Design of the IMACS 8K x 8K Dewar and Detector System

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ABSTRACT

The Inamori-Magellan Areal Camera and Spectrograph (IMACS) features a 8K x 8K, 6.7 Megapixel detector system, which is mounted in a cryogenic vacuum vessel with a combination of features that are unique among the current generation of astronomical multi-detector array systems. Closed-cycle coolers, commercial stages for flexure compensation, flexure control detectors, array focus control, composite thermal isolation truss and other features are described.

Keywords: Dewar, Focal Plane Array, Flexure Control, Cryocooler

1. INTRODUCTION

The IMACS (Inamori Magellan Areal Camera and Spectrograph) is the principal multi-object spectrograph and imager for the 6.5m Magellan I telescope. The five year, five million dollar project to build the instrument is its final stages of completion in the instrument laboratories of the Observatories of the Carnegie Institution of Washington, Pasadena, CA. The intent of this paper is to describe the 8K x 8K detector system and some of its interesting features. See other papers in these proceedings by Dressler[1] (target science for IMACS), Epps[2] (the optically athermalized f/2 camera), Bigelow[3] (Status of IMACS project), and Sutin[4] (echellette mode) for additional information about the IMACS instrument.

The Observatories of the Carnegie Institution of Washington (OCIW) and its Magellan Project partners are currently completing two 6.5m telescopes, located at the Las Campanas Observatory in Chile. Concurrently, the Observatories are in the final stages of development and construction of three first generation optical and infrared instruments. See Shectman[5] in these proceedings for a report on telescope progress, and Bernstein[6] for the MIKE double-echelle spectrograph.

The 8K x 8K detector system is in many ways the heart of the IMACS instrument, and the single most expensive sub-system. The SITe 2048 x 4096 x 15 micron pixel devices alone cost $48,000 each, for a total science array cost of $384,000. The detectors were purchased under a collaborative effort with the National Optical Astronomical Observatories (NOAO). Crucial to the performance of the entire instrument is the support and control of the eight science detectors. This paper describes the detectors, the design of the 8K array, and the features of the dewar.

2. SPECIFICATIONS

2.1 CCD Detectors

The IMACS detector system consists of eight 2K x 4K x 15 micron pixel devices. The following specifications describe requirements for the CCDs:

Geometry:	2048 (serial) x 4096 (parallel) pixels	
	15 micron pixels	
	package width:	31.39 mm
	package length:	84.96 mm
	package height:	5.50 mm (excl. bump-bond cover)

Flatness:	flatness 40 microns P-V at operating temperature, required	
	flatness 15 microns P-V at operating temperature, goal	
Amplifiers:	one amplifier devices:	
	read noise	10e at 50kpix/sec/chan.
	read noise	5e at 50 kpix/sec/chan.
	read noise	3e at 25 kpix/sec/chan.
	two amplifier devices:	
	first amp. read noise	7e at 100 kpix/sec/chan.
	second amp. read noise	12e at 100 kpix/sec/chan.
Quantum Efficiency (QE):	typical values based on Visar coating at room temp:	
	80% minimum from 400-800 nm	
	40% minimum at 340 nm	
	40% minimum above 900 nm	
	QE to vary smoothly with wavelength	
	Uniformity (chip to chip) better than 5%	
Charge Transfer Efficiency (CTE):	CTE 0.999995 for a 5000 electron signal	
	CTE 0.99999 for a 200 electron signal	
Full Well (FW):	FW 90,000 electrons	
	FW 50,000 electrons multi-pin phased (MPP)	
	Image persistence after 10 sec. cont. clocking: 10e-5 of FW	
Dark Current (DC):	DC 3e pixel/hour at -100C in MPP mode	
Cosmetics:	per device:	
	no more than 2 bright columns	
	no more than 2 dark columns	
	no more than 20 point cluster defects	
	no more than 2 bright columns	

2.2 CCD Mosaic

The eight CCDs are mounted on a single base plate in order to form the 8K x 8K array. The following specifications describe the requirements for the assembled array.

Mosaic Flatness:	mosaic flatness not to exceed worst device flatness:	
	flatness 40 microns over the full array required	
	flatness 15 microns over the full array goal	
Gap Geometry:	inter-chip gaps :	1.0 mm required
	inter-chip gaps:	0.5 mm goal
Column Alignment:	less than 5 pixels (75 microns) over 4096 pixels, required	
	less than 0.5 pixels (7.5 microns) over 4096 pixels, goal	
Flexure Control Translation Strokes:	X,Y:	+/- 75 microns req.
	X,Y:	+/- 150 microns goal
	Z (focus)	+/- 1.0 mm req.
	Z (focus)	+/- 2.0 mm goal

Resolution:	X,Y translations:	0.01 pixel (0.150 microns)
	Z translation (focus):	1.5 micron
Bandwidth:	X,Y,Z trans. - update at 1/min.	
Array Stability Requirements:	X and Y translations:	+/- 0.75 microns
(for 180 degree rotations)	Z translation:	+/- 1.6 microns
	X and Y rotations:	+/- 1.5 arcsec
	Z rotations:	+/- 1.75 arcsec

2.3 Dewar/Cryostat Requirements

The CCDs are mounted as a mosaic, and housed in a vacuum vessel that is cooled to cryogenic temperatures. The following specifications describe the requirements for the dewar.

Nom. operating temperature (detectors) :	170K	
Temperature hold time:	N2 cryostat:	18 hour hold time required
	N2 cryostat:	24 hour hold time goal
	Closed-cycle cooler hold time:	unlimited
Geometry:	values for cryostat, including on-board electronics:	
	length not to exceed	350 mm
	width not to exceed	650 mm
	height not to exceed	300 mm
	weight not to exceed	50 Kg incl. electronics
Mechanical Interfaces:	Mounting flange to cameras	
	Fill/vent lines (LN2)	
	Gas lines (closed-cycle coolers)	
	Vacuum pumping flange	
Electronic Interfaces:	Temperature sensors	
	CCD Clock/drive signals in (science and flexure detectors)	
	CCD Video signals (science and flexure detectors)	
	Flexure control signals (piezo stage)	
	Focus drive control signals (drive motor, home/limits)	

3. DETECTORS AND CONTROLLERS

3.1 Science Detectors

The science detectors selected for IMACS are SITe (Scientific Imaging Technologies Inc, Tigard, OR) ST002 CCD detectors, thinned and back-side illuminated, with 2048 x 4096 x 15 micron pixels. The cosmetic requirements lead to the acquisition of devices falling in between SITe Grade “0” and Grade “1” quality. The devices are mounted on Invar packages, 31.39-mm wide, 84.96-mm long, and 6.35-mm thick. The packages come with drilled and tapped mounting holes, and are tapered normal to the active surface of the detector to facilitate assembly of the devices in mosaics. Electrical connection to the devices is made via a 3-inch long ribbon cable assembly.

3.2 Science Array Controller

IMACS uses two locally designed detector controller systems; one for the Magellan-standard guide cameras, and a second for the 8K x 8K science array. Both controller systems were designed by Greg Burley and Ian Thompson of OCIW. The basic array system electronics (BASE) design is based on a digital signal processor (Motorola DSP56303), with multiple channels of clock drivers and signal processing. The DSP directly generates the sequences used to clock the serial and parallel charge transfers on the CCDs. All of the detectors are clocked in lock step.

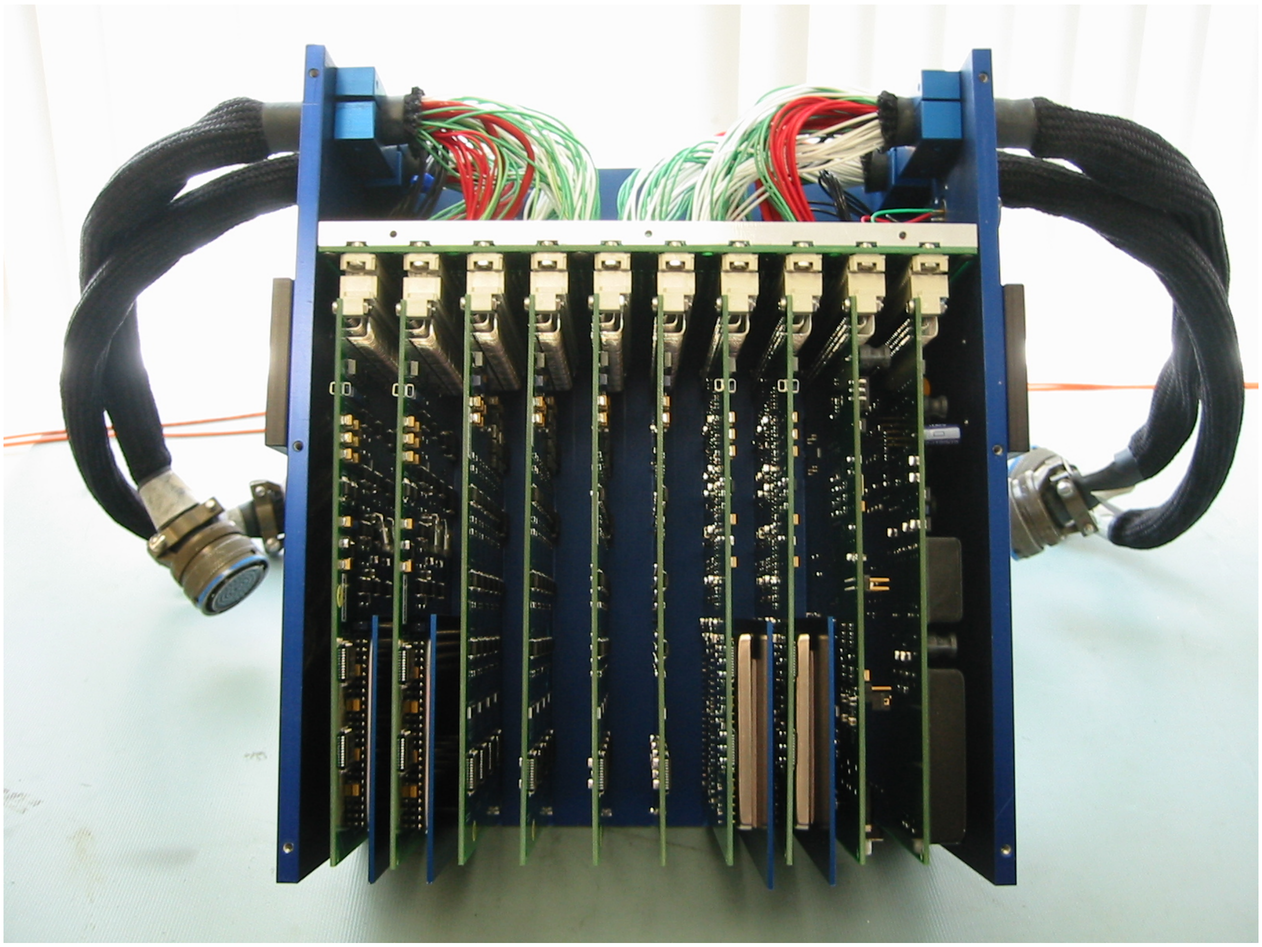

Figure 1. IMACS 8Kx8K CCD Controller

Each clock driver board provides independent, software-programmable parallel and serial clock voltages for two detectors. Each signal processing board has two dual-slope integrator channels, with 1 microsecond 16-bit Analogic ADC4320B analog-to-digital converters. The eight channels of digitized image data are multiplexed by the DSP, and transferred by an 80 Mbps optical link to a PCI interface in a host computer running Linux. The controller provides an individual temperature monitor and programmable heater current to each detector. It can provide a signal to trigger an external shutter. The DSP software directly operates the CCD controller electronics, and allows programmable features such as image size, subrastering, exposure time, binning, clock timing, signal processing gain and offsets.

Physically, the BASE system for IMACS consists of an electronics box [4.75" x 8.25" x 10"] housing one DSP board, four dual-channel clock driver boards, four dual-channel signal processing boards, a power conversion board, and a back-plane board. In addition, there are four dual-pre-amp boards inside the dewar. The BASE system is an open-source design - all of the hardware schematics, circuit board layouts, programmable logic files, DSP code, interface software routines, and test results are available on the OCIW website at www.ociw.edu/~burley/ccd/mosaic.html.

Table 1. shows a matrix of readout times for a single detector as a function of binning and gain. All eight chips are read out in parallel, so the mosaic readout time is the same as that for one chip. We have found that the IMACS BASE electronics give read noise values that are at least one electron lower than the SITe data sheets for any individual CCD in the array.

Table 1.

Noise (e-)	Time (1x1 binning), seconds	pixels/second (Kpix/sec)	Gain (e-/DN)
7.9	65	129	3.3
5.9	81	104	1.8
4.5	122	69	0.8
4.0	190	44	0.4

4. DEWAR

4.1 Dewar Overview

The conceptual design of the IMACS dewar was developed jointly by the authors, while the detail-design and fabrication was managed by Luppino. Features include a flexure-based focus stage, a commercially available image motion compensation stage, a thermally isolating composite truss for the CCD mosaic, and closed-cycle coolers for temperature control of the mosaic. Translation of focal plane arrays within the dewar has been demonstrated in other projects (McCarthey[7], Hastings[8]), but previous systems have used custom-designed motion stages.

The original specifications for the dewar allowed for the possibility of using a traditional liquid nitrogen (LN2) vessel for cooling the chips, but due to the large size of the array, the expected thermal loads, and the desire to minimize daytime maintenance, the closed-cycle coolers were always considered the first choice. A complete design for a large LN2 vessel was produced during the preliminary design stage, but was not fabricated and will not be discussed here. There are two main components to the dewar assembly. The first is the vacuum vessel, which includes the dewar body, dewar mounting plate with window, side covers with pre-amp printed circuit boards (PCB), back plate, vacuum gauge, vacuum valve, cryo-coolers, copper cooling straps, and electronics feed-throughs. The second is the CCD detector array assembly, which includes the CCDs, the mosaic mounting plate, the thermal isolation truss, the XY flexure compensation stage, and the titanium focus flexure with stepper-motor drive.

4.2 Vacuum Vessel

The IMACS dewar vacuum vessel is based on a standard GL Scientific design, which has been used in various other instruments (for example, see Cuillandre[9]). The body of the vessel is roughly a hollow cube which was machined from a single ingot of 6061-T6 aluminum. The body of the dewar is polished on the inside to minimize emissivity, and blue-anodized on the exterior for appearance and to prevent corrosion. The body has six apertures – two large mounting faces with o-ring grooves for the front and bottom plates, and windows on the four remaining sides, also with o-ring grooves and mounting hole patterns, for attaching the side plates. The side plates are also aluminum. Two of the four carry hermetic connectors for passing signals between the detectors and the array controller, and one carries the mounting plate for the twin cryo-coolers. The front plate includes the mounting hole pattern for connecting the dewar to the optical cameras, and the mounting features for the dewar window, a plano-concave lens that also serves as the final, field-flattening lens in the optical train of both cameras. Indexing pins on the front plate allow the dewar to be mounted repeatably to 50 microns on the two optical cameras, and the dewar may be rotated by 90 degrees on either camera in

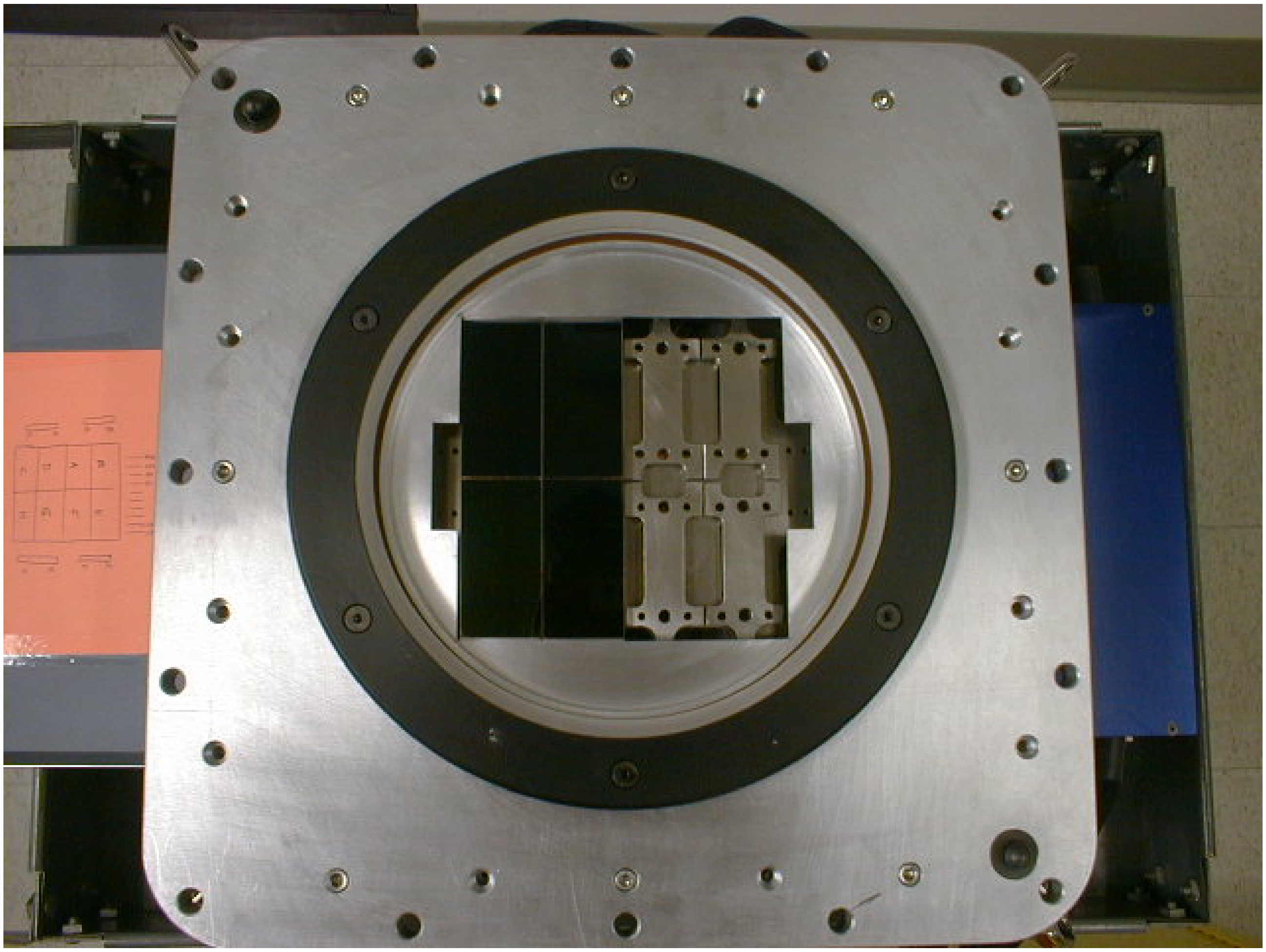

Figure 2. Half-filled CCD mosaic in the dewar. Note the two indexing pins (opposite corners of the mounting plate) for aligning the dewar with the optical cameras. Next to the installed CCDs are the four empty "boat" carriers for the remaining detectors.

order to orient the long gaps in the mosaic in the dispersion direction for spectroscopy. The dewar bottom plate serves as the base for the detector mosaic assembly, and includes vacuum feed-throughs for the flexure control stage piezo actuators and capacitive displacement sensors. Also attached to the dewar body are the four over-centering latches which attach the dewar to the cameras, and lifting eyes in the plane of the dewar's center of gravity. The dewar is vacuum-pumped through a MDC (Harward, CA) Angle Valve (p/n KAV-050), and vacuum level is measured with a Granville-Phillips (Mansfield, MA) Convectron 275 sensor and Convectron 375 Controller. The dewar body, side plates, and cryo-cooler mounts were fabricated by Steve Lamb of Ampersand Precision (Longmont, CO). The various parts of the dewar body can be seen in Figures 2. and 4.

To cool the detector array, two IGC Polycold (Petaluma, CA) Cryotiger closed-cycle coolers are mounted on the side of the dewar. The two cold heads are operated by their own compressors, which can be mounted up to 45 meters away from the cold ends. Flat copper straps in multiple thin layers connect the CCDs to the cold bus bar. Operating in parallel through a copper bus bar, the two coolers can bring the CCD mosaic down to an operating temperature of –100C in approximately 5 hours. Testing has demonstrated the capability to operate the mosaic with a single cooler, but it requires about twice as long (10 hours) to reach an operating temperature of –90C. The coolers and compressors are designed and rated to operate continuously for 5 years without maintenance.

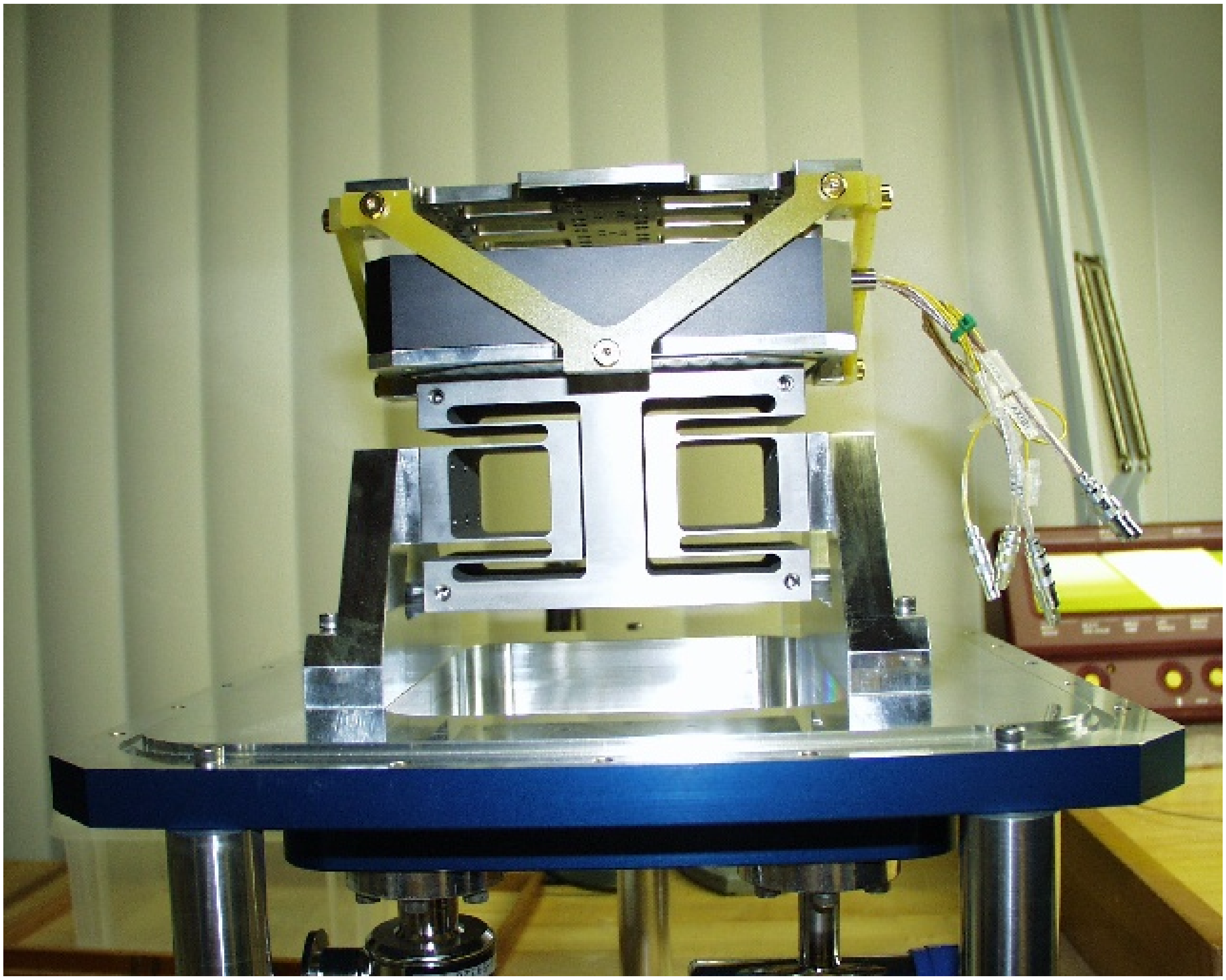

Figure 3. Detector array assembly with focus flexure, PI flexure control stage, G10 truss, and mosaic base plate

4.3 Detector Array Assembly

The detector array assembly, including the dewar bottom plate, can be seen in Figure 3. Starting at the bottom, the assembly includes the stepper-motor and worm-gear focus drive, the focus ball-screw with vacuum bellows, the focus flexure mounting legs, titanium focus flexure, flexure compensation stage, thermal isolation truss, and CCD mosaic.

The focus drive consists of a Phytron (Waltham, MA) model ZSS 32.200.1.2 stepper motor (200 pulses/revolution), a Berg (East Rockaway, NJ) 50:1 anti-backlash worm gear reducer (W48S-3S and AW48BS21-S50), a BSA (San Jose, CA) MRB0802 2mm-lead ball-screw, and a stainless steel bellows which allows the moving parts of the focus system to remain outside the vacuum.

The focus drive assembly attaches via an interface plate to the bottom of the titanium focus flexure. This flexure, designed by Jeff Douglas, and based on previous UH Institute for Astronomy flexure design (see Douglas[10]), allows 2-mm of focus stroke, while remaining acceptably stiff against translations in the plane of the detectors, and against out of plane tilts. The flexure is a single piece of 6AL-4V titanium, which was electronic discharge machined (EMD) to produce the very deep flexure blades.

Figure 4. Dewar assembly showing dewar body, twin Cryotigers, and mounting latches. The four cylindrical legs are used only during assembly.

Mounted on top of the focus flexure, through a second interface plate, is the image motion compensation stage, a commercial translation stage supplied by Polytech PI (Tustin, CA). The motion stage, a Physik Instrument model P-527.2C, is a vacuum rated, piezo driven motion stage with capacitive position sensing. An E-500 series 2-axis, low-voltage PZT, closed-loop controller operates the motion stage and communicates with the instrument computer via a RS-232 serial link. The motion stage provides +/-100 microns of X,Y stroke in the plane of the CCD mosaic, which corresponds to approximately +/- six pixels of image motion compensation. The motion stage and controller were purchased from Polytech at a total cost of about $26,000.

Attached to the moving side of the PI motion stage, another interface plate serves as the base for the G10 fiberglass-composite truss which supports the CCD mosaic. The truss not only mechanically supports the mosaic, but also provides thermal isolation between the warm dewar and the cold detector mosaic.

The mosaic baseplate, or “platten”, is supported by the G10 truss, and in turn supports the eight science detectors and two flexure sensing “wing” detectors. The platten is made of Invar, to match the Invar CCD packages. The platten was ground and lapped to provide an optically flat mounting surface for the CCDs.

Small interface blocks between the platten and the G10 truss were shimmed in order to bring the mosaic plane perpendicular to the dewar's optical axis.

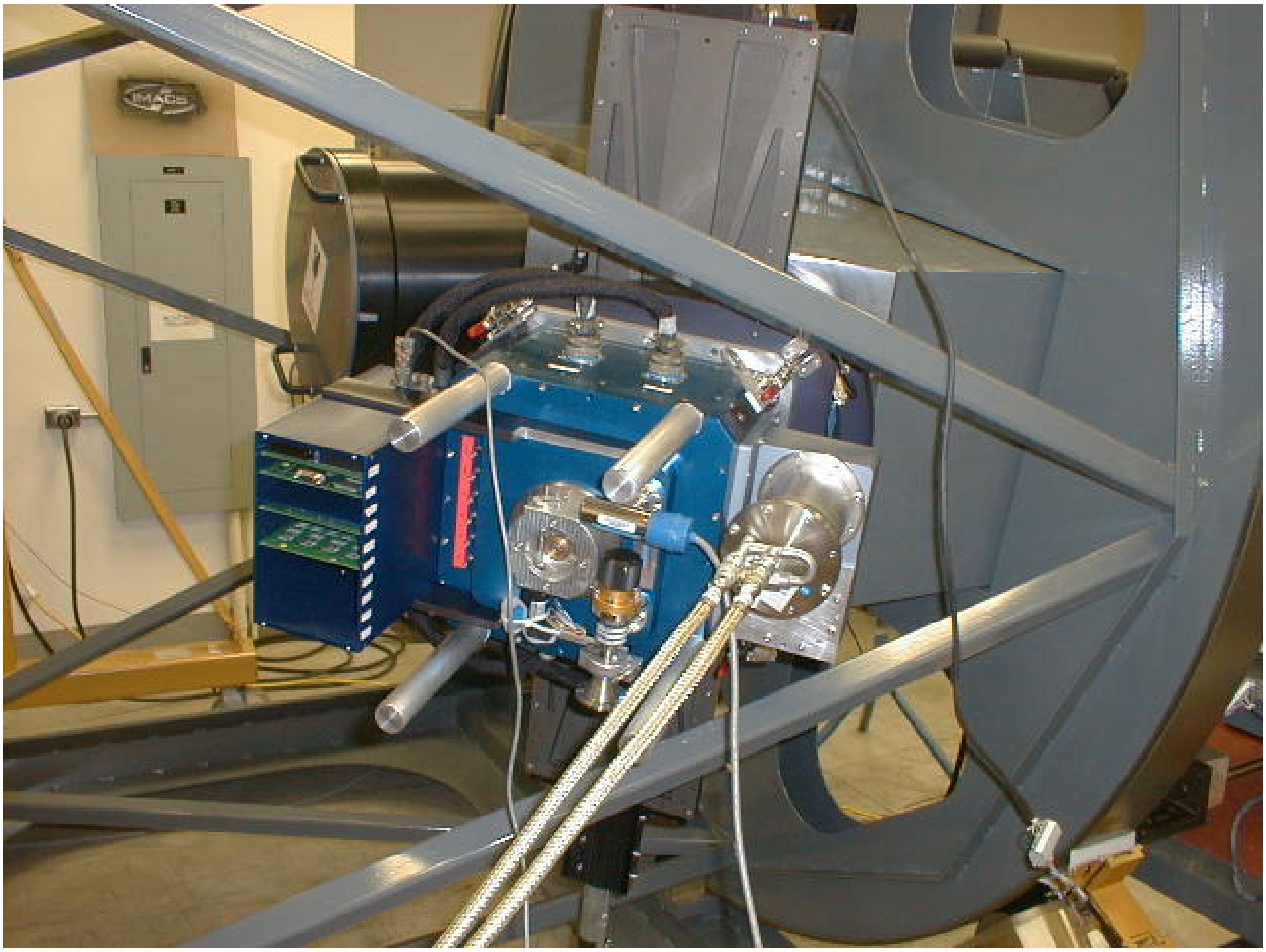

Figure 5. Dewar assembly with controller and single Cryotiger for first light testing.

Each CCD is mounted on its own "boat", Invar interfaces between the CCD packages and the Invar platten. An assembly jig was used to mount each CCD on its boat, in order to make each CCD/boat unit interchangeable with any other unit in the mosaic. Each boat has three "feet", each of which was lapped in order to bring all of CCD/boat units within a few microns of the same height. The eight CCD/boat units were aligned within 0.5 pixels over 4096 pixels, and flattened to within 7.5 microns using a Keyence (Woodcliff Lake, NJ) LT-8110 laser focus displacement sensor. In conjunction with a precision XY motion stage, the Keyence sensor can perform non-contact height measurement over the full surface of the mosaic, to two micron accuracy. Thus mounted, any CCD/boat unit can then be placed in any position on the mosaic, while still maintaining the required gap, angular alignment, and height within the eight chip array. The CCD mosaic is flanked on two sides by 500 x 1200 pixel "wing" CCDs which will be used as image motion feedback sensors in a future, closed-loop control system for flexure. The wing chips will be controlled by a separate dual-channel set of BASE electronics. Closed-loop signals will be measured from centroiding on either star images in the direct imaging mode, or by bright ski emission lines in the spectroscopic modes. The possibility also exists for open-loop guiding, with offsets determined from measurements of instrument flexure as a function of Nasymth Instrument Rotator (NIR) angle.

CONCLUSIONS

Design and fabrication of the IMACS dewar and detector system is still incomplete as of late July 2002. Although all parts of the dewar are complete, assembled, and tested, only four of the eight CCDs have been installed to date. First light imaging with the four chips (see Figure 5) indicate that not only is the IMACS optical system performing to specifications, but all four chips are in focus, perpendicular to the optical axis, and image quality across the full field of view is excellent, with most of the energy from a 0.25 arcsec pinhole falling within three 0.11 arcsec pixels (f/4 camera). Final testing of the detector system, including all eight CCDs, is scheduled for completion in the fall of 2002. At the time of writing, the dewar and detector system appears to be fully functional, and within the stringent performance specifications.

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