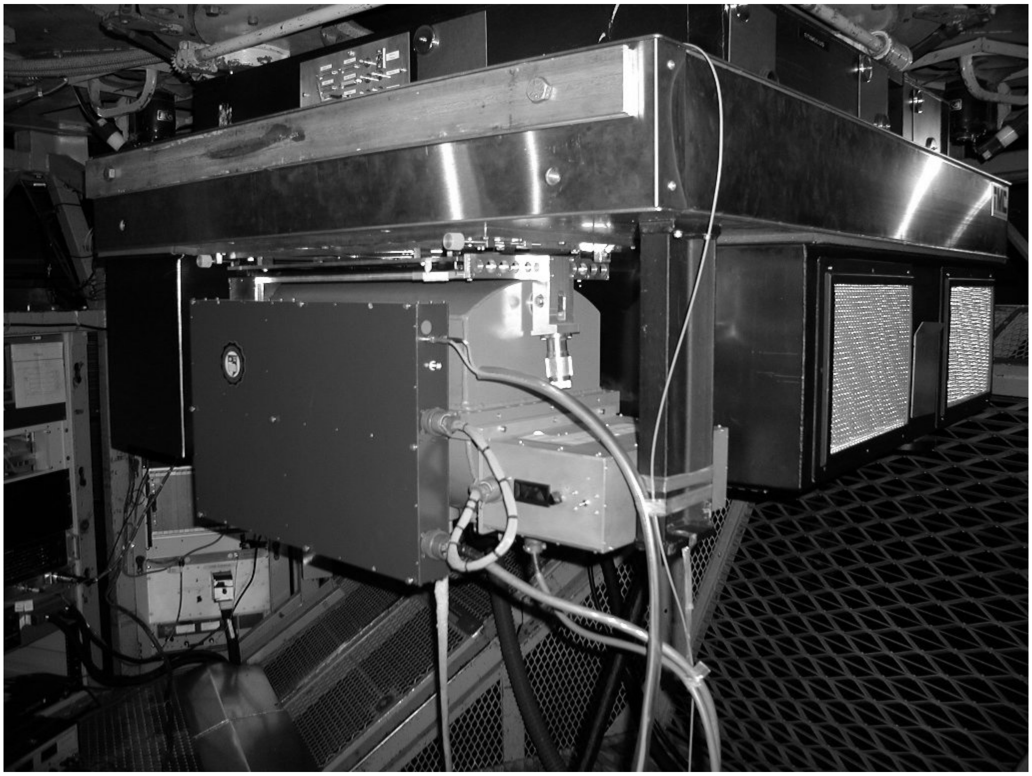
Cornell University Department of Astronomy



PHARO

Palomar High Angular Resolution Observer

User's Manual
Volume 1: Operations

by Tom Hayward and Bernhard Brandl

Revised 2002 January 30

Change log:

2000 Aug 8: Initial release.

2002 Jan 30: Updated Filter and Grism Wheel tables (1-6 and 1-7) after installation of NDC Br-γ, CH_4_Long, K_{cont}, H2 v=1-0 S(1), and [Fe II] filters. Note that the CH_4_Short filter in Table 1-6 has been received but not yet installed in the instrument as of this date.

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Chapter 1. PHARO Overview

1.1 Introduction

PHARO (short for Palomar High Angular Resolution Observer) is a near-infrared camera built by members of the infrared astronomy group at Cornell University especially for the Palomar Adaptive Optics (AO) system. The AO system itself was built for the 200-inch Hale Telescope by members of the Spatial Interferometry Systems Group at NASA/JPL.

The PHARO manual is split into two volumes. This one, Volume 1, provides background and reference information, and describes the operation of PHARO during a "typical" AO observing run. However, remember that the AO system and PHARO must both function properly in order to make a successful observation, and an observer needs to operate both subsystems during a run. This manual will attempt to provide some basic descriptions of AO operations in order to tie them together with PHARO, but for details the AO documentation should be consulted. In the future, perhaps a separate set of procedures covering the combined operation of both systems will have to be written, but at this writing those procedures are still under development.

For further information on PHARO, see the world-wide web site http://www.astro.cornell.edu/PHARO/pharo.html. The site may contain more up-to-date data on currently installed filters, recent sensitivity measurements, etc., that are difficult to maintain in a printed manual. Information on PHARO's design is contained in "PHARO – A Dedicated Near-Infrared Camera for the Palomar Adaptive Optics System," PASP 113, 105 (January 2001). Questions may be directed to one of the PHARO team members at the following addresses.

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1.2 Design & Construction

PHARO is designed first and foremost to be a camera capable of recording the high quality, near-diffraction-limited near-infrared images delivered to it by the AO system. It does not do any image-correcting itself, but relies entirely on the AO system to correct the aberrations induced by both the earth's atmosphere and the "imperfect" telescope optics (with apologies to the builders of the amazing Hale telescope). The basic capabilities of the AO system in the J, H, and K near-IR bands are listed in Table 1-1. The principal goal of PHARO's designers was to provide a high-throughput imaging system that would not degrade the images provided by the AO system. Two secondary goals were to provide a high-quality coronagraph mode and a basic spectroscopic capability to extend the AO system's versatility.

PHARO's detector is a 1024×1024 HgCdTe "HAWAII" array manufactured by the Rockwell Science Center. Detector specifications are listed in Table 1-2. The array is divided into 4 quadrants as shown in Figure 1-1. Each quadrant has a separate signal output which is connected to its own preamplifier channel and A/D converter in the warm electronics.

The optical design, illustrated in Figure 1-2 and summarized in Table 1-3, is all-reflecting with two off-axis paraboloid (OAP) mirrors and two folding flats. The AO system f/15.7 focus lies inside dewar at the Slit wheel which contains several field masks, coronagraphic masks, and spectrograph slits. The collimator OAP collimates the beam and forms an image of the telescope pupil on a cold Lyot stop. A wheel allows one of several stops to be placed in the beam for optimal performance in standard imaging and coronagraphic modes. The Lyot wheel is followed by a Filter wheel carrying filters for imaging and order-sorting, and a Grism wheel carrying three grisms for spectroscopy as well as additional filters. The collimated beam then passes a cold shutter and is focused by one of three mirrors onto the detector. The first is a fixed OAP that provides a scale of 25 mas/pixel on the detector, critically sampling the diffraction-limited PSF down to J-band. In this mode the field of view across the 1024-pixel array is 25 arcsec. A second OAP on a rotating carousel can be placed in the beam to give 40 mas/pixel that critically samples the H- and K-band PSFs and provides a wider, 40 arcsec, field of view. The third mirror, also on the carousel, is a hyperboloid that images the pupil plane onto the detector to facilitate alignment between the telescope, AO system, and PHARO.

Cross sections of the dewar showing the configuration of the workplate and liquid nitrogen cans are shown in Figure 1-3. The 11 liter outer can is coupled to a radiation shield surrounding the entire workplate. The 3.3 liter inner can is coupled directly to the workplate. Both cans are under the workplate and so are equipped with insert tubes so they may be operated "inverted," with the necks pointing down.

Details of the optical elements carried in the four wheels are presented in Tables 1-4, 1-5, 1-6, and 1-7. The filters manufactured by OCLI and NDC are made to very high quality especially for AO applications as specified by the "Gemini Consortium." Their general characteristics are listed in Table 1-8. Other filters are standard-quality stock filters made by Barr. All filters are mounted in their wheels at the 5° angle of incidence for which the OCLI and NDC filters are designed, which effectively eliminates ghost images caused by reflections between the filters, window, and detector. We are currently endeavoring to obtain additional high quality, narrow-band filters under additional orders by the AO consortium.

Specifications for the grism spectroscopy modes are listed in Table 1-9. The three grisms are designed to disperse the J, H, and K bands across the detector with the carousel in the 40 mas/pixel configuration. In the spatial direction, the slit extends across the full 40 arcsec width of the detector. The overall optical design is not optimized for a spectrograph (to reduce the thermal background properly, the Lyot stop should be placed ahead of the slit), but for near-IR applications the background problem is not too severe and the spectrometer mode performance is satisfactory.

Additional subsystems inside the dewar include six cryogenic Phytron stepper motors that drive the four wheels, the carousel, and the shutter. A fiber is provided so that laser light can be piped into the dewar and beamed back into the AO system through a small BK-7 window next to the main IR window. The AO system will use this light source to measure and correct non-common path errors caused by flexure between the AO and PHARO optics. Finally, a shutter blade just after the second folding flat inside PHARO is driven by a small stepper motor. The blade can block the beam during an integration if the AO system temporarily looses lock. As of this writing neither the fiber nor the shutter operations have been integrated into the AO control system, although they are installed in PHARO itself.

A schematic of the PHARO control system is shown in Figure 1-4. At the dewar, there are two electronics boxes: a red box containing the detector electronics and an aluminum box containing stepper motor drivers. The detector electronics consist of device driver, pre-amp, and A/D boards and an FPGA-based control board with a fiber optic interface. The control board communicates with a Sun Sparc2 workstation over the fiber optics both to receive commands to control the detector and stepper motors, and to send image data from the detector. The workstation runs custom GUI-based control software in the X-Windows environment for instrument control and data display.

Table 1-1. AO System Capabilities

Band	λ (μm)	Diffraction FWHM (mas)	Max. Strehl Ratio[b]	Guide Star V=12 Strehl Ratio[c]	Isoplanatic Angle (arcsec)
J	1.25	48.9	0.20	0.02	25
H	1.65	64.5	0.41	0.05	34
K	2.20	86.0	0.63	0.12	50

(a) Strehl ratios and isoplanatic angles are dependent on many factors, so the quoted values are approximate.
(b) For a V < 7 guide star in < 1″ visible seeing.
(c) For a V ≈ 12 guide star in 1″ visible seeing.

Table 1-2. HAWAII Detector

Detector Material	HgCdTe
Detector format	1024×1024, divided into four 512×512 quadrants
Number of output channels	4
Pixel Pitch	18.5 μm
Wavelength Range	~ 1 – 2.5 μm
Quantum Efficiency	~ 0.4 @ J to ~0.70 @ K
Well Depth	~ 1×10^5 e^-
Dark Current	~ 0.1 e^-/s
Read Noise, correlated double sampling	~ 6 e^-

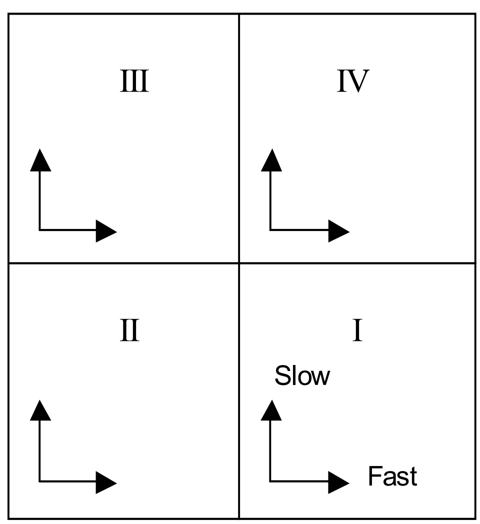


Figure 1-1. HAWAII Detector format. The array is divided into four 512×512 pixel quadrants, each of which is clocked as shown. Each quadrant is coupled to a separate output line.

Table 1-3. PHARO Optical Properties

f/15.64 Image Scale	2.584 arcsec/mm
f/18.69 Image Scale	39.91 mas/pixel
f/29.91 Image Scale	25.10 mas/pixel
Pupil Diameter	16.88 mm
Collimator OAP focal length	254.0 mm
f/18.69 Camera OAP focal length	303.4 mm
f/29.91 Camera OAP focal length	485.6 mm
Pupil Imaging focal length	203.4 mm
Pupil Imaging conic constant	– 0.060

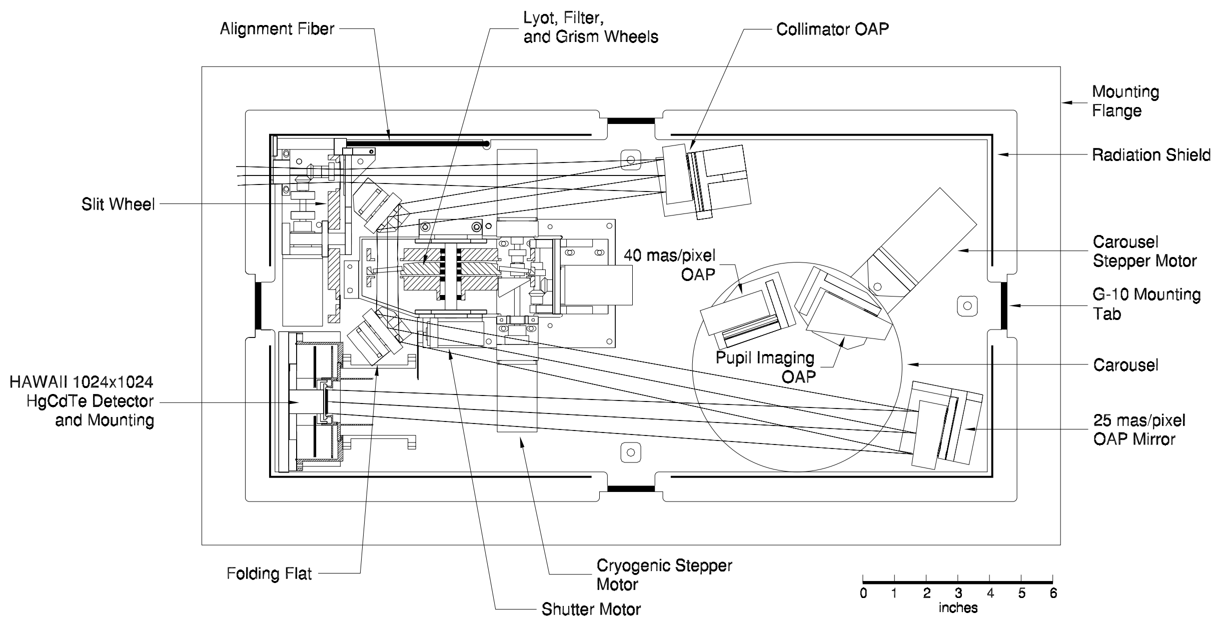


Figure 1-2. PHARO optical layout, with the carousel in the 25 mas/pixel configuration.

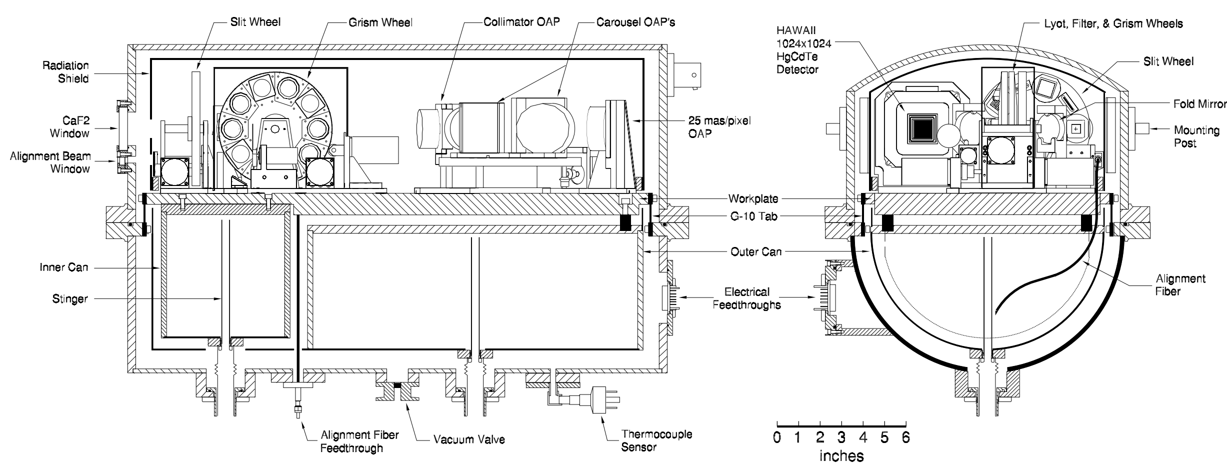


Figure 1-3. PHARO dewar design.

Table 1-4. Slit Wheel

#	Step	Name	Dimension	Comment
0		Home		
1	0	0.43″ Spot	Dia. = 166 μm	5 Airy rings @ 2.2 μm
2	400	0.13″ Slit	Width = 50 μm	R ~ 1500
3	800	0.97″ Spot	Dia. = 375 μm	11 Airy rings @ 2.2 μm
4	1200	0.26″ Slit	Width = 100 μm	R ~ 750
5	1600	Pinhole Grid		optical testing
6	2000	0.52″ Slit	Width = 200 μm	R ~ 375
7	2400	40″ Field Mask		Imaging
8	2800	Open Slit		Spare
9	3200	25″ Field Mask		Imaging
10	3600	Occulting Bar		Imaging

Table 1-5. Lyot Wheel

#	Step	Name	Dimension	Comment
0		Home		
1	0	Block		Cold block
2	400	Open		Open hole
3	800	Std. Cross	6.1, 16.5, 0.25	Std. Cross for imaging
4	1200	Std. Cross – 45	6.1, 16.5, 0.25	2nd cross rotated 45 deg.
5	1600	Medium Cross	7.6, 15.4, 0.83	Oversize cross for coronagraphy
6	2000	Large Cross	9.4, 13.5, 1.75	Oversize cross for coronagraphy
7	2400	Std. Spot	6.1, 16.5	Central obscuration mask w/o spiders
8	2800	Spare 1		Spare
9	3200	Spare 2		Spare
10	3600	Spare 3		Spare

(a) Central obscuration diameter, outer diameter, spider vane width (mm). Telescope primary mirror outer diameter corresponds to 16.88 mm (the pupil diameter) at the Lyot stop. Telescope central obscuration diameter corresponds to 6.08 mm.

Table 1-6. Filter Wheel – 2002 Jan 26

#	Step	Name	Central λ (μm)	Bandpass (μm)	Peak Trans. (%)	Sensitivity		Manufacturer
						Strehl	Mag[a]	
0		Home						
1	0	Open	–	–	–			–
2	400	J	1.246	0.162	87	0.019	21.3	OCLI
3	800	H	1.635	0.296	85	0.046	20.9	OCLI
4	1200	K	2.196	0.336	90			OCLI
5	1600	K_s	2.145	0.310	92	0.11	19.6	OCLI
6	2000	CH_4 Short	not yet installed					NDC
7	2400	CH_4 Long	1.690	?	?			NDC
8	2800	Br-γ	2.166	0.02	75			NDC
9	3200	CO Bandhead	2.295	0.02	72			Barr
10	3600	Kcont	2.26	0.06	83			NDC

(a) Magnitude for S/N = 10 in 3600 s total observing time w/ half time spent on target and half on background. Measured 2000 May while guiding on V ≈ 12.3 star 10″ from science target. Strehls increase by about 3× and sensitivities by about 0.8 mag with very bright (V < 7) guide stars.

Table 1-7. Grism Wheel – 2002 Jan 26

#	Step	Name	Central λ (μm)	Bandpass (μm)	Peak Trans. (%)	Sensitivity	Manufacturer
1	0	ND-1	–	–	1	–	Janos
2	400	H Grism	–	–	–		–
3	800	Open	–	–	–		–
4	1200	K Grism	–	–	–		–
5	1600	Fe II	1.648	?	?		NDC
6	2000	H Continuum	1.668	0.018	65		Barr
7	2400	Open	–	–	–		–
8	2800	H2 1-0 S(1)	2.122	?	?		NDC
9	3200	J Grism	–	–	–		–
10	3600	ND-2	–	–	0.1		Janos

Table 1-8. Filter Specifications

Type	AO Quality	Std. Quality
Manufacturer	OCLI, NDC	Barr
Flatness	< 0.0183 λ/(n-1)	
Surface Parallelness	< 5 arcsec	
Mounting angle	5 deg	

Table 1-9. Grisms

Grism	Wavelength Range (μm)	Dispersion (nm/pixel)	Material	Apex Angle	Grating Lines/mm	*R* with 0.13 arcsec slit
J Grism	1.17-1.33	0.15771	Ohara S-LAH60	30.05	322.7	1850-2110
H Grism	1.49-1.78	0.28467	Ohara STIH10	25.78	183.9	1310-1550
K Grism	2.03-2.37	0.33215	Ohara STIH10	28.89	149.7	1690-1970

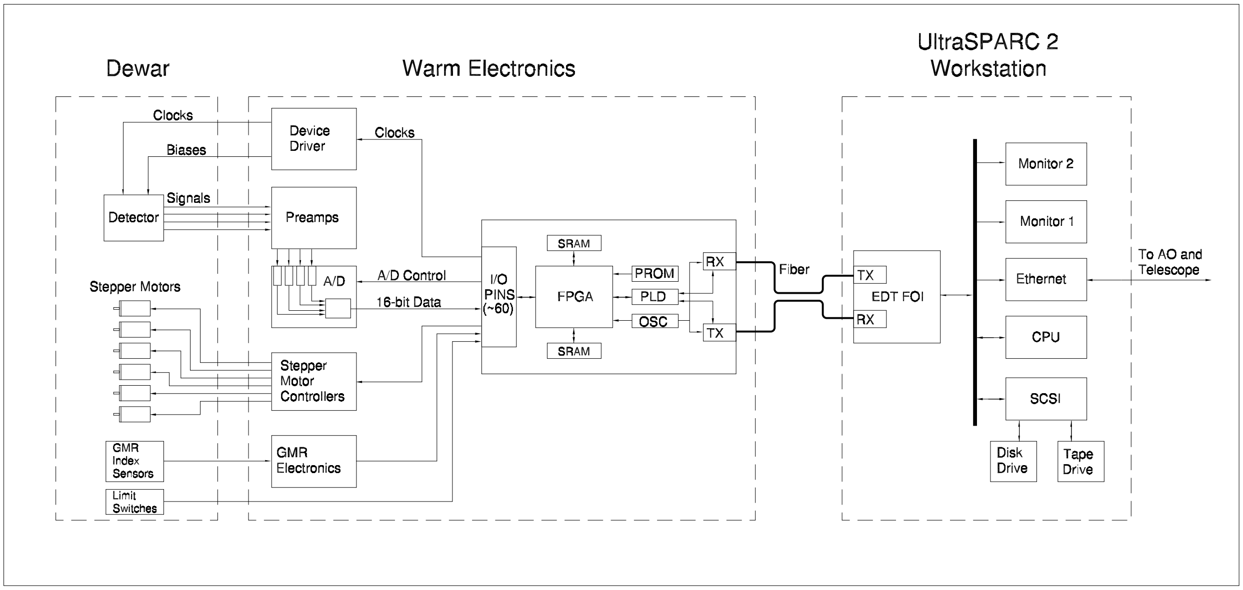


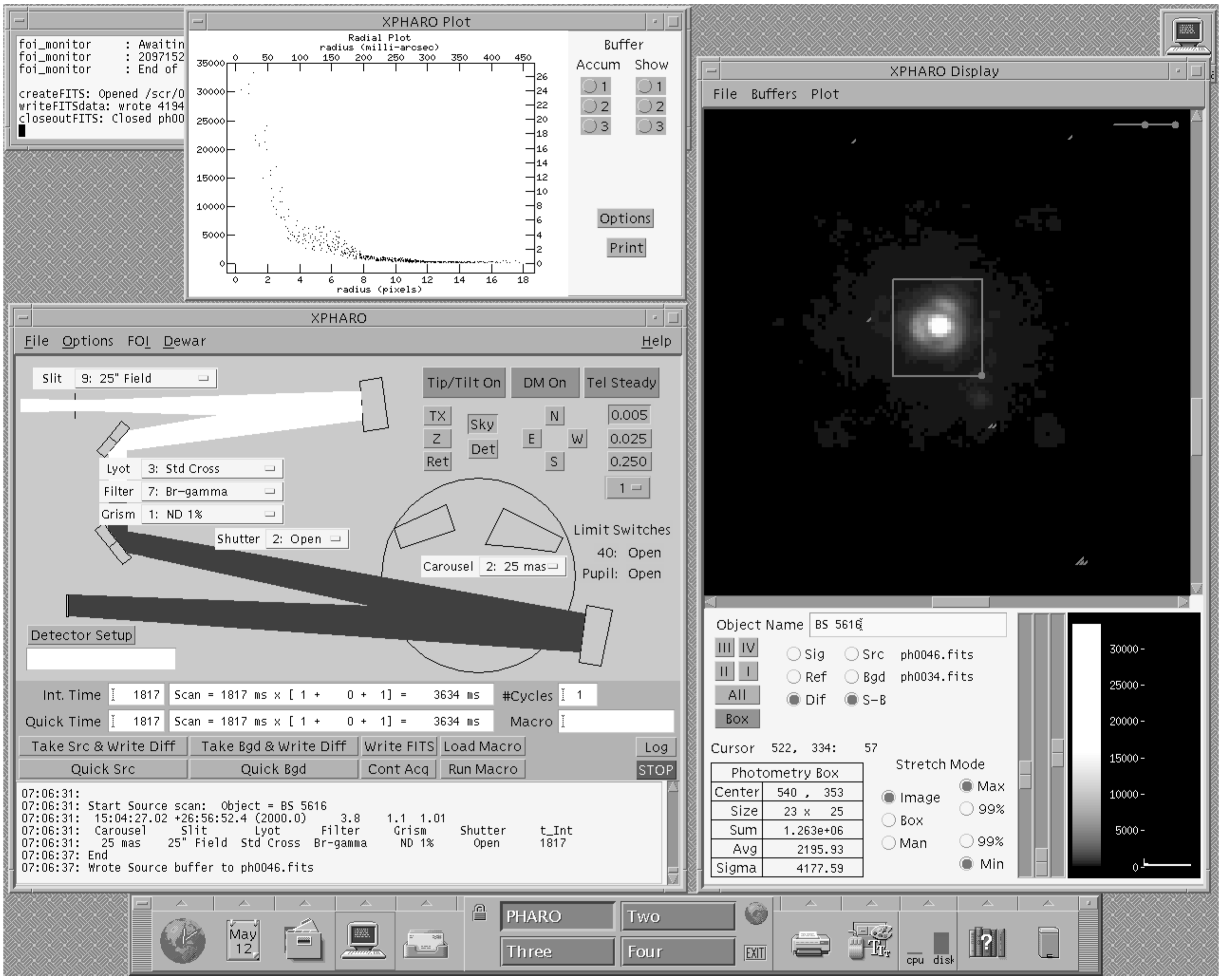
Figure 1-4. PHARO electronics and control system.

Chapter 2. PHARO Operations

2.1 Introduction

2.2 Safety

2.3 Starting Up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Slit
9: 25" Field
Tip/Tilt On
DM On
Tel Steady
Lyot
3: Std Cross
Filter
7: Br-gamma
Grism
1: ND 1%
Shutter
2: Open
Carousel
2: 25 mas
Limit Switches
40: Open
Pupil: Open
Detector Setup
Int. Time
Quick Time
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Macro
Take Src & Write Diff
Take Bgd & Write Diff
Write FITS
Load Macro
Log
Quick Src
Quick Bgd
Cont Acq
Run Macro
STOP
07:06:31: Start Source scan: Object = BS 5616
07:06:37: End
07:06:37: Wrote Source buffer to ph0046.fits
Object Name
BS 5616
ph0046.fits
ph0034.fits
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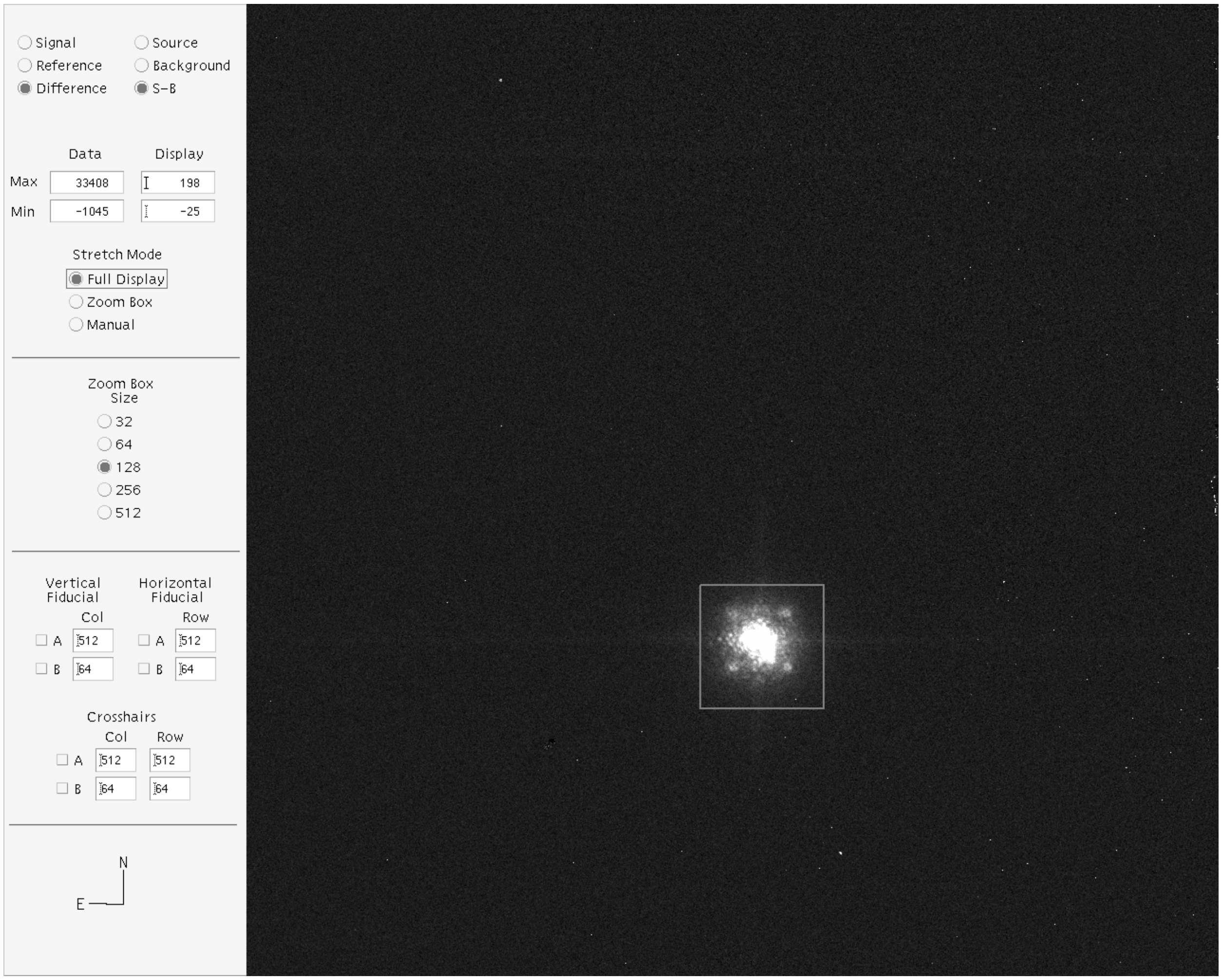
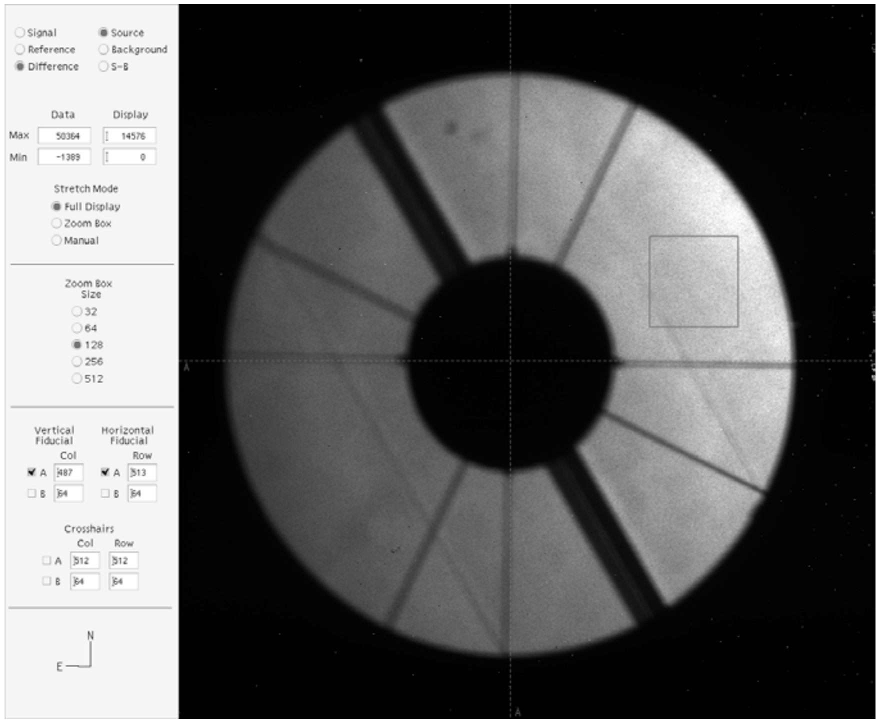


2.4 Pupil Alignment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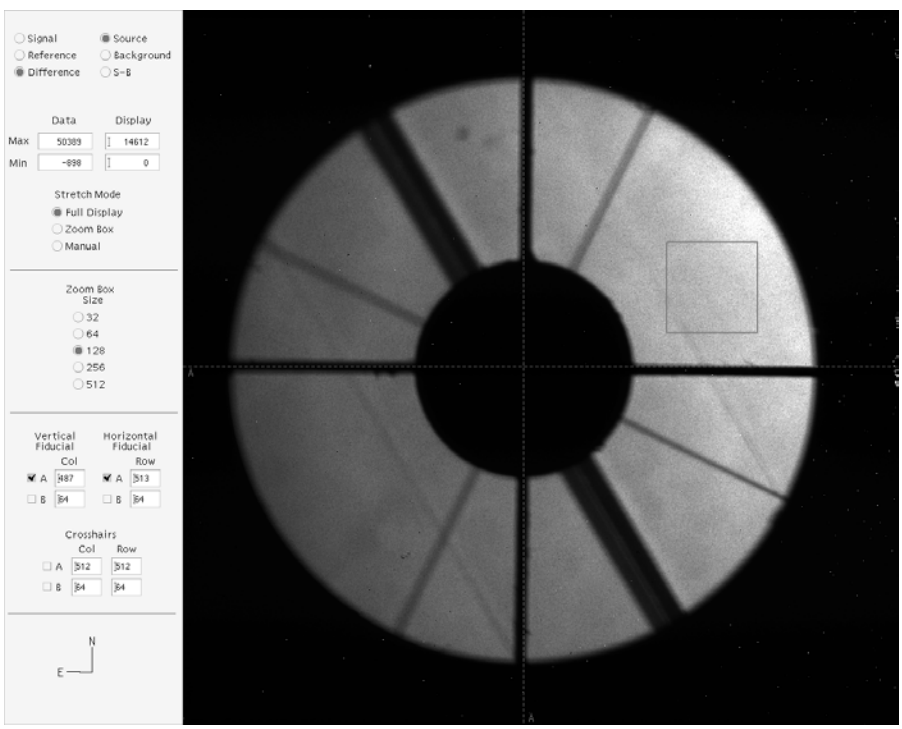
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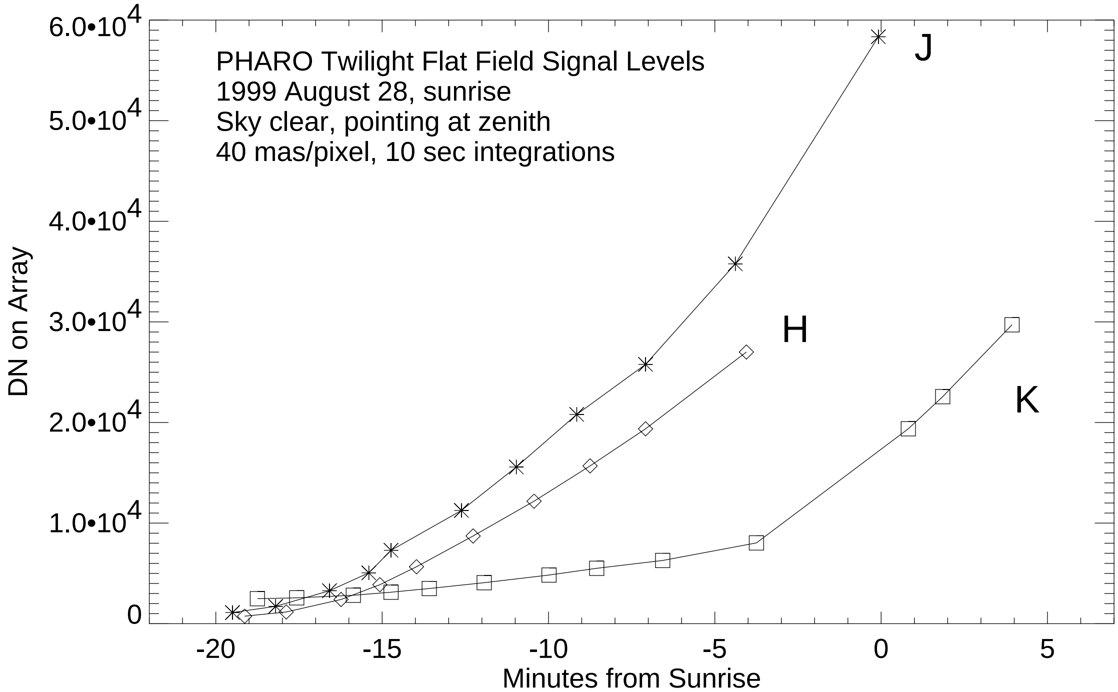
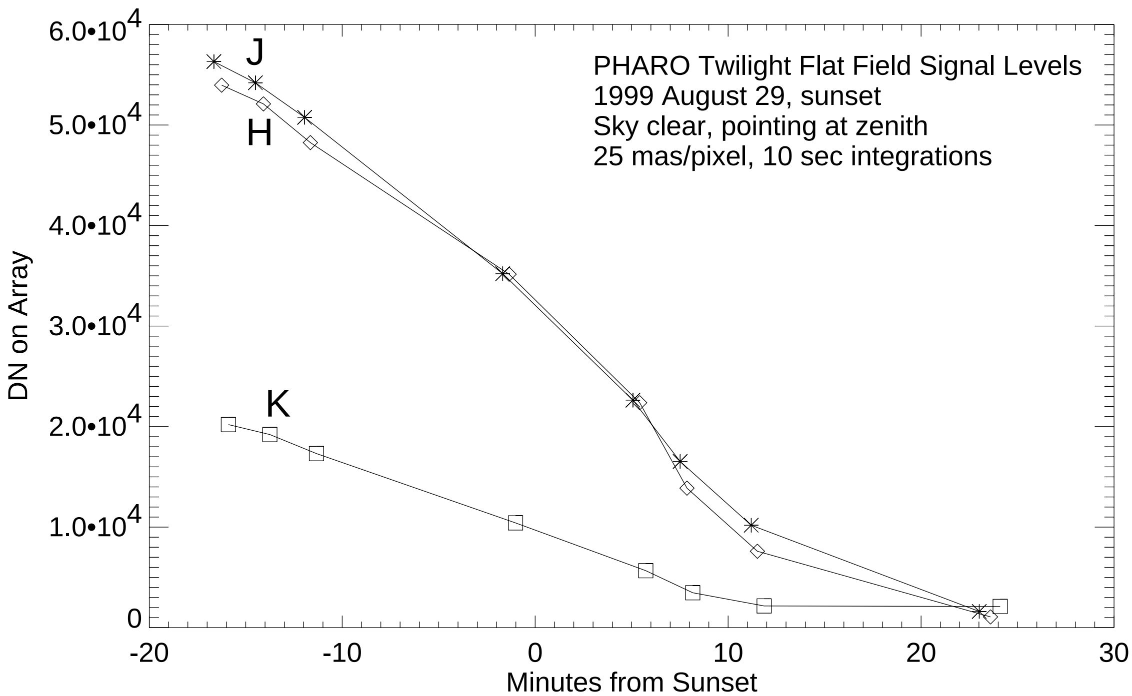
Row
A
487
A
513
B
64
B
64
Crosshairs
Col
Row
A
512
512
B
64
64
N
E

2.5 Flat Fields

Twilight flats appear to give satisfactory results. Take J, H, and K flats near sunrise or sunset with the following procedure. See Figure 3.1 below which shows the signal level relative to the sunrise and sunset time in the J, H, and K filters in the 40 and 25 mas/pixel modes. **Be aware that when the sky is bright enough for flat fields the WFS camera easily saturates.**

1. Plan to start taking data about 15-20 minutes before sunrise or immediately after sunset.
2. PHARO should be powered up and ready for operation. **Set the Lyot wheel to Block.**
3. Point telescope at Zenith and turn off tracking.
4. Open dome and mirror covers and set AO to pass light to PHARO.
5. Set the integration time to about 10 sec, which is suitable for the broadband filters. The narrow band filters will require longer times and may have to be taken with the sun high above the horizon to get enough signal. It is not known how much the flat field changes between the broad and narrow-band filters.
6. Set the carousel to 25 or 40 mas/pixel mode. Do one mode or the other; moving the carousel in the middle of a sequence of flat fields is likely to corrupt the data.
7. Set the Slit to 25 or 40 field mask, Lyot to Block, Grism to Open.
8. Take 1 or 2 bias frames with Lyot wheel set to block, save in Bgd buffer.
9. 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. A brighter sky is preferred over a longer integration time to minimize interference from background stars. Either dither near a fixed position on the sky (preferably away from the Galactic plane) or park the telescope at zenith to let the sky track by while taking flats to further reduce the effects of stars.
10. **Set Lyot wheel to Block when finished.**
11. Take another bias frame with the Lyot on Block.





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