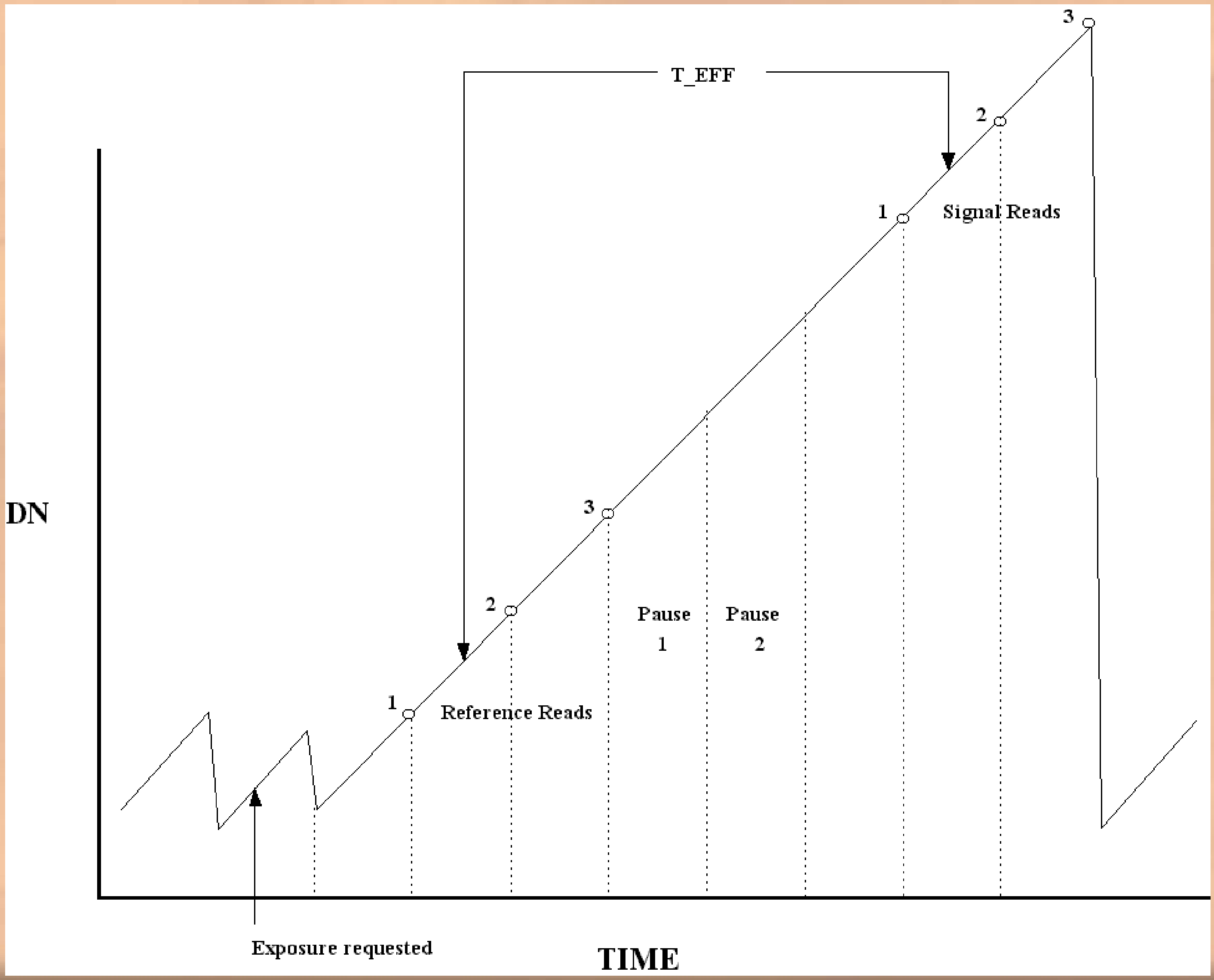
NPAUSEFR= 0 / N Pause Frames

- 1817 is the time entered by user in xpharo GUI
- T_FRAME depends on quadrant size
- Time to read the entire array: T_FRAME + T_FRGAP = 1817
- Effective exposure time: T_EFF = EndPt. * 1817 + Pause * 1817 = 1817 ms
- Time calculated for xpharo GUI: T_INT = T_SCAN - (T_FRAME + T_FRGAP)

PHARO Array / Multiple Sampling

- Array example = 51 x 51 pixels / quadrant
- Integration Time entered = 1000 ms
- xpharo calculates / changes integration time to 826 ms
- End Points entered = 3 to reduce read noise
- 2 Pause frames are entered automatically by xpharo to fill the requested exposure time
- Image sent to xpharo display is the difference of the average signal images minus the average reference images [Diff = Sig (average) - Ref (average)]
- PHARO was not designed to be a fast read detector

Single Pixel / Multiple Sampling



Multiple Sample Header

example: 51 x 51 pixel array; 3 End Points; 2 Pause Frames

Int Time 826 Scan = 118 ms x [3 + 2 + 3] = 944 ms

Header

T_SCAN = 944 / Detector total scan time (msec)

T_INT = 826 / Detector integration time (msec)

T_EFF = 590 / Effective integration time (msec)

T_FRAME = 18 / Frame clocking time

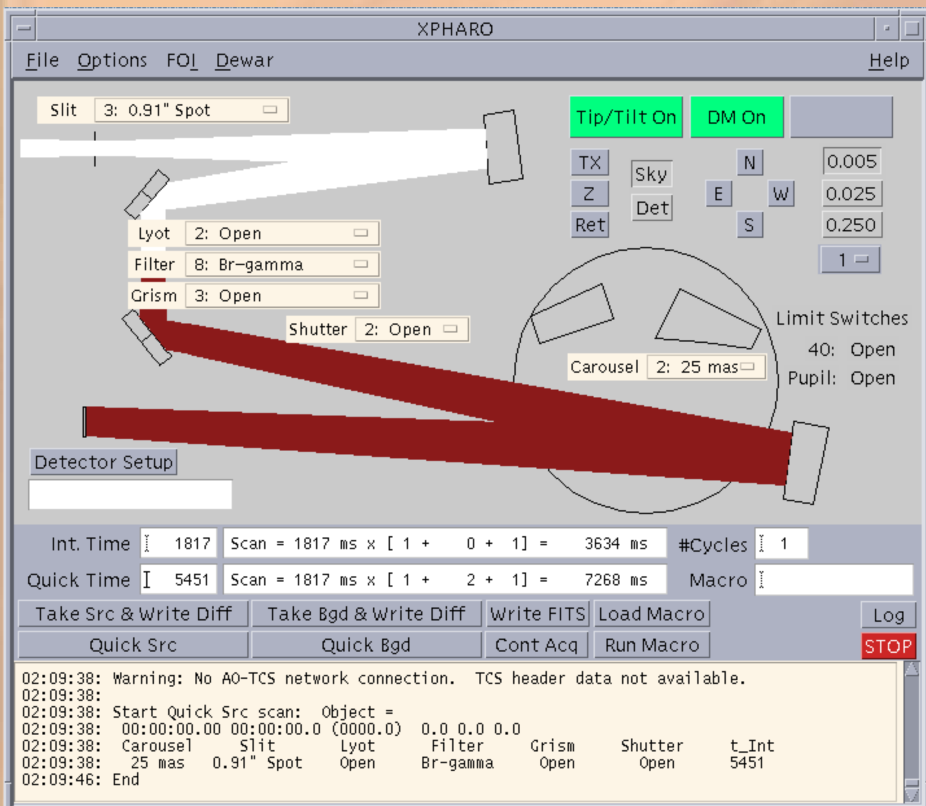
T_FRGAP = 100 / Pause time between frames

NENDPTFR= 3 / N End Pt. Frames

NPAUSEFR= 2 / N Pause Frames

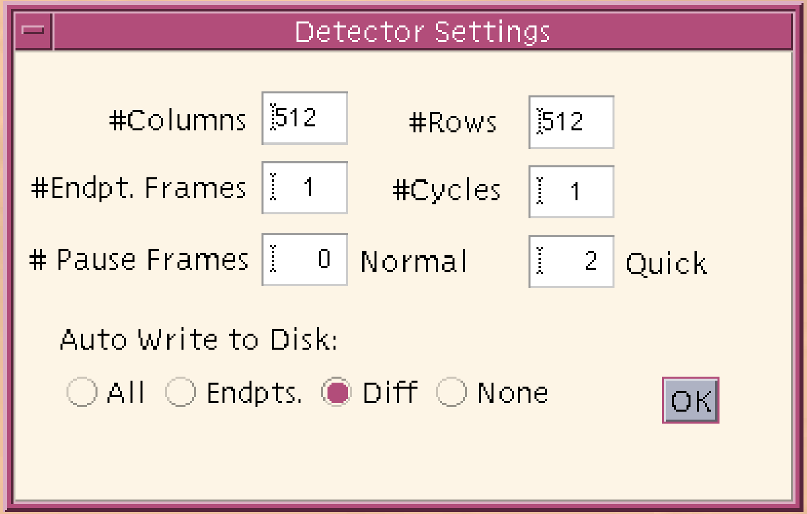
- 1000 is the time entered by user in xpharo GUI
- T_FRAME depends on quadrant size
- Time to read the entire array:
  T_FRAME + T_FRGAP = 118 ms
- Effective exposure time:
  T_EFF = EndPt. * 118 + Pause * 118 = 590 ms
- Time calculated for xpharo GUI:
  T_INT = T_SCAN - (T_FRAME + T_FRGAP)
  = 944 - 118 = 826 ms

PHARO Exposures



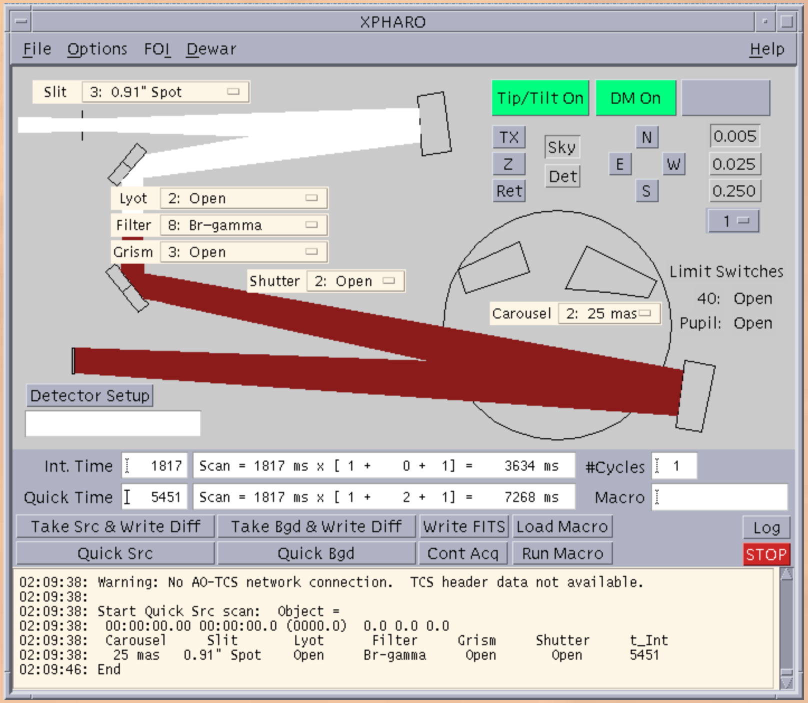
- All exposures are sent to either the Src or Bgd buffer
- Quick exposures are not written to disk
- Take & Write exposures are written to disk as standard 3 dimensional FITS files [x, y, quad#]
- No co-adding is done before write to disk

PHARO Exposure Options



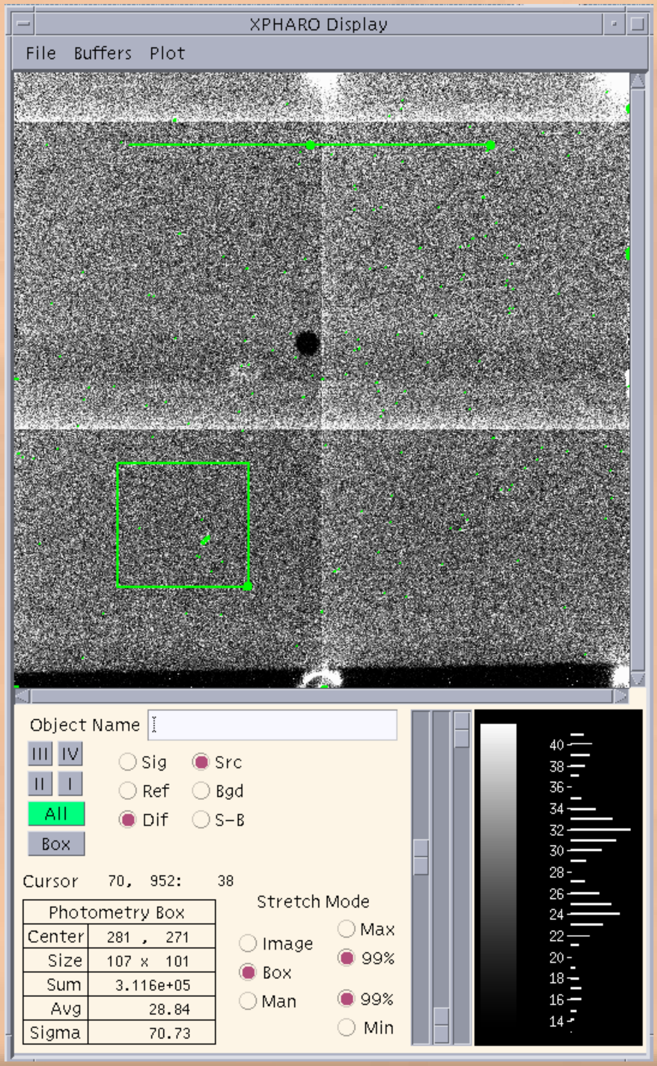
- Detector Setup button opens Settings popup window
- Quadrant size can be changed
- End Points can be added
- All frames, all end points, or just the difference can be written to disk

More Pharo Exposure Options



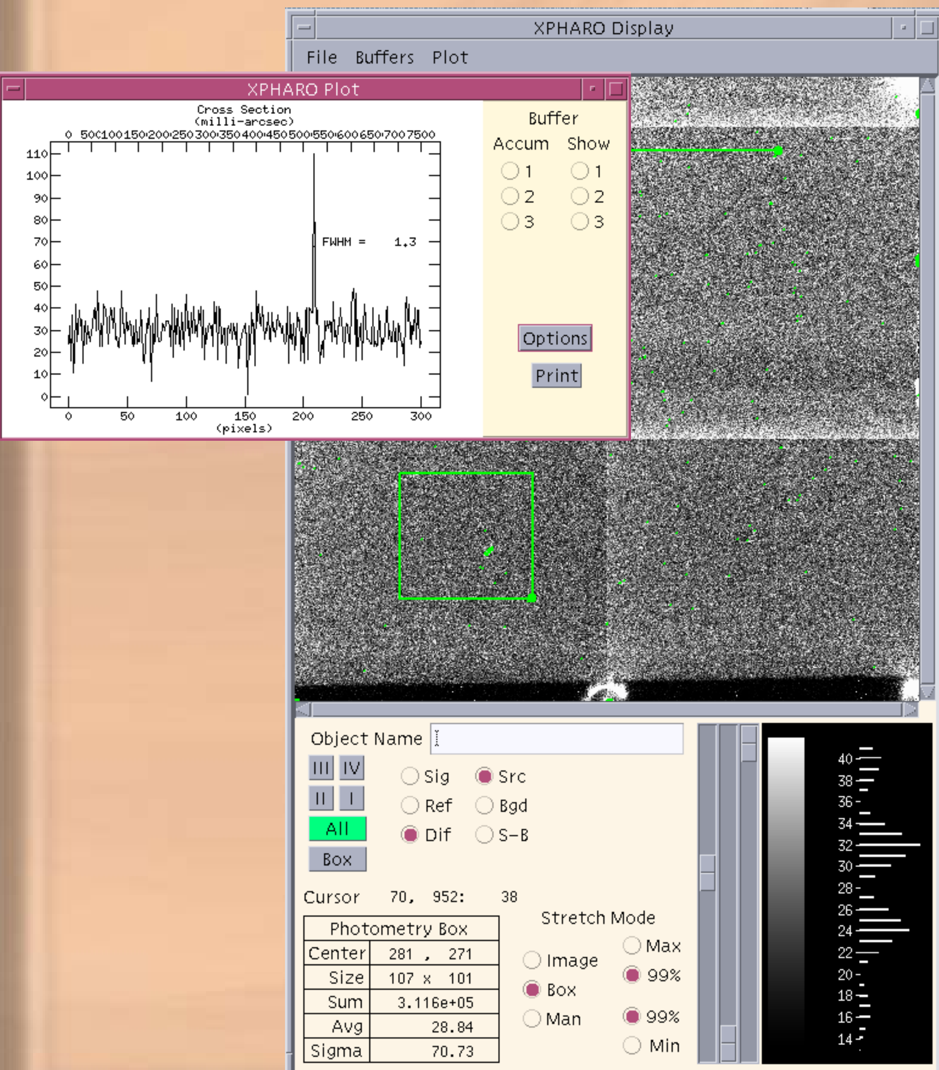
- Write FITS button writes displayed image to disk
- Cont Acq button takes a Quick Src image every 2 seconds automatically
- #Cycles text box value is number of Quick and/or Take & Write exposures to be taken in a row, with all Take & Write files written to disk

xpharo Display



- Src buffer, Bgd buffer, or the difference (S-B) can be displayed
- Multiple zoom modes available
- Multiple stretch modes available
- Photometry box lists statistics under green box
- Radial, line, other plots available
- A second monitor (not shown) displays the full field at all times

xpharo Display / Strehl Analysis



- Strehl Ratio = ratio of peak flux of an observed point source to that of a theoretical peak flux (calculated value)
- Procedure:
  - With the green statistics box over a star, select Radial Plot
  - The right hand scale from the xpharo Plot popup window is calculated as:

    peak pixel / sum in box * 1000
  - Use normalization on next slide to estimate the Strehl
- Example: Using the K filter and the 25 mas plate scale, a star in the box produces a right hand plot value of 27.
  - Strehl ratio = 27 / 55 = 50%

xpharo Display / Strehl Analysis

- The correct Strehl normalizations (as calculated accounting for plate scale and the diffraction limited resolution (including obscuration):

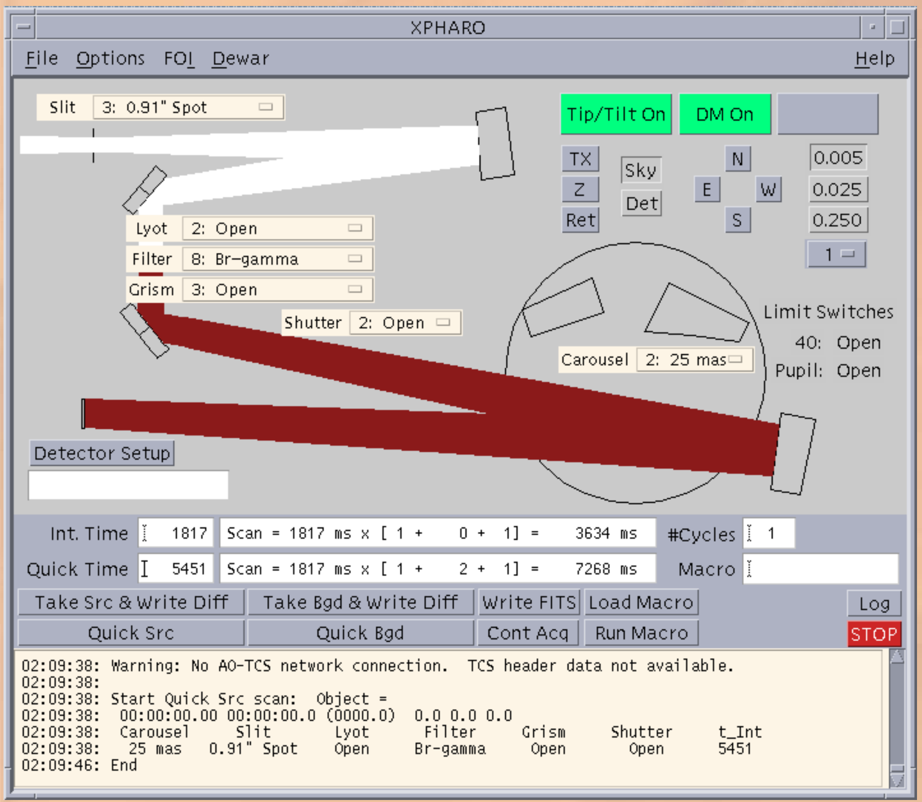
λ	25 mas	40 mas	Smallest FWHM
J	158	346	0.050”
H	96	229	0.066”
K	55	137	0.088”

Moving Objects / Closed Loop

(Dithering)

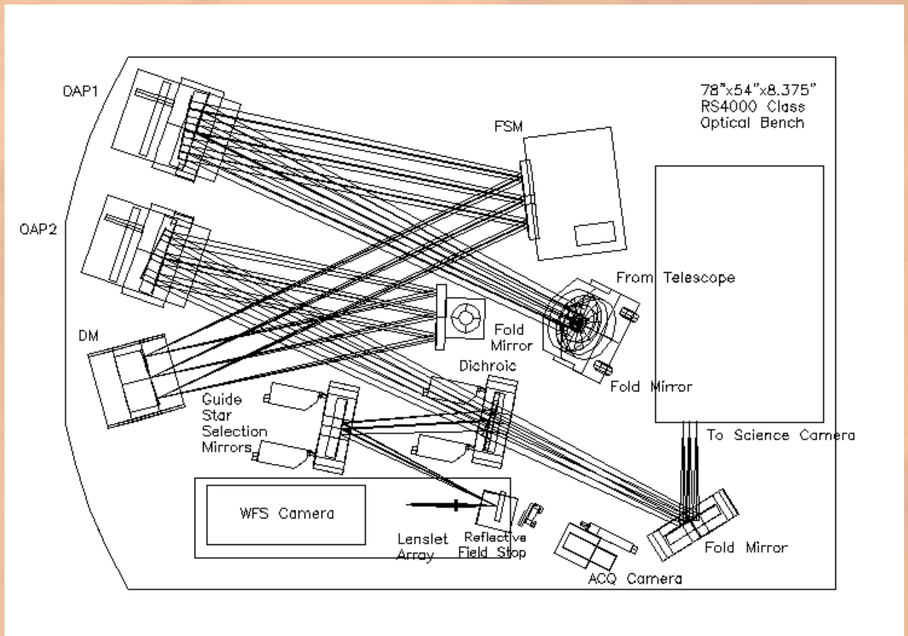
- Moves objects on the array
- Does NOT move guide star off of Field Stop
- 5 arcsecond maximum allowable move followed by a 1 - 2 second settle time required to maintain stable lock
- There are no error checks; this is a common mistake made during observing
- If observer moves too far or too fast, DM may “break”. If this happens, try to move back first. If this doesn’t work, open the loops. AO operator can reload saved AO file to recover observing parameters

How To Move Objects / Closed Loop



- xpharo Buttons
  - Can move in either Sky or Detector coordinates
  - Mover buttons (N,W,S,E) moves the two AO SSM optics to reposition the science object without moving the guide star
  - SSM motors suffer hysteresis. At worst accuracy is > 10 pixels; at best accuracy is ~ 1 pixel
  - Controlled by observer
  - Used to dither on array and for fine positioning of object behind coronagraphic spot and slit.

How To Move Objects / Closed Loop



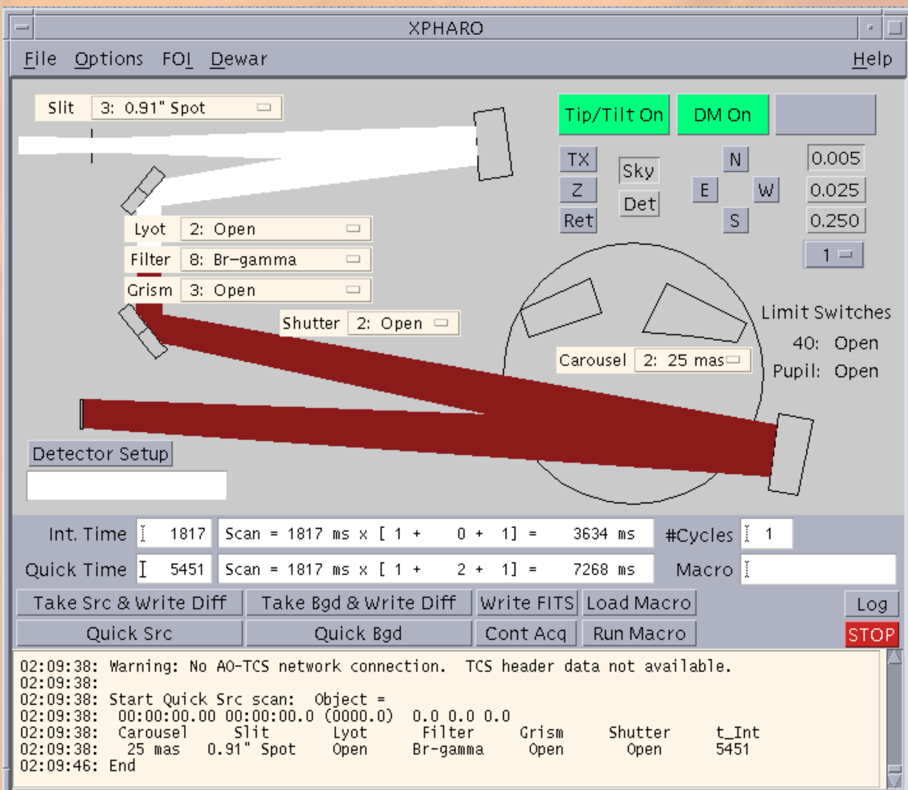
- Digital Dithering
  - Global Tip / Tilt is applied to the centroid offsets to fine tune image position
  - Accurate to < 10 mas
  - Range is limited to ± 0.2”
  - Controlled by AO operator
  - Used for very fine positioning of object behind coronagraphic spot and slit

Moving Objects / Open Loop

(Nodding)

- Moves everything (guide star, science object)
- No limit to distance or direction and no pause necessary
- Good for background sky frames, field identification, star hunting

How To Move Objects / Open Loop



- OPEN LOOPS FIRST (common mistake)
- Xpharo buttons (N,W,S,E) command the telescope to move when loops are open
- Telescope hand paddle or telescope operator may also be used

xpharo Macros

```
! Macro file "example"
lyot 3             ! Std Cross
filter 2           ! J
take_src
move_e 5000   ! milliarcsec east
pause 5            ! sec
filter 4           ! K
take_src
move_n -5000 ! mill-arcsec
pause 5            ! sec
take_src
lyot 1             ! block
```

- Macros are simple text files that live on xpharo computer
- Macros are loaded with the Load Macro button
- Macros are run with the Run Macro button
- A pause is necessary after 5 arcsecond nods (SSM closed loop moves)
- Move_n -xxxx for south moves; move_e -xxxx for west moves

Coronagraph Observing Hints

- Slit wheel is in focus. Remove coronagraphic spot during flats. The wheel is not repeatable to better than a few pixels. Specks on substrate and spot itself will not line up perfectly after a move
- xpharo mover buttons good for object moves in one direction toward coronagraph
- Digital dithering perfect for fine moves when close to coronagraph, and for moves to return to spot if you overshoot with the buttons
- Due to non common path errors (flexure), objects may drift from behind the spot on the order of once every 10 minutes (large hour angles?)
- xpharo display Line Plot is a good tool for centering bright objects behind the coronagraph

Slit Observing Hints

- Carousel should be left alone in the 40 mas position
- Select the desired slit, order sorting filter, and grism
- Take a 30 second exposure on blank sky, examine the vertical Telluric lines
- Tweak the slit wheel in Current mode to make the lines exactly vertical
- Take an exposure of a star on the slit, examine the horizontal spectra
- Tweak the grism wheel in Current mode to make the lines exactly horizontal
- Don’t move the wheels if at all possible

PHARO Issues / Network

- xpharo connects through Adaptive Optics to get to the telescope control computer
- If AO goes down, xpharo automatically simulates the network so data can be taken
- No header data available, no telescope move commands available
- Tip / Tilt and DM buttons go blank when Xpharo simulates the network
- When AO is back up, uncheck “Simulate Net” under the Options menu

PHARO Issues / FOI Interface

- Occasionally the fiber optic interface (FOI) between xpharo and the control electronics hangs
- Symptoms include
  - Exposure counts down to negative infinity
  - Wheel GUI selector stuck on MOVING after a move request
- To fix, select “Reset FOI” under FOI menu

PHARO Issues / Grism Wheel

- We’ve observed the grism wheel intermittently vignetting the light path
- We’ve made recent attempts to fix the problem, but it may remain
- We suggest looking at the light path by using the Carousel’s Pupil mode whenever you move the grism wheel until we can isolate the problem

PHARO Issues / Shutter

- We removed the shutter blade from the shutter motor in January 2002
- It is no longer dangerous to use the shutter GUI selector
- The shutter motor will be replaced in the near future

PHARO Issues / Carousel

- The Carousel is fitted with magnets designed to draw the wheel into the hard stop when the limits are approached
- Unfortunately these magnets are not working at 77° Kelvin
- Tweaks are necessary to “Trip” the limits when the limits are approached

PHARO Issues / Fast Readout

- In order to take faster exposures than the 1817 ms default (512 x 512 pixel quadrants), the array quadrants must be downsized
- Quadrants smaller than 54 x 54 pixels are unstable. Most, if not all, exposures are lost when using quadrants smaller than 54 x 54
- Quadrants larger than 54 x 54 are stable

PHARO Issues / New Filters

- New filters were installed in January 2002
- New filters include Methane Long, Br-gamma, Kcont, Fe II, and H2
- Filters removed are K' and Pa-ß
- The PHARO web page has not yet been updated to reflect these changes, and we don't have specs yet at Palomar. They should be available in the next two weeks
- The AO web page has limited info on the new filters
  - http://ao.jpl.nasa.gov/ Technical Information For Observers / Pharo Operations Manual and Notes
- The final new filter, Methane Short, will be installed February 16, 2002

PHARO Issue / #Cycles Bug

- When exposing with #Cycles > 1, the timestamp information (TIME-OBS and TIME_TCS) does not update after the first exposure
- The relative exposure timing is very accurate, so timing for later exposures can be easily extrapolated
- This bug will be fixed soon

Further Information

- Web Sites
  - JPL Adaptive Optics Web Page
    - http://ao.jpl.nasa.gov/
  - Caltech Adaptive Optics Web Page
    - http://www.astro.caltech.edu/palomar/200inch/palao/ palaohome.html
  - Cornell PHARO Web Page
    - http://astrosun.tn.cornell.edu/PHARO/pharo.html

Further Information

- Palomar Engineers
  - Rick Burruss
    - rsb@bigeye.palomar.caltech.edu
    - 760 - 742 - 2106
  - Jeff Hickey
    - jhickey@astro.caltech.edu
    - 760 - 742 - 2108

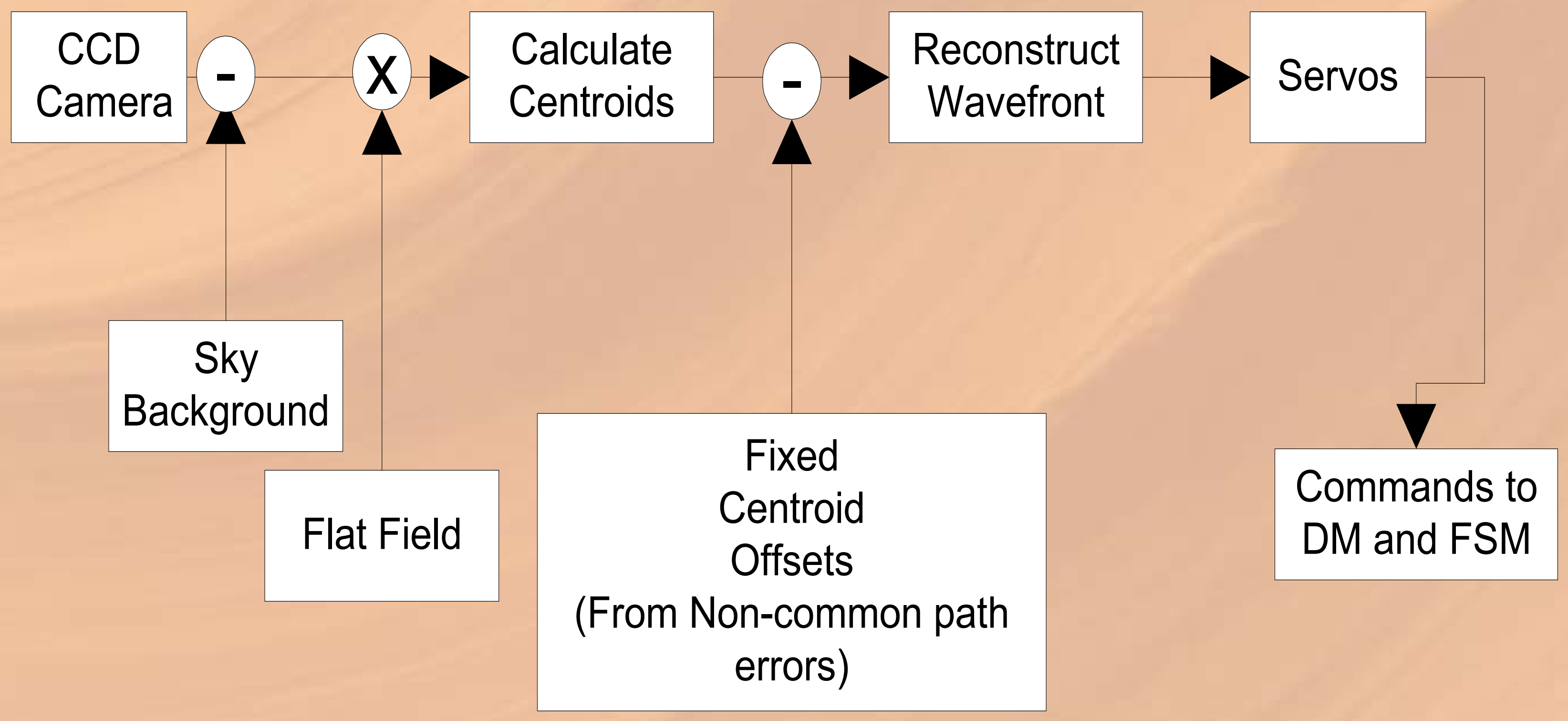
Factors Affecting Performance

Mitchell Troy
mtroy@jpl.nasa.gov

Outline

- Changing Sky Background Levels
- Extended sources as Guide Stars
- “Color” of Guide Star
- DM/Lenslet misregistrations
- System Performance Predictions

AO Schematic



Changing Sky Background

Problem:

- An incorrect WFS background will bias the centroid estimates
- All centroids will be over or under estimated in an amount proportional to centroid position

$$P_{calc} = \left(P_{raw} - P_{offset}\right) \cdot P_{gain}$$

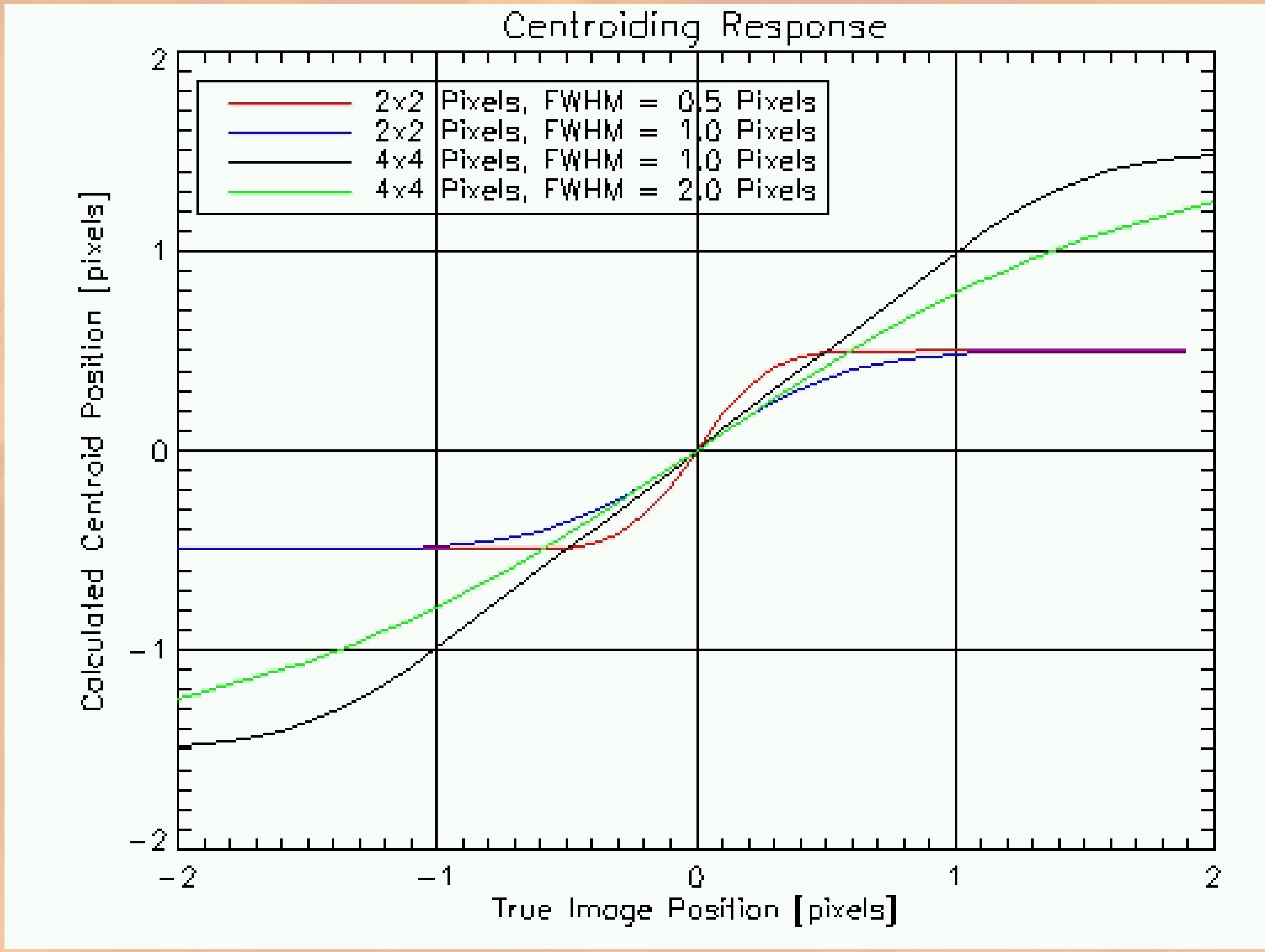
$$Xcentroid = \frac{\sum_{i=1}^{4}\left[i\left(\sum_{j=1}^{4} P_{calc}(i,j)\right)\right]}{\sum_{i=1}^{4}\left(\sum_{j=1}^{4} P_{calc}(i,j)\right)}$$

Changing Sky Background (cont.)

- Result:
  - The wavefront error introduced is proportional to the non-common path error.
  - PHARO image will be astigmatic and out of focus
- Solution
  - Ask AO operator to take new WFS background
  - Takes less then 1 minute
- Example situations
  - Twilight
  - Object near a planet
    - Move to location with similar background
  - Cassegrain ring rotation

Extended sources as guide stars:
Problem Statement

- Corrected image quality (S-H AO systems) degrades when locking on extended sources (~1-4 arcsec)
- PSF of nearby point sources will show
  - Static aberrations
  - Larger temporal variations in PSF shape



Centroiding Response
2x2 Pixels, FWHM = 0.5 Pixels
2x2 Pixels, FWHM = 1.0 Pixels
4x4 Pixels, FWHM = 1.0 Pixels
4x4 Pixels, FWHM = 2.0 Pixels
Calculated Centroid Position [pixels]
True Image Position [pixels]
2
1
0
−1
−2
−2
−1
0
1
2

Static Wavefront Errors

- Relation between true and calculate centroid position is dependent on sub-image FWHM
  - If subimages are driven to null (center of centroid) then there is no error
  - If subimages are driven off null
    - Centroids will be driven to incorrect (true) position
    - PSF will take shape of non-common path errors
  - Size of the affect depends on
    - Subimage size
    - Size of Non-common path aberrations
- Implemented Solution
  - Re-tune PSF while locked on extended source

Dynamic Errors

- The size of the calculated mirror commands are a function of subimage size.
- Results in lower bandwidth of system
- Solution:
  - Increase servo loop gains based on subimage size.

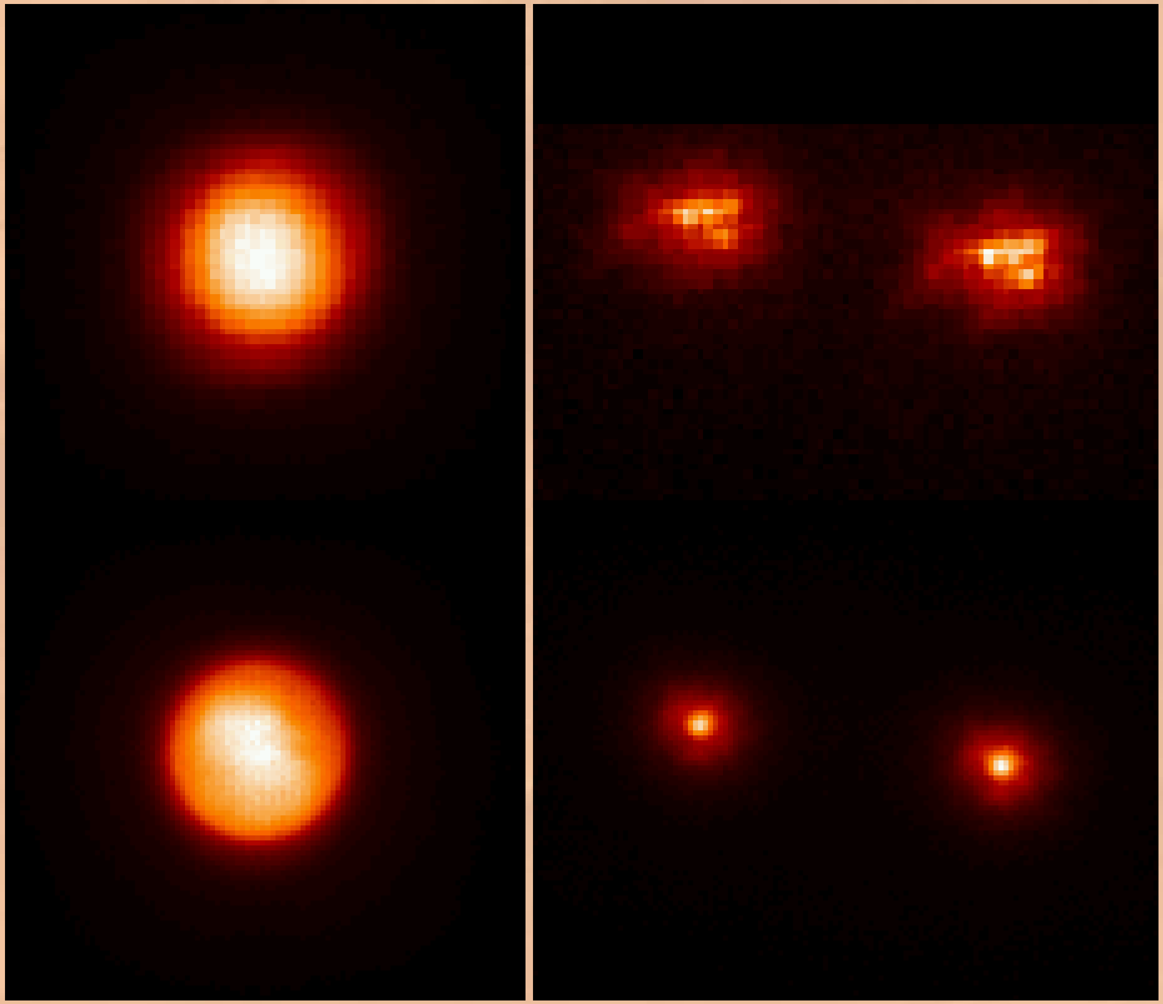
On Sky Results

- On 9/1/01 UT these methods were tried on the sky using the Palomar AO system.
- The seeing was ~0.7” at H band (R_0 = 12cm)
- Neptune (2.3”, H-band, measurements of Triton)
  - FWHM with nominal servo gains and centroid offsets: ~0.5”
  - FWHM with adjusted centroid offsets: ~0.3”
  - FWHM with adjusted centroid offsets and servo gains: ~0.2”
- Uranus (3.7”, H-band and measurements of moons)
  - FWHM with adjusted centroid offsets and servo gains: ~0.14”

Results from "Tuning" Titan

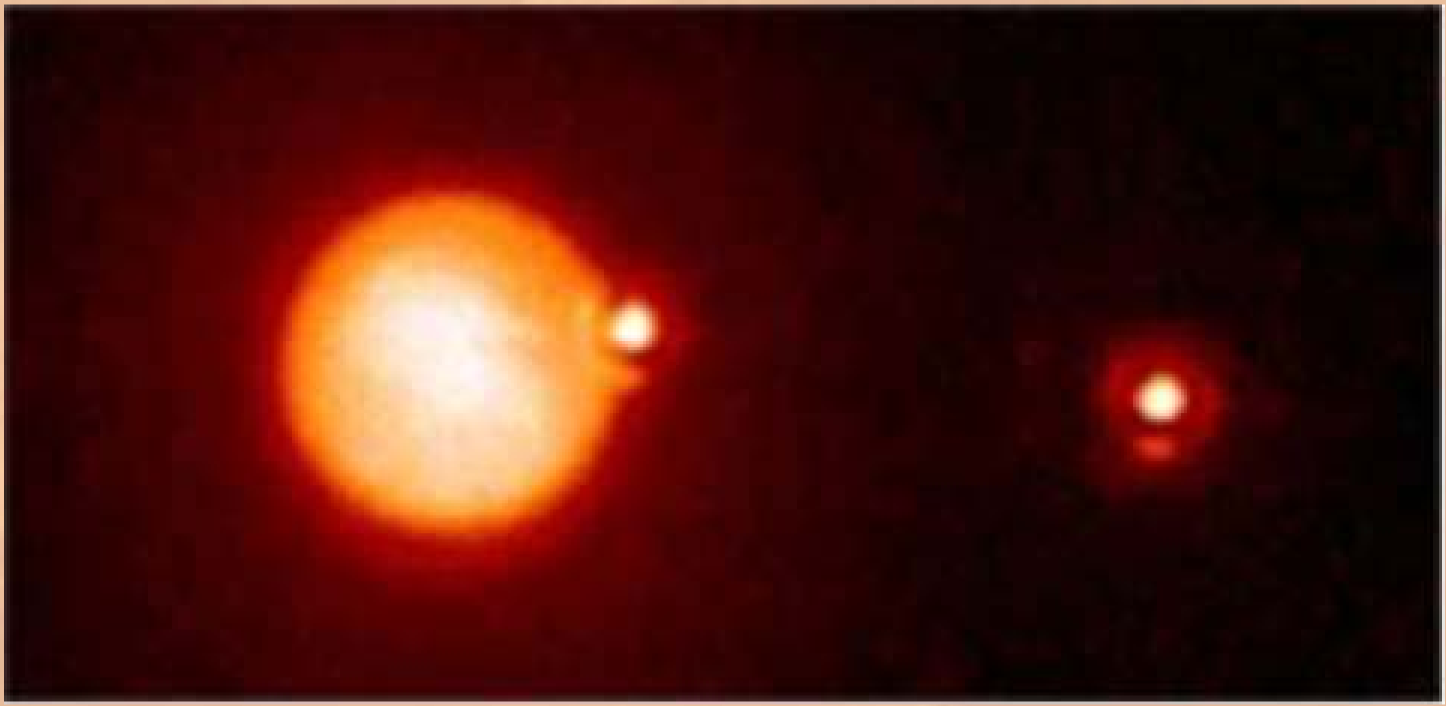
Before Tuning

After Tuning



~0.50 arcsec FWHM

~0.25 arcsec FWHM



PALAO/PHARO 2.2 μm image of Titan just starting to eclipse first star of a binary system. The binary separation is ~1.5 arcseconds.

Observations by Antonin Bouchez, Michael Brown, Robert West, Rick Burruss, Mitchell Troy, and Richard Dekany Data on 20-Dec-01 UT.

Extended sources as Guide Stars:
Summary

- Locking on extended sources degrades the AO lock
- Demonstrated science PSF FWHM improvement by ~2X by tuning system
- ONLY Rick and Jeff can currently execute this tuning
- If you will be locking on extended sources contact Rick or Jeff AHEAD of your observing run to coordinate system tuning
- Possible improvements to technique
  - Tune image using internal extended source
  - Automate [Veran and Herriot, J. Opt. Soc. Am A. August 2000]

“Color” of Guide Star

- Problem
  - Chromatic non-common path wavefront errors (from the WFS)
- Result
  - Currently tune the system to an internal source ~K5 or 700nm
  - Locking on objects of significantly different color will introduce aberrations into the wavefront.
  - In practice O, B, A and some F stars will be significantly out of focus.

“Color” of Guide Star (cont.)

- Current solution
  - Re-tune AO system while locked on the object of interest.
  - ONLY Rick and Jeff can currently execute this tuning
  - If you will be locking on such sources contact Rick or Jeff AHEAD of your observing run to coordinate system tuning
- Possible intermediate solution
  - Record the change in offset files for various colors of stars, problem is color is not well defined
- Long term solution
  - Replace WFS optics with non-chromatic design

DM to Lenslet Misregistration

- The DM actuators must be registered correctly to the lenslet subapertures to better then ~10% of a subaperture or image quality will suffer.
- An automated procedure is used to adjust the registration by moving the SSM's in "pupil mode"
- The registration is reoptimized when acquiring each new guide star
- Problem:
  - Dithering (moving the SSM's in image mode) will introduce some pupil motion.

DM to Lenslet Misregistration (cont.)

- Solution
  - After dithers of > 15 arcsec, ask AO operator to “register pupil”
  - Caveat: Registering the pupil will move the image slightly ~<0.5 arcseconds
- Implications
  - After large dithers to move science object readjust registration when object is close to final position
  - Don’t use PHARO macros for dithers greater than ~15 arcseconds
- Long term solution is better SSM’s
  - Design and cost estimates exist

System Performance Predictions

- What affects AO performance
  - Guide Star (magnitude, color, size)
  - Distance from Guide Star to science object
  - “Seeing”: $C_n^2(h,t)$, $V(h,t)$, r_0, mirror temperature, L_0
  - Airmass
    - Larger airmass degrades effective seeing, increases rate of non-common-path flexure
  - Variable sky conditions
  - Wavefront sensor background level
    - Changes when moon rises (or near sunrise)

AO scaling laws

Parameter	Wavelength	Zenith angle
– Fried's parameter (r_0)	$\lambda^{6/5}$	$(\cos \zeta)^{3/5}$
– Seeing width (λ/r_0)	$\lambda^{-1/5}$	$(\cos \zeta)^{-3/5}$
– Degrees of freedom (N_0)	$\lambda^{-12/5}$	$(\cos \zeta)^{-6/5}$
– Greenwood time delay (t_0)	$\lambda^{6/5}$	$(\cos \zeta)^{3/5}$
– Isoplanatic angle (θ_0)	$\lambda^{6/5}$	$(\cos \zeta)^{8/5}$
– Required WFS signal ($\gamma/m^2/s$)	$\lambda^{-18/5}$	$(\cos \zeta)^{-9/5}$

PALAO Predicted Bright Guide Star Performance

Atmospheric Condition	r_0 [cm @ 0.5 μm]	7	10	10	10	15	15
	Wind speed [m/s]	10	15	10	5	10	5
	Seeing [arcseconds @ 0.5 μm]	1.5	1.0	1.0	1.0	0.69	0.69
High Order Error Terms	Telescope [nm]	96	96	96	96	96	96
	Calibration [nm]	100	100	100	100	100	100
	Atmoshperic Fitting [nm]	138	102	102	102	73	73
	Bandwidth [nm]	266	277	198	139	141	79
	σ_{TOTAL} [nm]	330	326	262	205	211	176
	Strehl @ 2.2 μm	0.41	0.42	0.57	0.71	0.69	0.78
	Strehl @ 1.25 μm	0.06	0.07	0.17	0.34	0.32	0.46
Low Order Error Terms	Bandwidth [mas]	21	23	15	8	11	5
	Strehl @ 2.2 μm	0.79	0.75	0.87	0.96	0.93	0.98
	Strehl @ 1.25 μm	0.55	0.49	0.69	0.90	0.81	0.94
Predicted Performance	Strehl @ 2.2 μm	0.32	0.31	0.49	0.68	0.65	0.76
	Strehl @ 1.25 μm	0.03	0.03	0.12	0.31	0.26	0.43

Imaging

Mitchell Troy
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Imaging Outline

- Flat fields
- Skies
- PHARO sensitivity
- Background limited observations

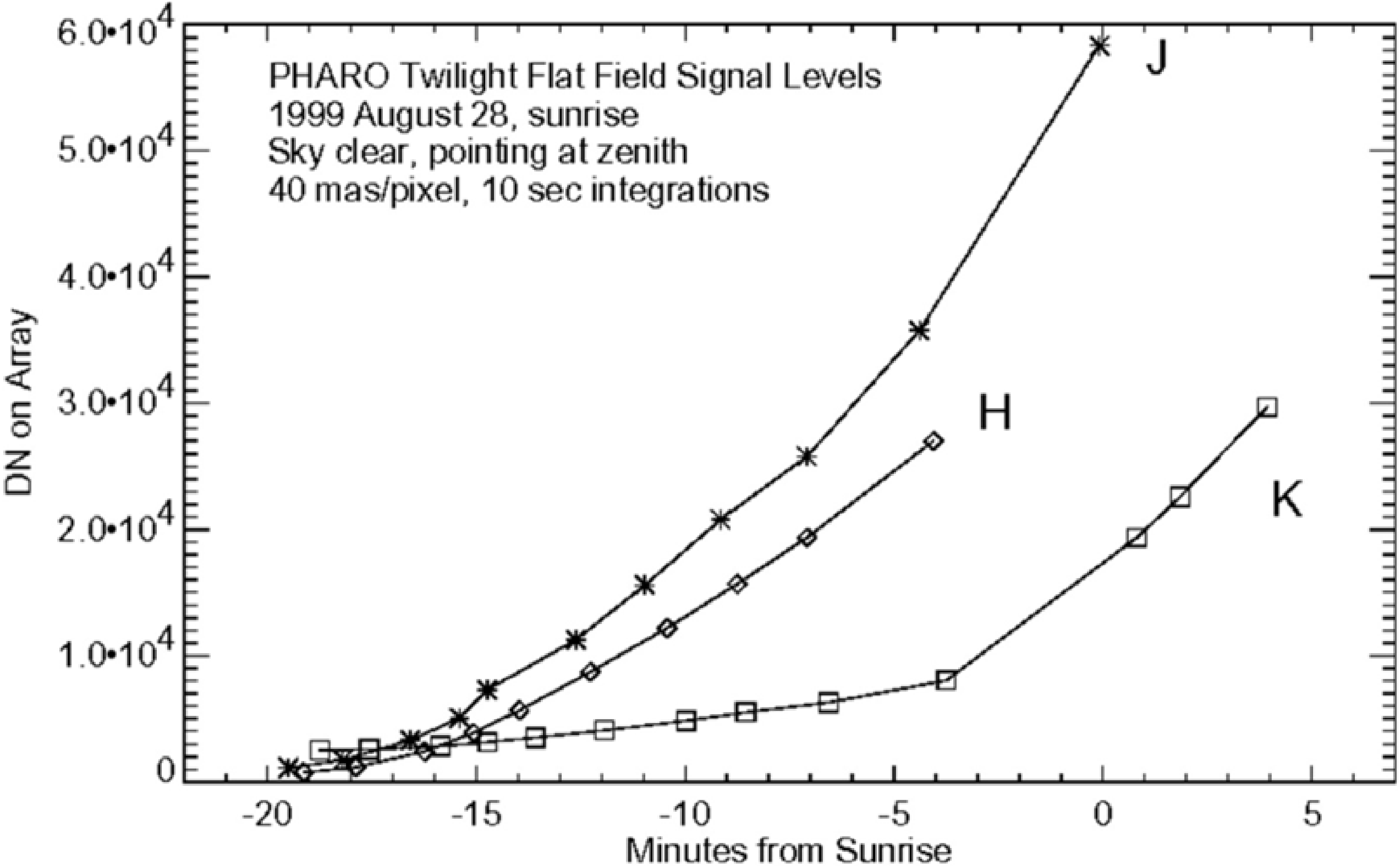
Taking Flat Fields

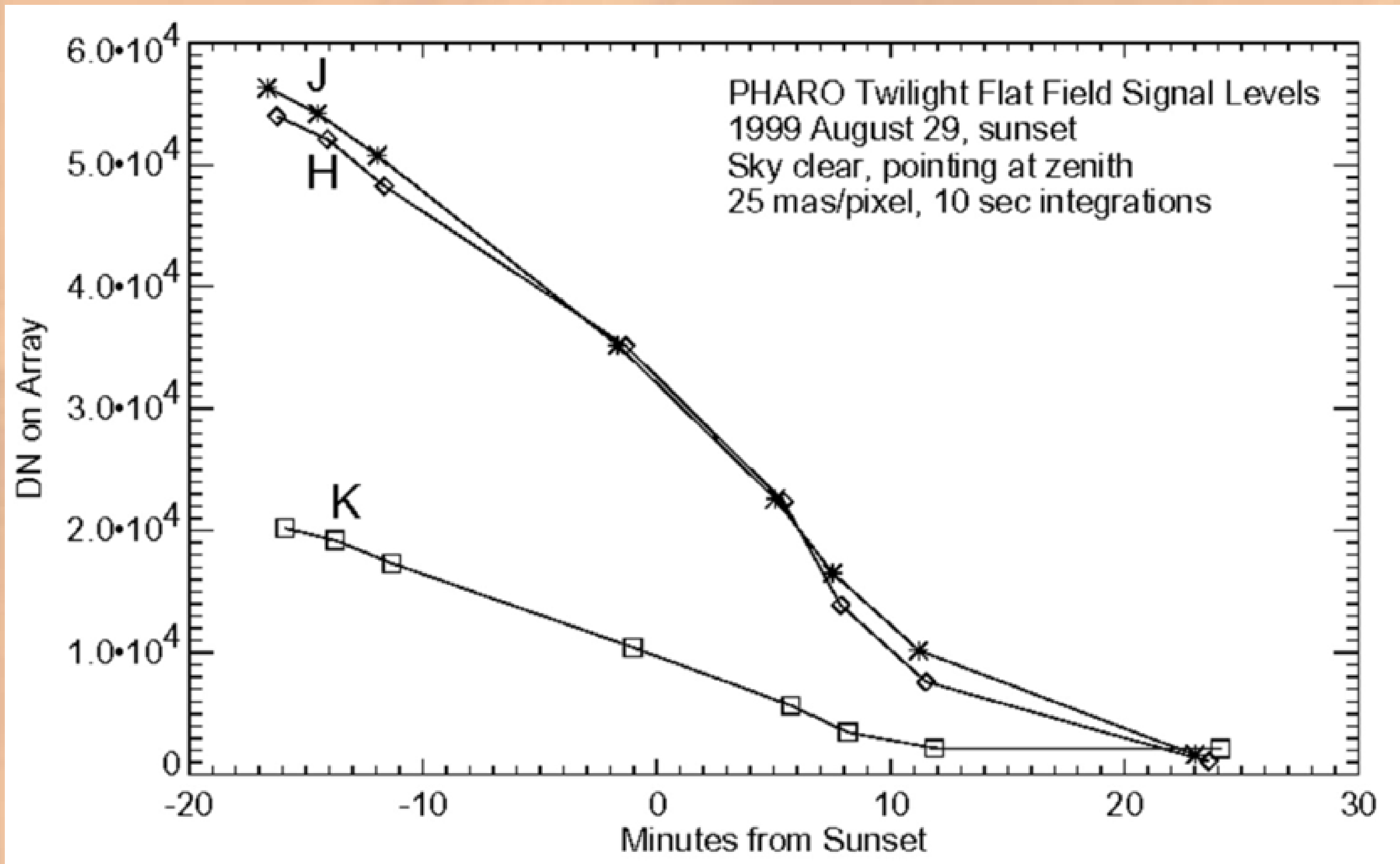
- Typically use twilight flats, have never tried “dome” flats
- Twilight flats need to be started at least 20 minutes before sunset or continue 20 minutes after for broadband filters. Narrow band K filters can require 1 hour.
  - Remember to schedule this extra time when filling out “green sheets”

- The following taken from Tom Hayward’s, “PHARO Operation Manual”, see http://ao.jpl.nasa.gov, “Technical information for users” link.

A Flat Fielding Procedure

- Point telescope at Zenith and turn off tracking.
- Open dome and mirror covers and set AO to pass light to PHARO.
- Set the integration time to about 10 sec.
- Set the carousel to 40 mas/pixel mode.
- Set the Slit to 40 field mask, Lyot to Block, Grism to Open.
- Take 1 or 2 bias frames with Lyot wheel set to block, save in Bgd buffer.
- Take images with J, H, K filters about once every 5 minutes. Ideally, the signal level should be at least a few thousand counts (to be well above the read noise) and the range of signal as the sky brightens or darkens should be a few x 10,000.
- Set Lyot wheel to Block when finished.
- Take another bias frame with the Lyot on Block.
- This is a good time to take other bias frames


PHARO Twilight Flat Field Signal Levels
1999 August 28, sunrise
Sky clear, pointing at zenith
40 mas/pixel, 10 sec integrations
J
H
K
DN on Array
0
1.0•10^4
2.0•10^4
3.0•10^4
4.0•10^4
5.0•10^4
6.0•10^4
-20
-15
-10
-5
0
5
Minutes from Sunrise



PHARO Twilight Flat Field Signal Levels
1999 August 29, sunset
Sky clear, pointing at zenith
25 mas/pixel, 10 sec integrations
J
H
K
DN on Array
Minutes from Sunset
6.0•10⁴
5.0•10⁴
4.0•10⁴
3.0•10⁴
2.0•10⁴
1.0•10⁴
0
-20
-10
0
10
20
30

Obtaining Sky Frames

	Dithering	Nodding
Overheads	~20 sec to move 15 arcsec	~20 sec to move telescope, open/close AO loops
Degradation in image quality	~10% in Strehl unless ask AO operator to re-tune DM-to-lenslet registration (~30 sec)	None
Imaging efficiency	100%	50%
Image position on array	Moves	Stationary (except for flexure)

Obtaining Sky Frames (cont.)

- In most cases it makes sense to dither and have AO operator re-tune if optimal image quality is important
- There is currently no mechanism to have PHARO macros adjust the DM-to-lenslet registration.
- For coronagraphic observations nodding is the only real choice

PHARO Sensitivity

TABLE 9

Bright Guide Star Point-Source Sensitivity[a]

Filter	Strehl Ratio	ROI Diameter[b] (arcsec)	Fractional Flux[c]	m for S/N = 10 in 3600 s[d]
J	0.062	0.275	0.31	22.0
H	0.14	0.250	0.31	21.7
K′	0.33	0.225	0.32	20.5

[a] Guiding on 47 UMa, $V \approx 5.1$, visible seeing ≈1″.1.

[b] Diameter of region of interest (ROI).

[c] Fraction of star's flux within the ROI.

[d] Half this time is spent on the source, the other half on the sky.

From Hayward, PASP **113, pp** 105-118 2001 January

Background Limited Observations

- ~2 seconds for K band filter
- ~20 seconds for J band filter
- Can determine if background limited by looking at PHARO histogram
  - View source
  - Put photometry box over a large section of chip
  - Look at histogram
    - A Gaussian at ~40 ADU or higher indicates background limited
    - An exponential distribution is indicative of being read noise limited

PHARO Image Reduction Software

Name/Contact	Language	Features	Comments
"AOred" Mitchell Troy http://huey.jpl.nasa.gov/~mtroy/AOred	IDL C – for Strehl estimation	•Pipeline of basic IR processing •Calculates bad pixel maps, flat fields •Estimate Strehls	New version to be posted by 3/15/02
Matthew Britton	C++	•Automated reduction of PHARO and NIRSPEC data	Object-oriented library of functions
Others (?)	?	?	?

Spectroscopy

Antonin Bouchez
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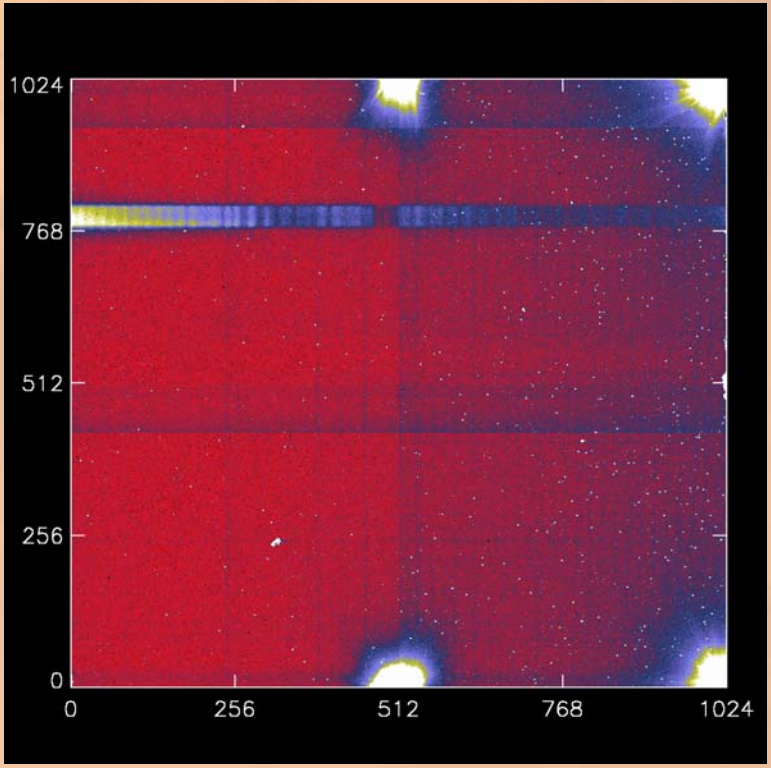
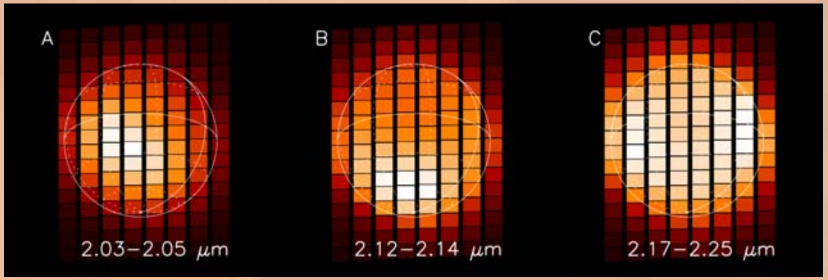
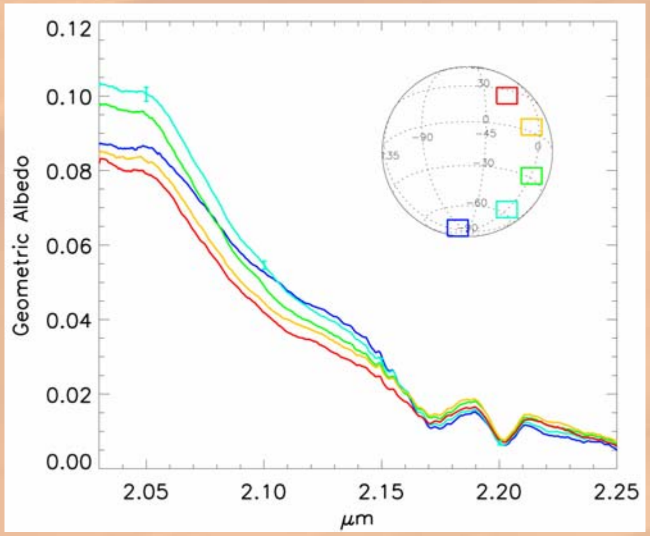
PALAO/PHARO Spectroscopy







PALAO/PHARO Spectroscopy Outline

- Observing strategy
- Options for flats
- Detector fringing
- Typical observing sequence
- Typical reduction sequence

Observing Strategy

- Subtraction of a sky spectrum removes bias, dark current, & sky emission (OH airglow lines and thermal background).
  - Alternatively: one can subtract a dark frame and measure the sky emission along-slit.
- Division by an imaging flat corrects for ~10% pixel gain variations.
- Division by a calibrator star spectrum corrects for atmospheric and instrumental transmission.
- Wavelength scale and slit angle determined from sky lines.
- Grism angle determined from target or cal. star spectrum.
- Photometric calibration performed by comparison to a calibrated narrow-band image of the target.

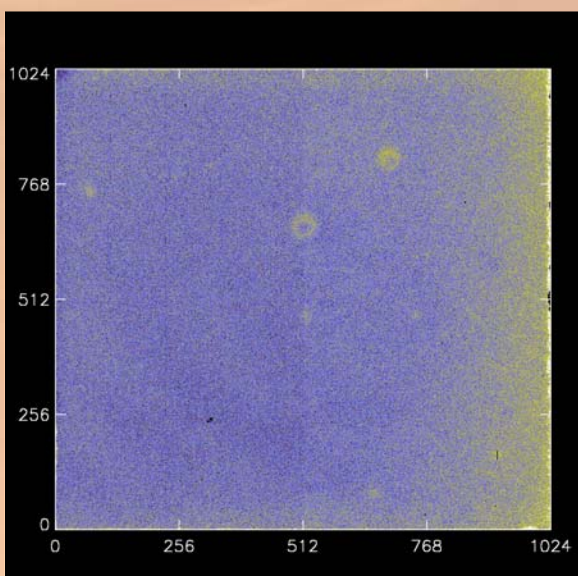
Note:

Slit and grism angle are not precisely repeatable. Therefore, you must devise an observing sequence which allows you to not change these between object and sky, target and calibrator star.

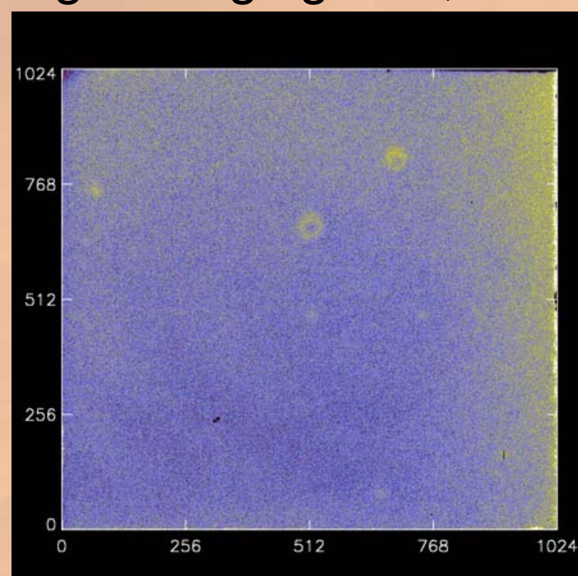
Necessary calibration frames: Flats

- Twilight sky spectra are not acceptable, since detector fringing pattern is not repeatable due to small shifts in wavelength scale. Dome spectra immediately after target/calibrator might be OK.
- Broadband twilight imaging flats seem to work well. Subtract dark frame of same integration time from each twilight image.

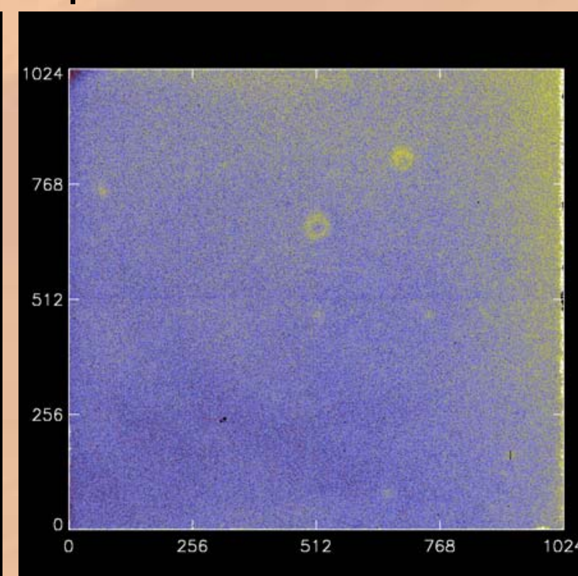
K’ twilight imaging flats, 0.040 ”/pix



26 Sep. 1999



20 Jul. 2000

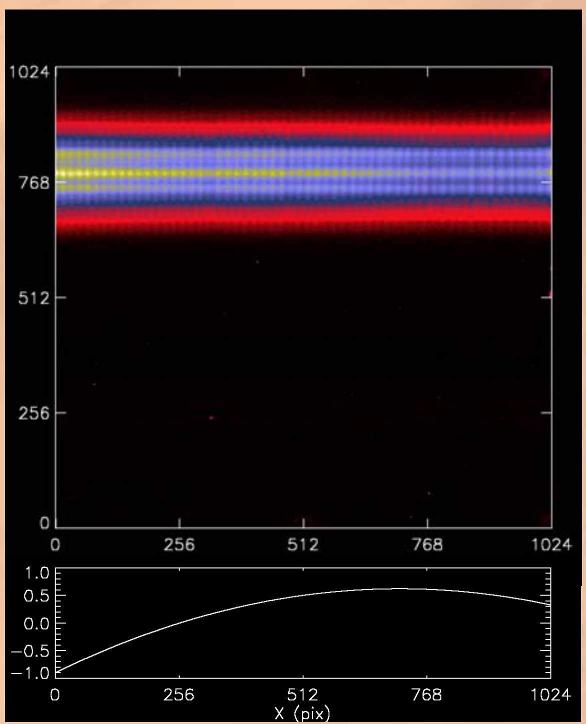


20 Dec. 2001

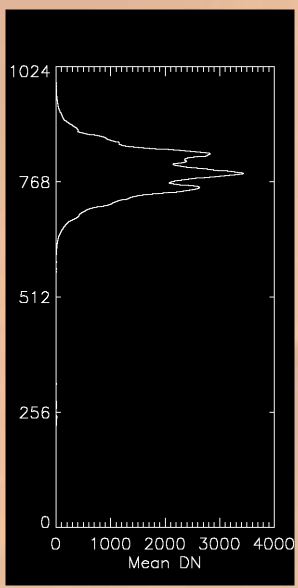
Necessary calibration frames: Flats

- Another option is to combine your pixel gain map with the atmospheric transmission measurement, e.g. by dividing the open-loop spectrum of a G5 star by the mean counts in each detector row.

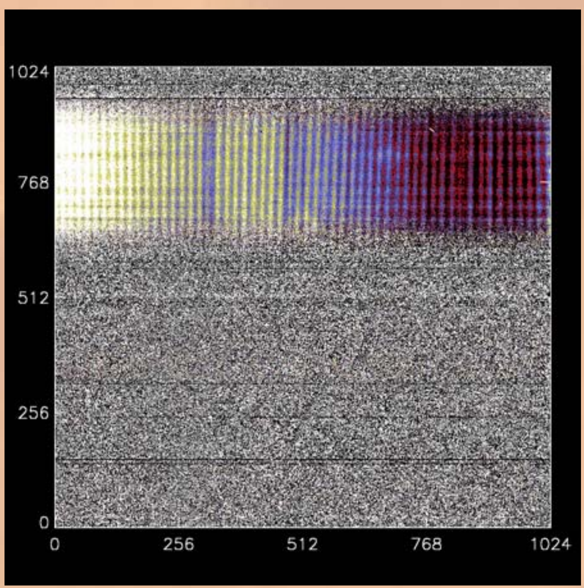
HD32923, 4x60s, K, 0.025 “/pix



1. Correct grism angle



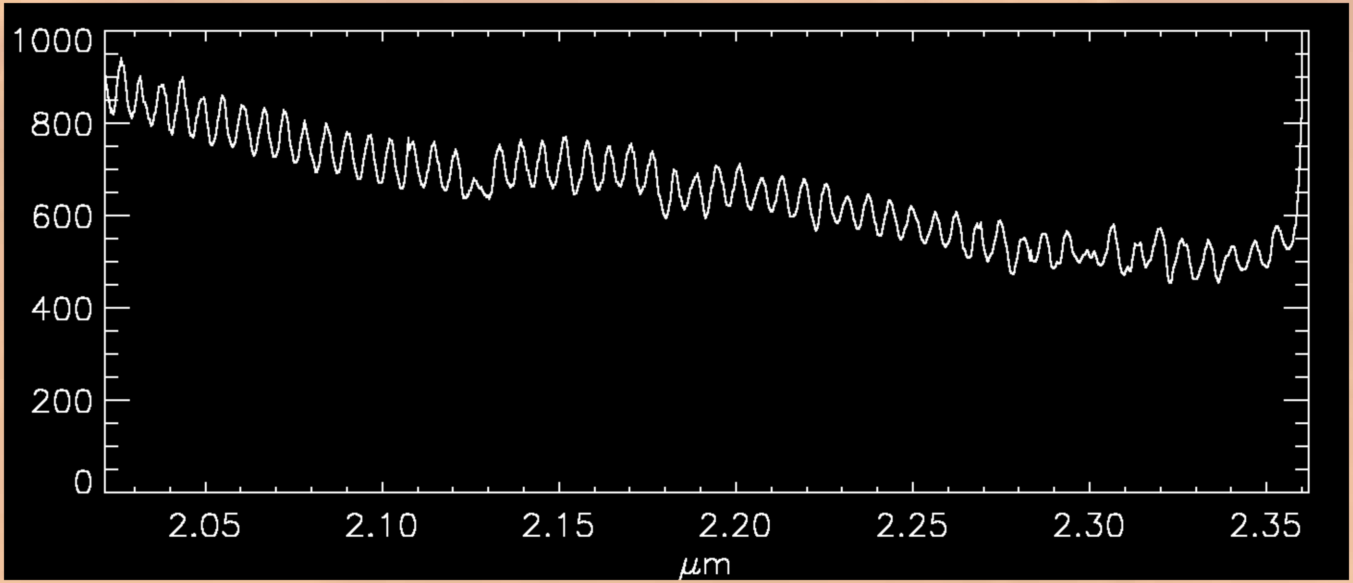
2. Divide by row mean



Result

Detector fringing

- Fringing is present at ~20% level in H and K spectra taken with PHARO. Since it is a function of both detector position and the wavelength of incident light, it varies with slit and grism position. The **only** way to deal with it is to acquire a spectrum of a calibrator star without moving either the grism of slit wheels.

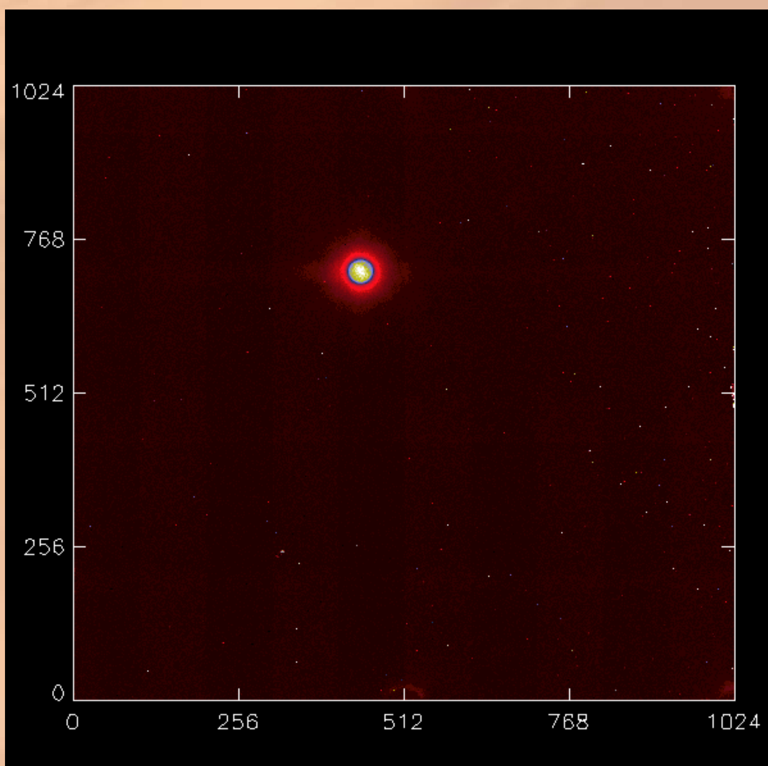


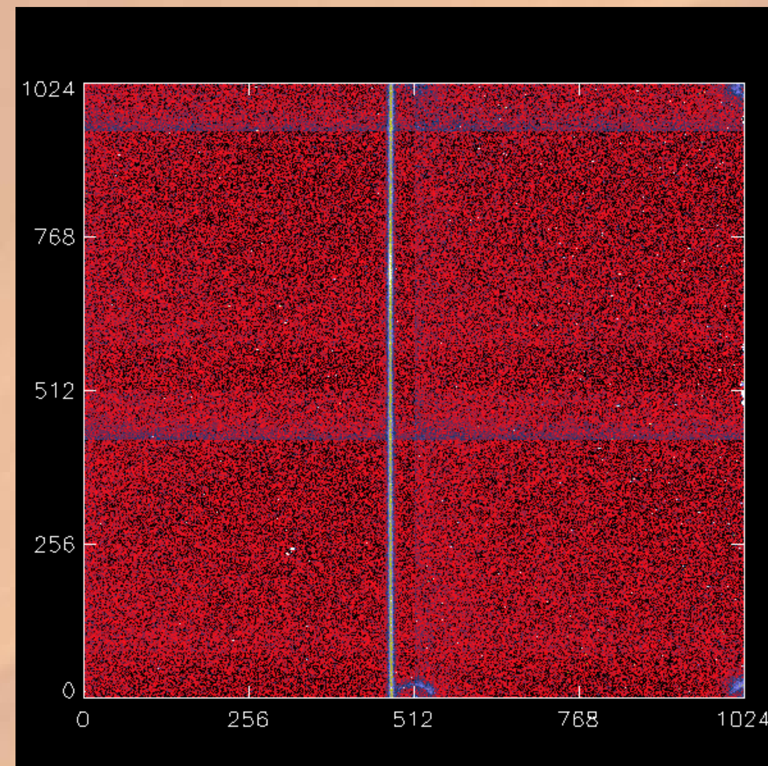
HD32923, 4x60s, K, 0.025 “/pix

Typical observing sequence

(Titan K spectral scan, 20 Dec. 2001)

1. Image slit to *roughly* determine its position and angle. (2s integ., K, 0.025 "/pix, 0.13" slit)

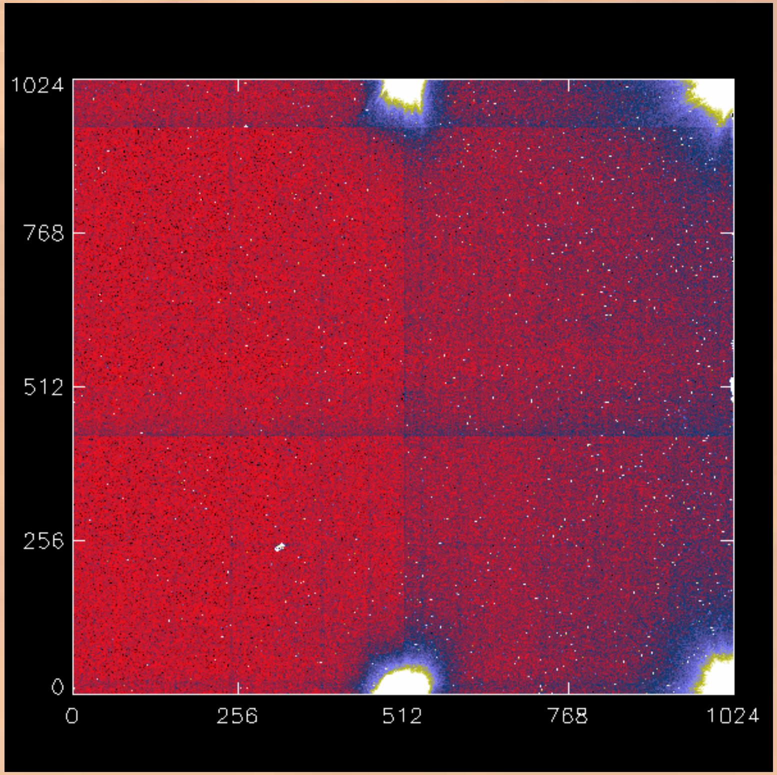


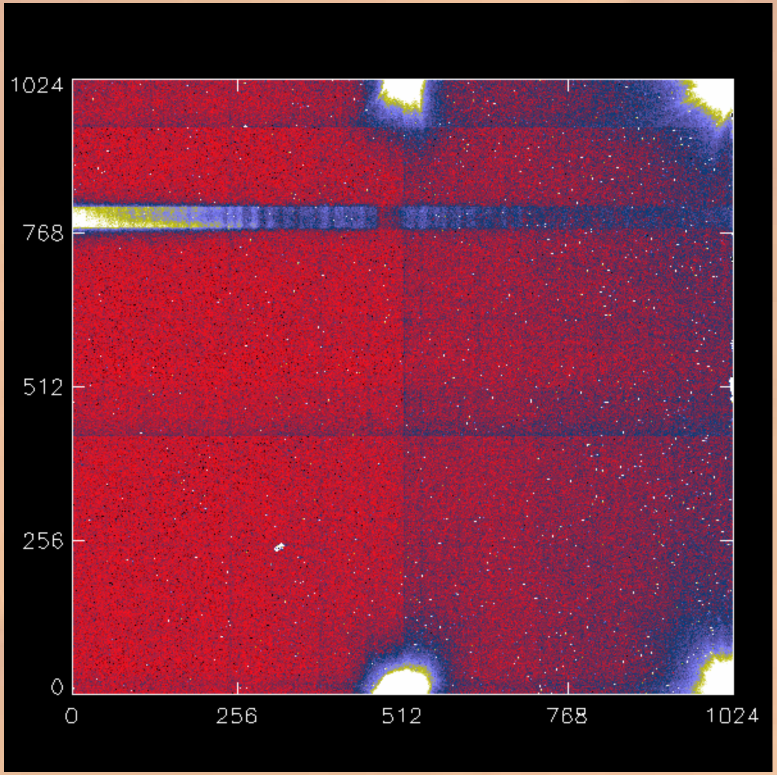


2. Determine which direction non-common path flexure is taking target. Steer target onto slit.

Typical observing sequence (cont.)

3. Target spectra – in this case a set of 21, stepping 0.10” with flexure drift. (120s integ., K, 0.025 “/pix, 0.13” slit)

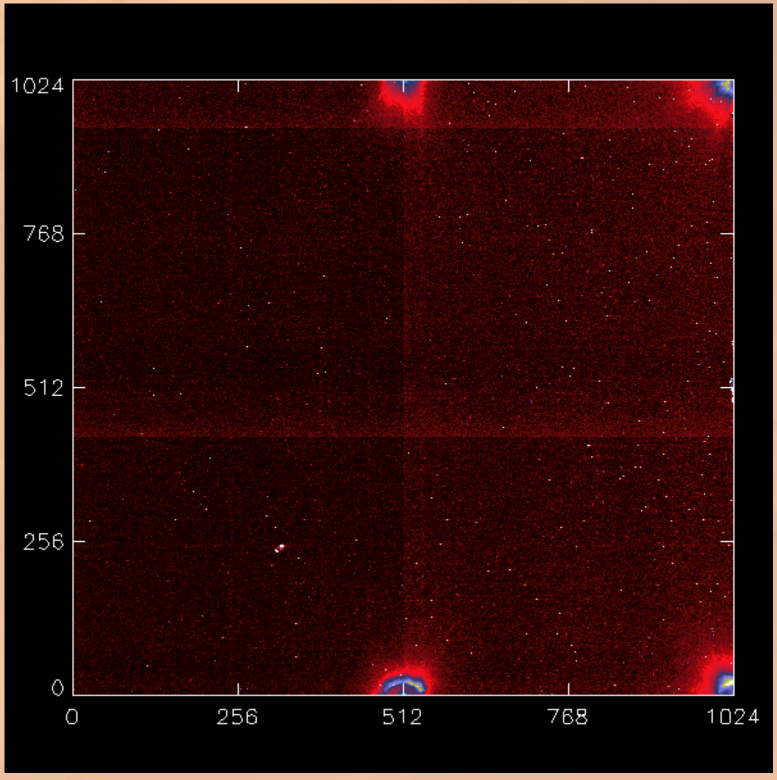


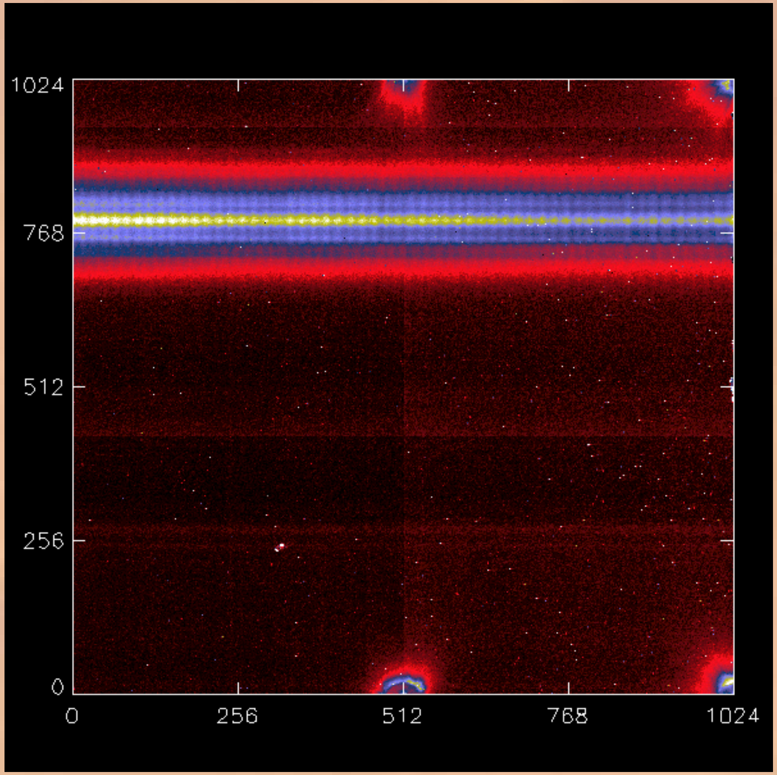


4. Nod 60” and take sky spectra

Typical observing sequence (cont.)

5. Take open-loop cal. star (early O or G5) spectrum **without moving slit or grism**. (HD32923, 60s)

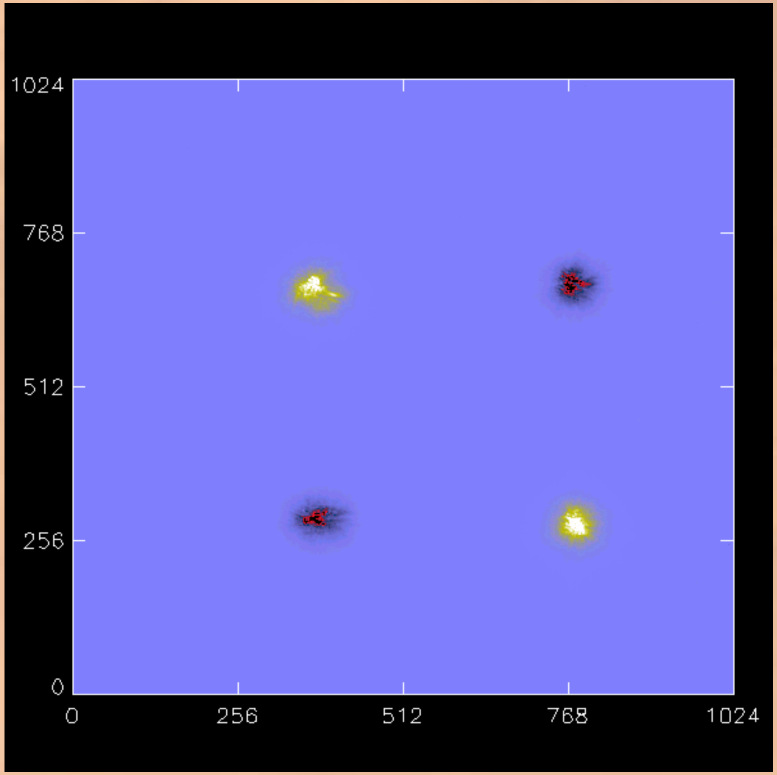


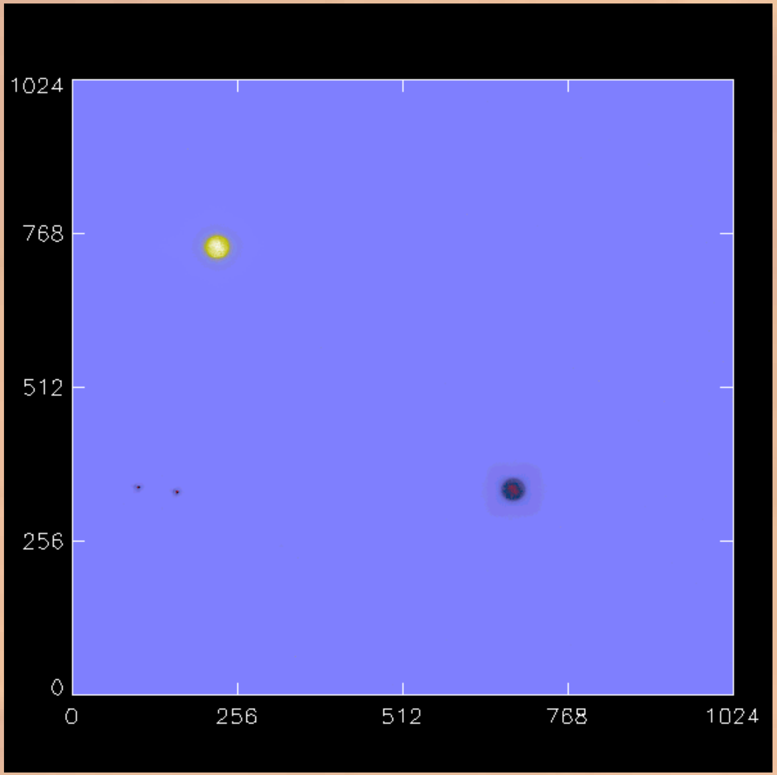


6. Nod 60” and take sky spectra

Typical observing sequence (cont.)

7. Narrow-band images and sky frames (or dithered images) for photometric calibration. (2x10s, K’)

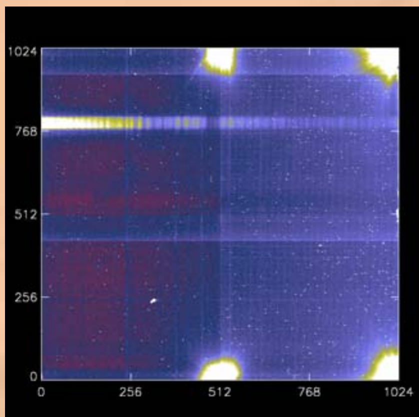




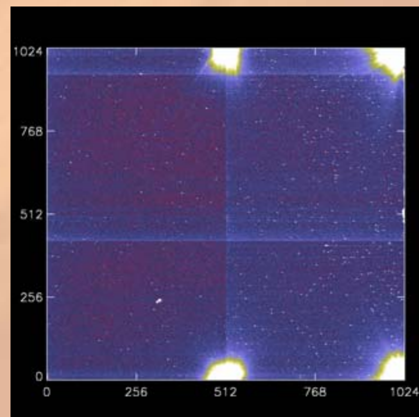
8. Narrow-band open-loop images of photometric calibration stars. (BS 816, open-loop, 4 x 2s, K’)

Typical reduction pipeline

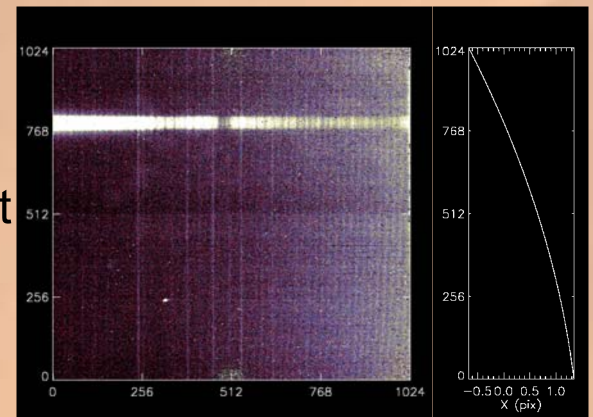
1. Determine slit angle and wavelength scale from mean target spectrum



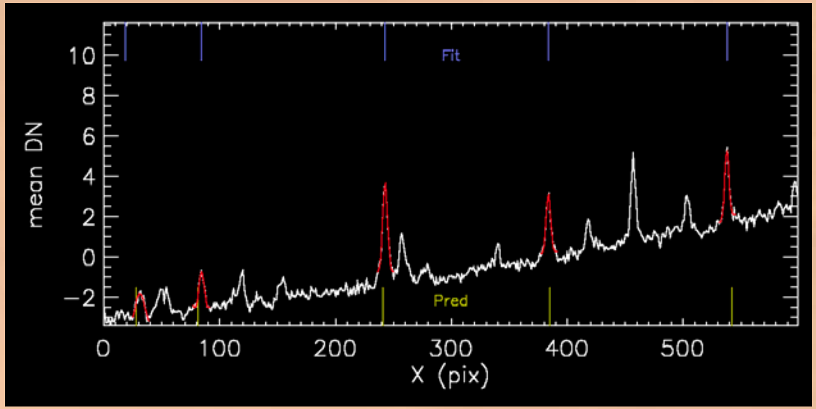
-

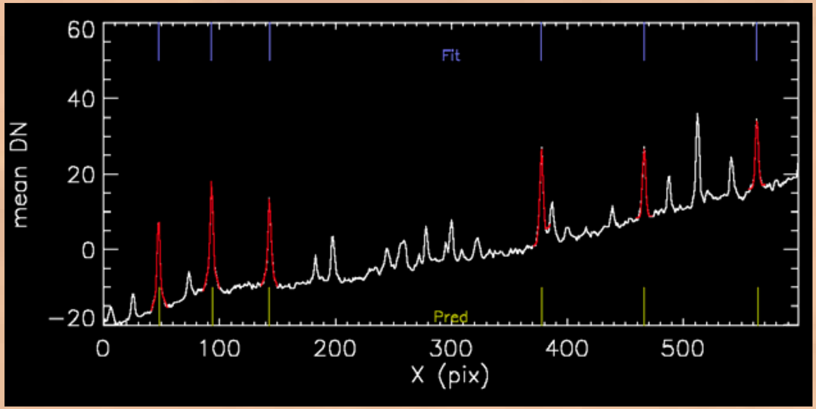


÷ flat



mean of 21x120s Titan spec. mean 120s dark Fit 2nd order poly. to sky lines.



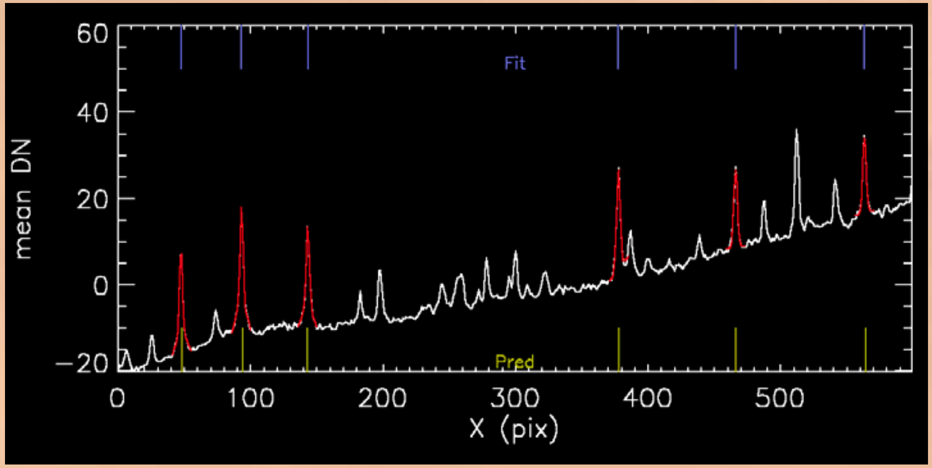


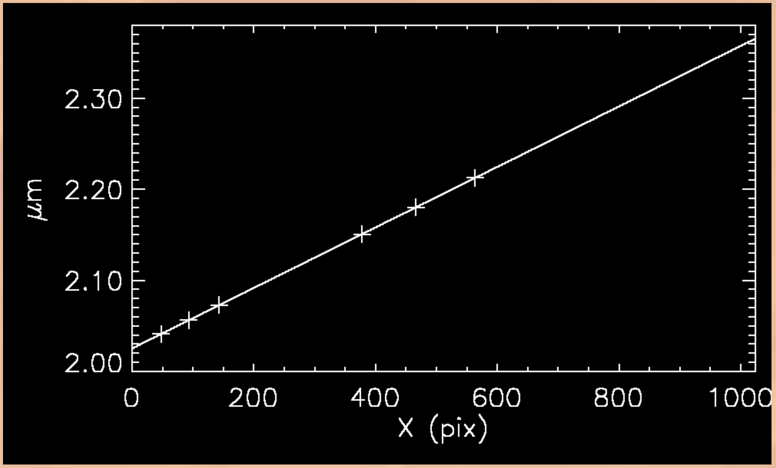
0.025 "/pix linear fit to OH line position;s vs. wavelength 0.040 "/pix
(see next slide)

Typical reduction pipeline (cont.)

(Using OH Meinel lines to determine wavelength scale)

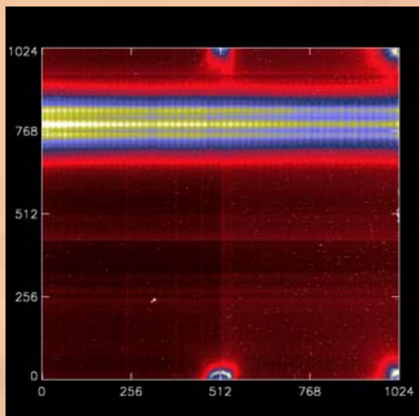
- A good line list with typical intensities:
  http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/oh.html
- Lines which I use (K band):
  0.025 "/pix: 2.10680, 2.11766, 2.15073, 2.18022, 2.21255 μm
  0.040 "/pix: 2.04127, 2.05636, 2.07290, 2.15073, 2.18022, 2.21255 μm
- General procedure:
  1. Subtract a dark frame from as deep as spectrum as available.
  2. Measure slit angle and curvature by cross-correlating rows.
  3. Correct slit angle and curvature, sum over slit to get sky spectrum.
  4. Fit Gaussians to 5-6 lines, fit linear wavelength scale to positions.





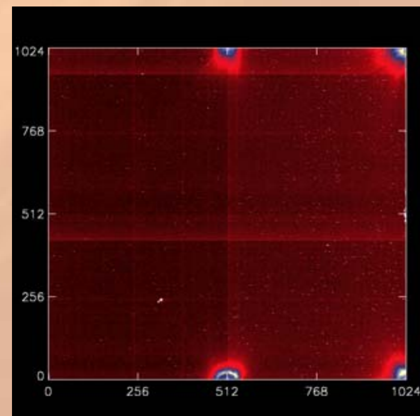
Typical reduction pipeline (cont.)

2. Reduce calibration star spectra



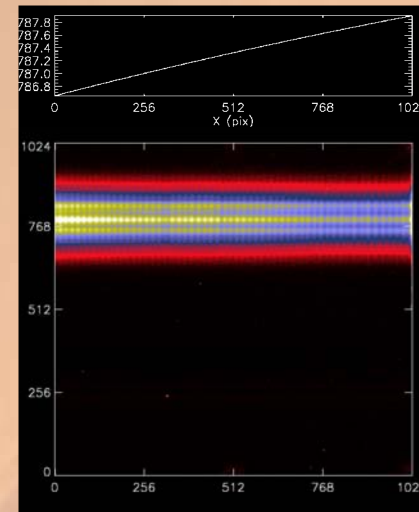
mean of 4x60s cal. spec.

-

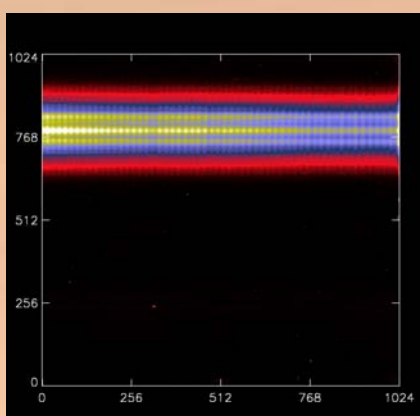


mean 60s sky spec.

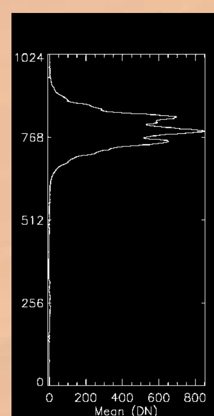
÷ flat

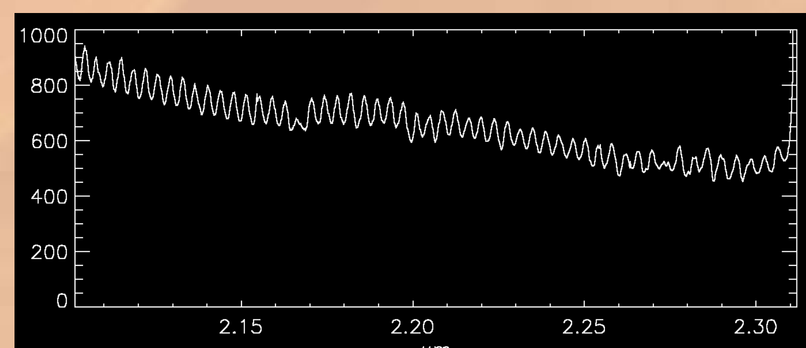


measure grism angle



rectify slit & grism angles

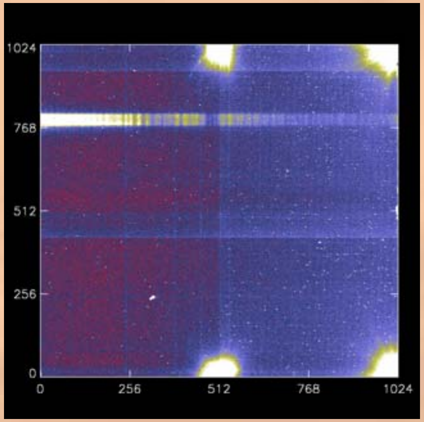




Extract weighted mean 1D spectrum

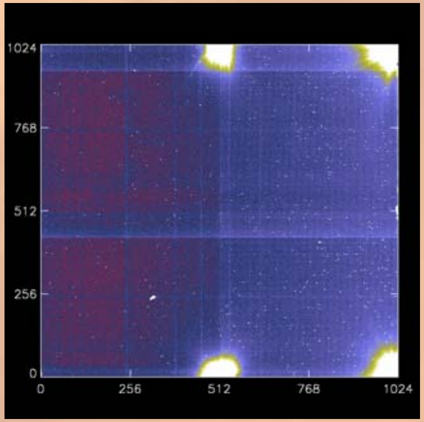
Typical reduction pipeline (cont.)

3. Reduce individual target spectra



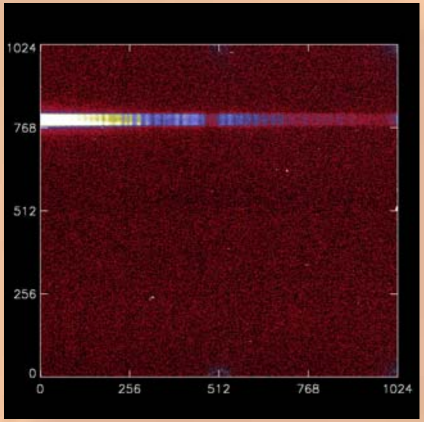
120s target spec.

-

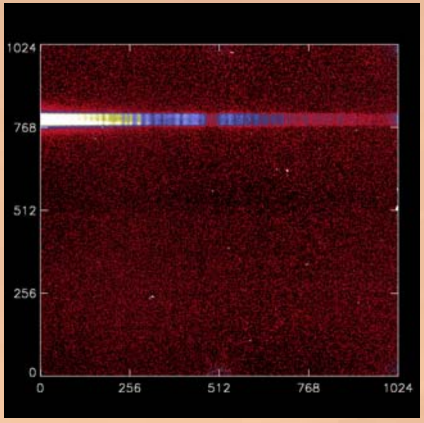


mean 120s sky spec.

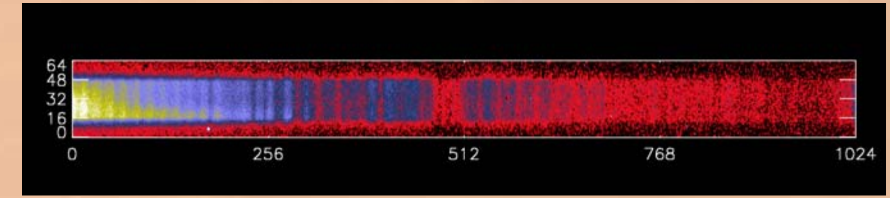
÷ flat



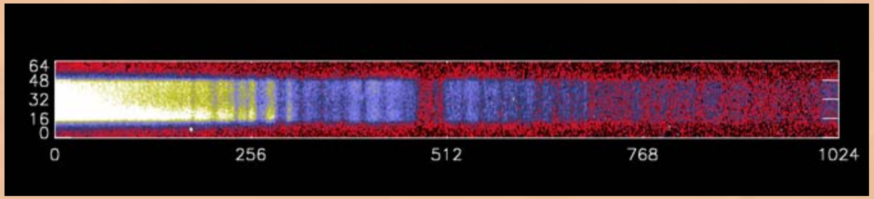
looks better…



rectify slit & grism angles



before…



…and after division by cal. star spectrum

Coronagraphy

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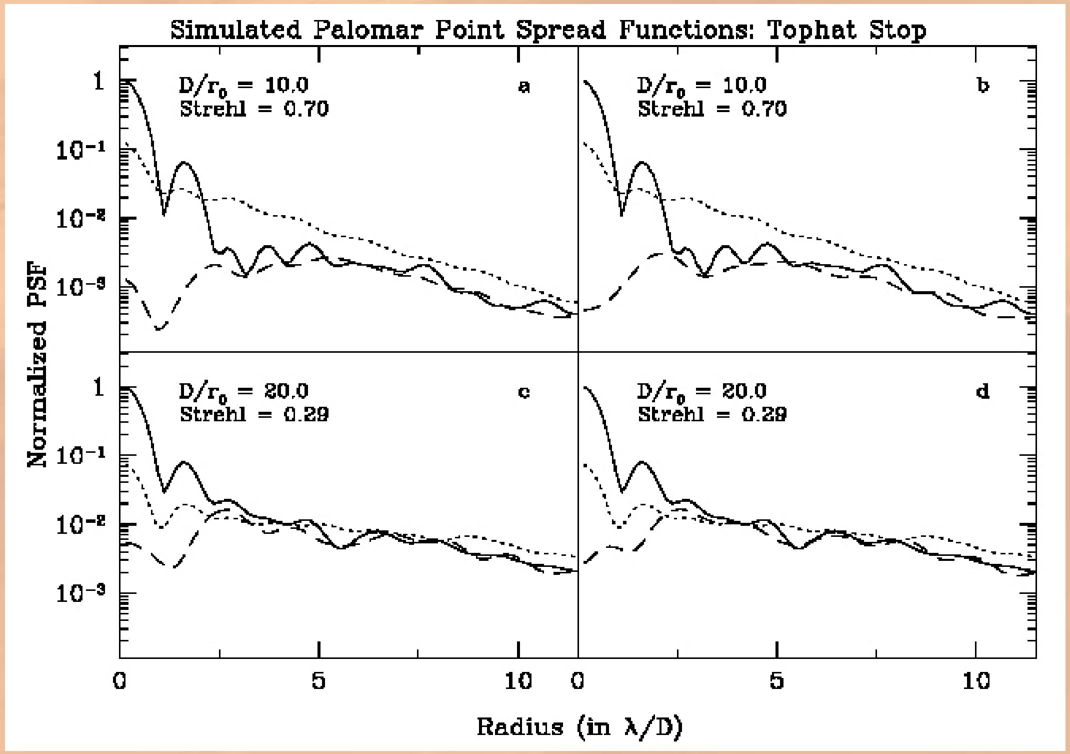
Coronagraphy

- Function of a coronagraph
- Contrast limitations
- Non-common path flexure
- Calibration strategies

Function of a coronagraph

- Used to suppress *diffraction*
  - Does not suppress residual seeing halo, so use limited to high Strehl ratio correction
- AO correction
  - A deformable mirror with N actuators across the primary diameter can control the PSF within a spatial frequency (angular radius) range $0 < k < N\lambda/2D$
    - k_{max} (2.2 μm) = 0.71 arcsec at Palomar for current N=16 system
      - k_{max} (2.2 μm) = 1.78 arcsec for proposed N=40 upgrade

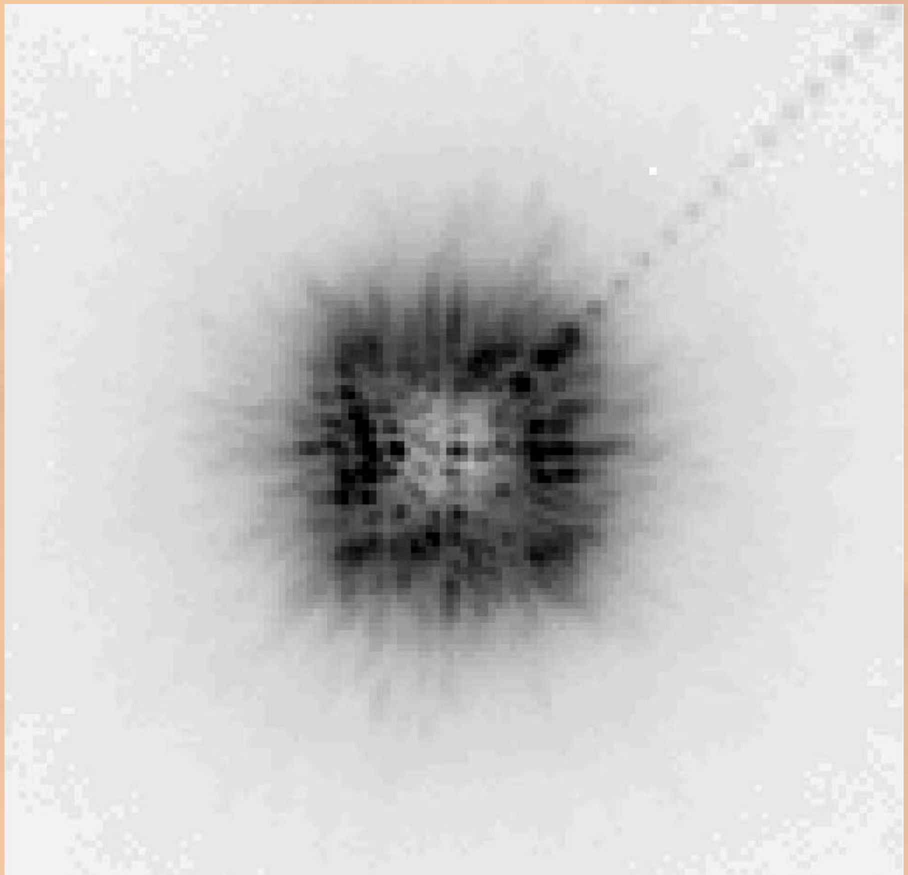
PALAO coronagraph predictions



- Azimuthally averaged PSFs for PALAO, assuming an occulting mask of 3l/D, and normal Lyot masking (left column) and aggressive masking (right column). Curves are AO-corrected PSF (solid), AO+coronagraph PSF (dashed), and seeing-limited PSF (dotted).

From Makidon, et. al., “Ground-based coronagraphy with high order adaptive optics”, SPIE 4007, (2000).

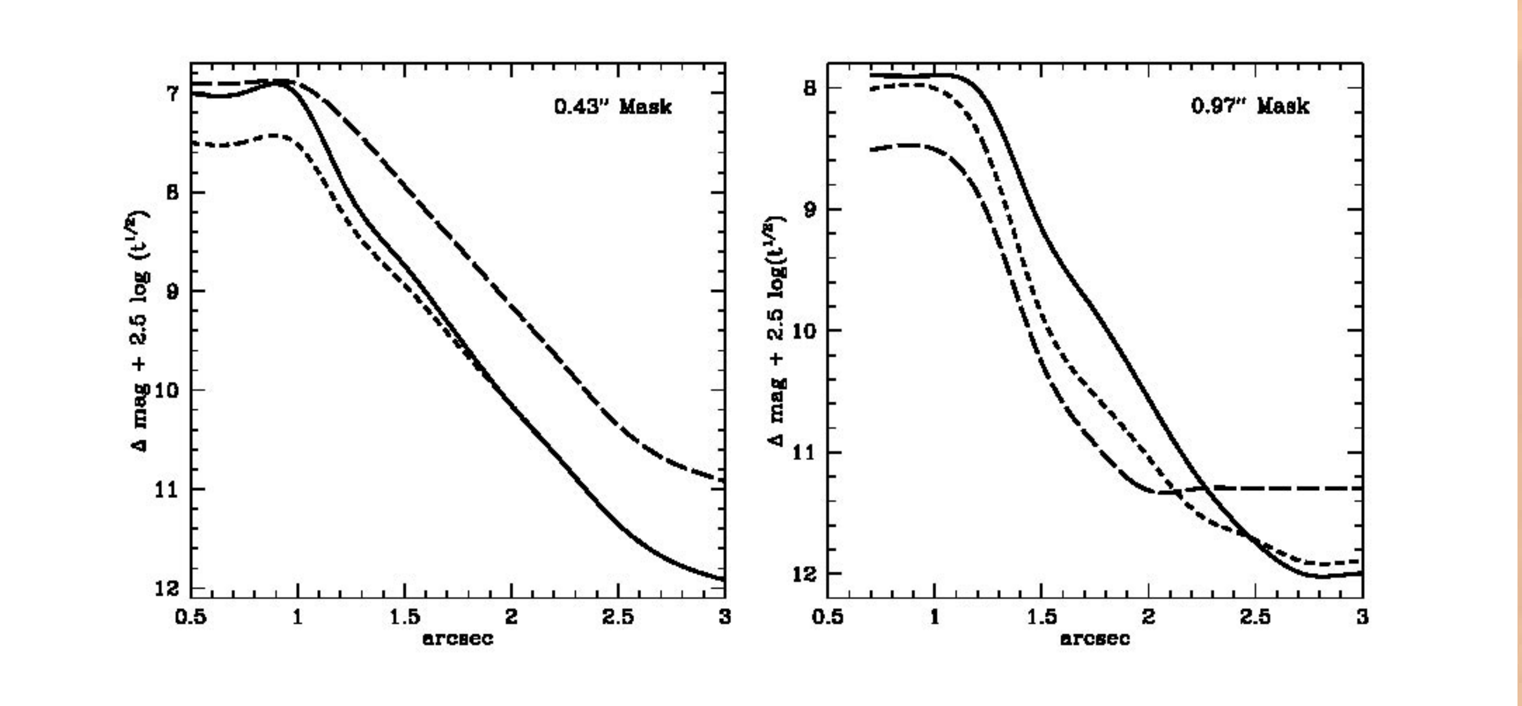
PALAO/PHARO coronagraph example



- A 256x256 pixel portion of a PHARO image of Gl 614 using the 0.97” (~ 9 λ/D) coronagraphic stop and the Big Cross Lyot mask
- Plate scale is 25 mas/pixel
- Total integration time 180 sec
- Artificial sources (5σ detection) introduced along 45 degree angle to produce sensitivity curves (next slide)

From Oppenheimer, et. al., “Companion Detection Limits with Adaptive Optics Coronagraphy”, SPIE 4007, March 2000.

PALAO/PHARO coronagraphic contrast limits

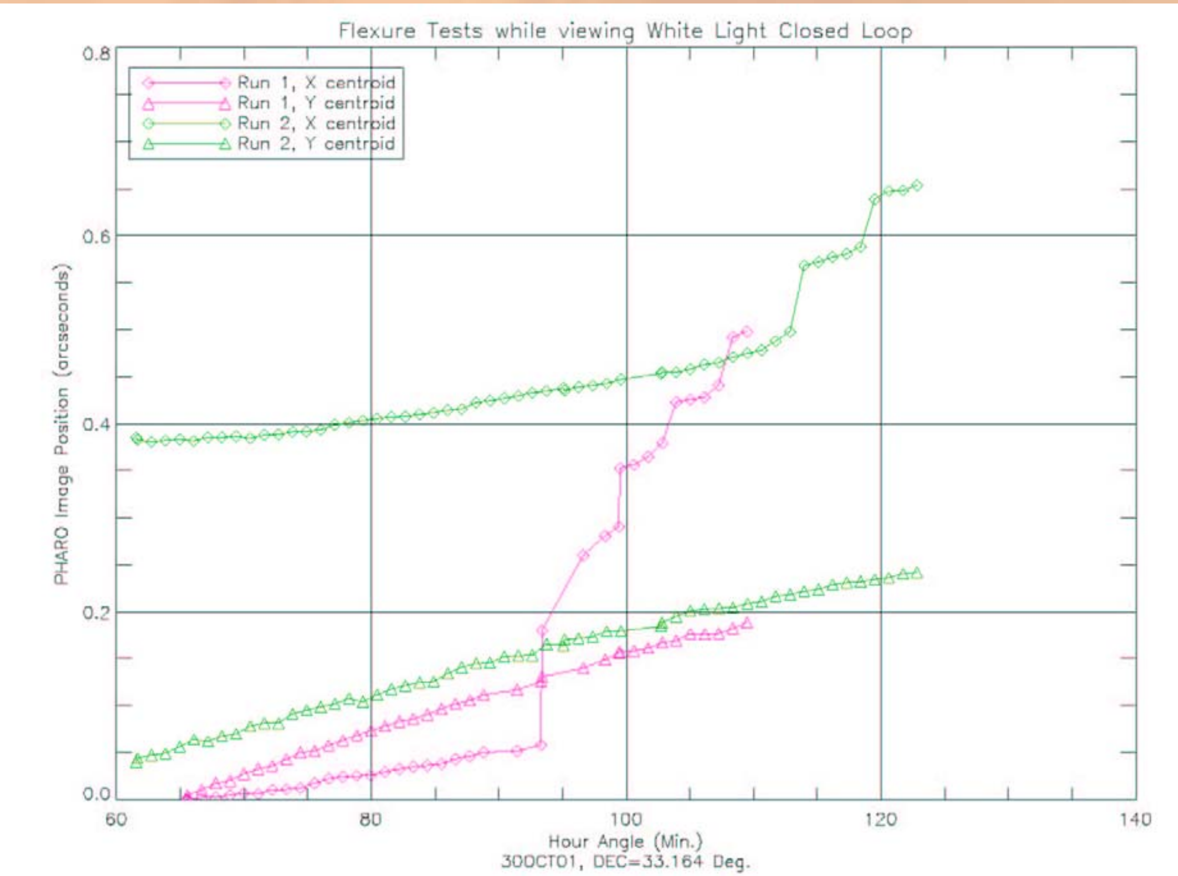


- Azimuthally averaged 5σ detection limits for faint point source near bright star in K-band. The three curves correspond to standard cross (solid line), medium cross (short dashed), and big cross (long dashed) Lyot masks.
- The curves are presented as magnitude difference from the bright star (in this case mK ~ 4) for 1 second of exposure. The azimuthal variation is less than 0.2 mag in all cases.

From Oppenheimer, Dekany, Troy, Hayward, Brandl, "Companion Detection Limits with Adaptive Optics Coronagraphy", SPIE 4007, March 2000.

Non-common path flexure

(Analysis by M. Troy and J. Eisner)



- Experimental results with PALAO locked on internal white light source
- Curves are observed image motion on PHARO
- Later experiments did not repeat the x-centroid 'jumps'

PSF calibration strategies

- PSF calibrator star
  - Alternate between target and PSF calibrator star
    - Same magnitude (to within ~0.5 mag (bright) or ~0.1 mag (faint))
    - Same color
    - Nearby on sky (same airmass and same gravity vector)
  - Use same PALAO/PHARO offset location (aka ‘sweet spot’ position)
  - For off-axis science target (e.g. galaxies)
    - Ideally, use a calibrator binary with same separation and orientation, one component satisfying requirements above
  - Suffers >2x overhead on observing time
- Cass ring rotation
  - Rotate system through several ring angles to ‘subtract’ systematic features of the PSF
  - A ‘self calibration’ technique, allows more time on-target
    - 90 and 180 degree rotations (standard cross Lyot mask)
    - 45 and 135 degree rotations (45 deg standard cross)
    - Other ring angles have unique obscuration and thus unique PSF
  - Boccaletti found detection SNR improvement of up to 50% over calibrator star for single image (and ~ 2x greater SNR when accounting for increased efficiency)
- PALAO telemetry
  - Use time-history of wavefront sensor DM positions and residual wavefront errors to estimate PSF
    - Telemetry can be recorded at up to 100Hz
    - Technique demonstrated on PUEO at CFH (curvature sensor AO system)
    - Theory developed for Shack-Hartmann sensor, but not yet demonstrated on PALAO data – research topic

Future directions

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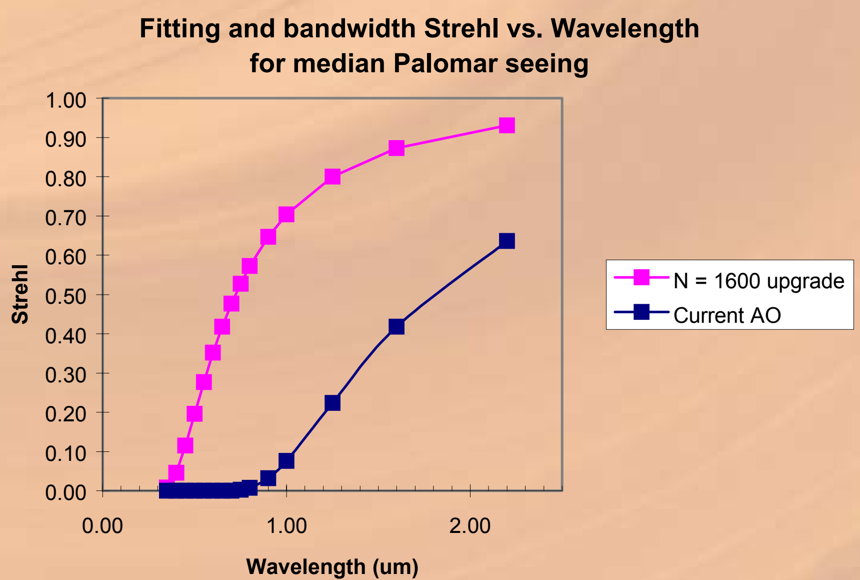
Near-term PALAO upgrades

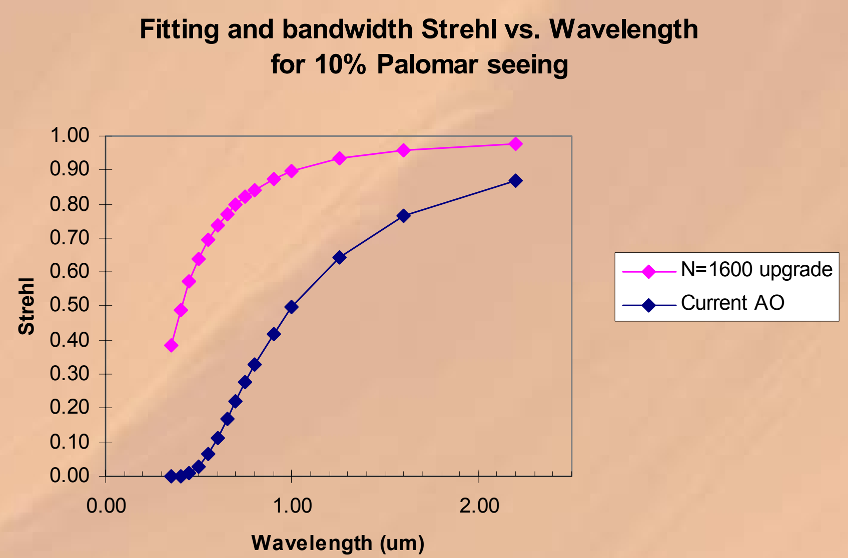
- Wavefront processor upgrade
  - New DSPs to replace existing (1995) technology
  - Increase sample rate from 500 Hz to > 800 Hz
- Wavefront sensor upgrade
  - Reduce read noise for faint guide stars
  - Should enable 0.5 mag increase in limiting V magnitude

PALMAO

- The Caltech/UC proposed 30m diameter telescope (CELT) requires unprecedented adaptive optics capabilities
- PALMAO is an evolutionary program designed to demonstrate major CELT challenges on the 5.1m telescope at Palomar
  - Increase sky coverage
  - Decrease residual wavefront error (i.e., shorter wavelengths)

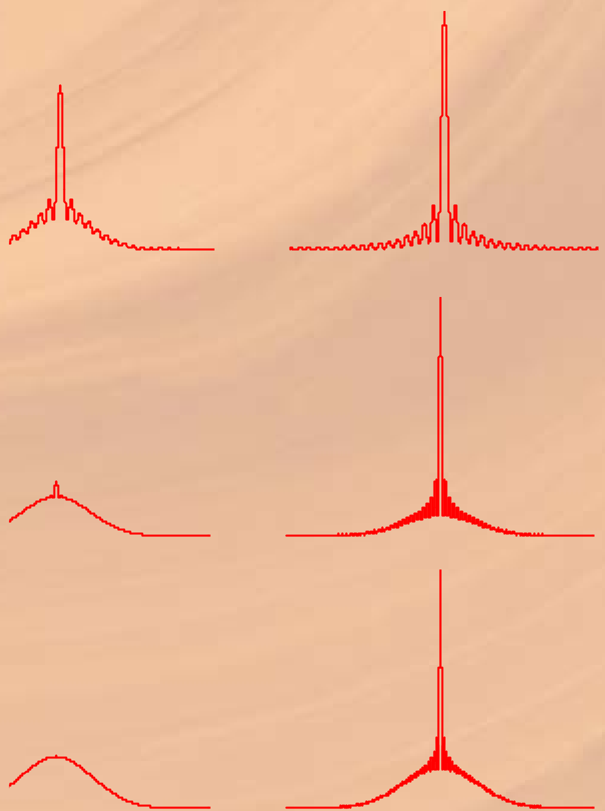
Strehl-limiting terms for PALMAO





(Not all Strehl terms included – final bright star Strehl somewhat lower (~ x0.7?))

PSF improvement with decreasing wavefront error



λ = 2.2 μm (SR = 87%)

λ = 1.0 μm (SR = 50%)

λ = 0.7 μm (SR = 24%)

300 nm rms (PALAO/PALM I) | 133 nm rms (PALM III)

PALM Technology Summary (2/02)

PALAO (Operational)	**PALM I**	**PALM II**	**PALM III**
1 241 actuator deformable mirror (DM)	1 241 actuator DM	1 241 actuator DM 1 1300 actuator DM	1 241 actuator DM 1 1300 actuator DM 1 4000 actuator DM
1 Natural guide star (NGS)	Multiple NGS's	Multiple NGS's	Multiple NGS's
No laser guide star (LGS)	1 10W sodium (Na) LGS	1 20 W LGS, split into 4 guide stars	4 20W LGS
1 Shack-Hartmann (SH) wavefront sensor (WFS)	4 SH WFS's	4 LGS WFS's 4 NGS WFS's	4 LGS WFS's 3 NGS WFS's
PHARO science camera	PHARO	New wide-FOV IR instrument	New visible instrument(s)
PALAO optical bench subsystem (OBS)	PALAO OBS	New PALM II OBS	PALM II OBS
PALAO real-time compute engine (RCE)	New PALM I RCE	Upgraded PALM I RCE	New PALM III RCE
500 Hz WFS camera rate	900 Hz WFS rate	900 Hz WFS rate	1.5 kHz WFS rate
2000	2003	2005	2008