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Upgrades to W. M. Keck observatory detector systems

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We report on our plans to upgrade the detector systems in the 2022–2024 time frame for three of the workhorse instruments (NIRC2, DEIMOS, and NIRES) operated by the W. M. Keck Observatory. The upgrades are done in collaboration with Observatory partner institutions and other Maunakea observatories. The main motivating factors behind these upgrades are to tackle obsolescence of hardware and software components, to boost observing efficiency, to enhance the instrument throughput, and to add new observing functionality.

KEYWORDS

detectors, image sensors, infrared arrays, CCD, CMOS

1 | INTRODUCTION

One of the methods by which the W. M. Keck Observatory (WMKO) maximizes scientific impact is by developing and deploying upgrades for existing facility instruments. Recent examples of refreshing technologies reported in the past include detector upgrades to both the OSIRIS and NIRSPEC instruments, two facility class instruments in use with Keck I and Keck II telescopes, respectively. In this paper, we present deployed and planned future upgrades to three of WMKO's instruments: NIRC2, NIRES, and DEIMOS. NIRC2 and DEIMOS are two of the older generations of instruments. They are in high demand, and based on publications and citations are two of the most productive instruments at WMKO among the suite of 10. NIRC2 is completing a detector controller upgrade while the project to upgrade the entire DEIMOS detector and controller system is just starting. Although NIRES is one of WMKO's newest instruments, the infrared acquisition camera employs older detector technology. With NIRES we upgrade the infrared camera to be used as a guider. In the next sections, we present details of the deployed and planned system upgrades as well as a discussion on the new modes and science that they enable.

2 | NIRC2 DETECTOR ELECTRONICS UPGRADE

NIRC2 (Near-InfraRed Camera 2) is the workhorse diffraction-limited infrared camera and slit spectrograph in use with the Keck II Adaptive Optics (AO) system in natural or laser guide star mode. NIRC2 is one of the most productive instruments at WMKO and has as of December 2022 contributed to 881 papers.

The deployed upgrade (see Table 1) is intended to increase frame rate to the limit imposed by NIRC2's Aladdin detector (Fowler et al. 1996). To accomplish this, a new STA Archon controller will replace the 1990s technology (Transputers), and the controller will be supported by a modern computer and operating system. Replacement of obsolete control and computer hardware minimizes risk of failure, allows for the system to be spared, and eases future maintenance. We anticipate that the overall observing efficiency in the thermal IR will increase from current 30% to 75%. A goal is to reduce the full frame transfer time to saved FITS file from 12 s to 0.5 s.

As part of the upgrade, the team is working on additional features that will benefit the scientific community. With the new hardware, the development team is providing additional readout schemes that will enable high-speed subframe readout mode in support of image-based wavefront sensing and pointing control at infrared wavelengths. Observing teams will have the option of saving raw images that contain individual frames in addition to processed images resulting from the co-addition of multiple frame differences already provided by the current system. The development team is maximizing charge collection efficiency (duty cycle) for the fast readout modes and minimizing detector readout artifacts while improving overall on-sky observing efficiency.

The new hardware is designed to be interchangeable with the existing instrument configuration during the development phase. At any time, it is possible to connect the NIRC2 detector to either the new controller system or to the original transputer-based system and be able to operate the instrument. The purpose of this approach is to allow for testing of the new hardware in between NIRC2 on-sky science observing sessions with the old hardware. This development approach allows the hardware to be deployed without downtime to NIRC2 science. Once the system is operational, the old hardware seen in Figure 1 will be removed.

A software interface to the Archon controller is provided via a server that uses TCP/IP sockets to transmit and receive status and commands. The interface can be used by engineers for testing and characterization using a terminal to type commands or write scripts to program automation functions, by external applications such as GUIs or scripts, and by any observatory environment such as the Keck Task Library (KTL—Lupton & Conrad (1993)). Software updates are in place to dovetail the new hardware with the existing legacy system so that the transition is seamless to the observing community.

The new system is already installed on NIRC2, and the team efforts are currently focused on fine tuning the Archon controller parameters for the different readout modes, finalizing the software delivered with the controller, characterizing the performance of the new system, and fully integrating the new system in the observatory operations. Figure 2 illustrates one of the first images taken with the new system using the Keck-II AO bench calibration fiber light source to corroborate the descrambling algorithm.

3 | NIRES ON-SLIT GUIDING IMPLEMENTATION

NIRES (Near-InfraRed Echellete Spectrometer) is a prism cross-dispersed near-infrared spectrograph that is mounted on the Keck II telescope at the right-bent Cassegrain port (Wilson et al. 2004). It has a separate

TABLE 1 NIRC2 detector system.

NIRC2	Current	Upgrade
Detector science	1K × 1K Aladdin-3	
Controller	INMOS transputers	STA Archon DC
Computer	Sun Ultra 60	ASL Lancelot 2884-SRT
Motivation	Increase observing efficiency New readout modes Tackle obsolescence	
Team	Caltech (PI D. Mawet, WMKO)	
Status	Summit AIT with release to operations by May 2023	

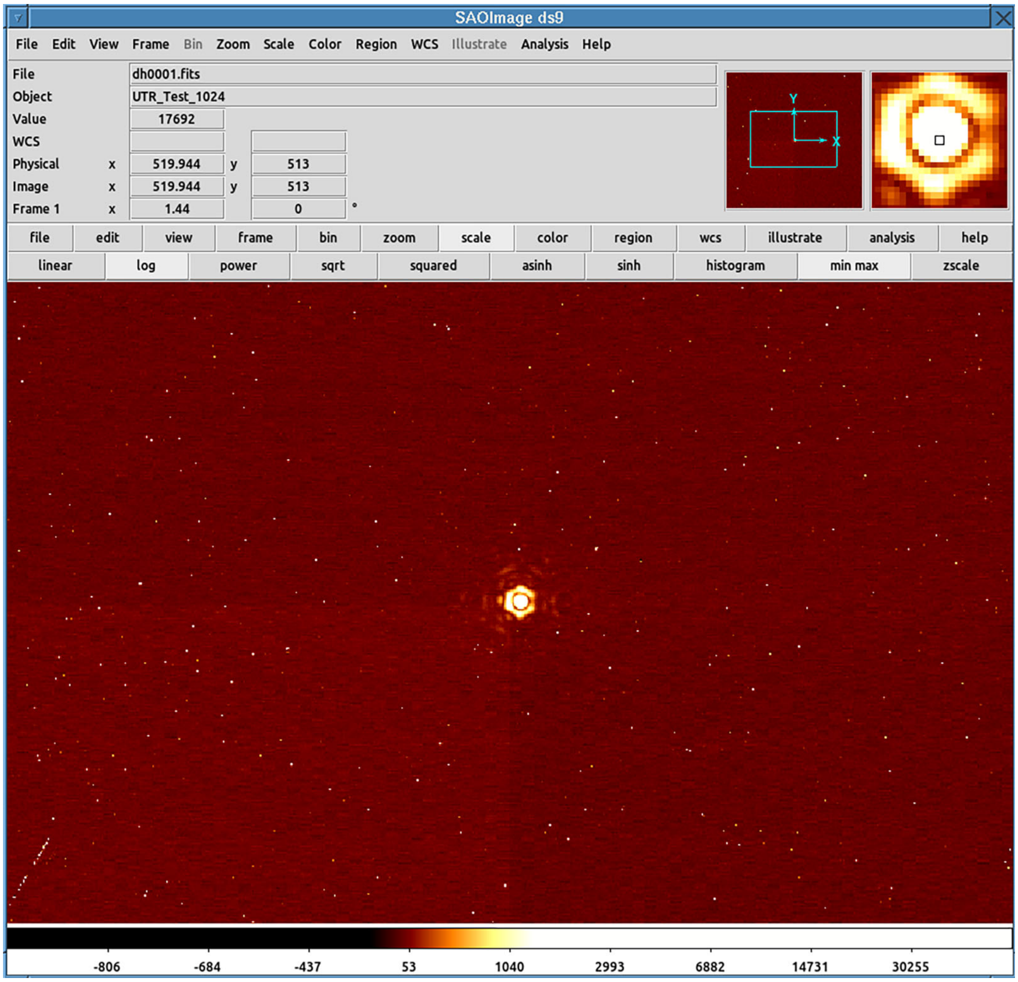
FIGURE 1 Timothee Greffe and David Hale from Caltech delivering the new controller. Behind them is the NIRC2 instrument (D-82 dewar) and the 6-ft tall electronics cabinet that the new controller replaces.

slit-viewing camera (SVC) to enable real-time source identification and guiding in the near-infrared K band (see Table 2). The NIRES wavelength coverage, spectral resolution, and permanent availability on the telescope make it an ideal instrument for time domain astronomy. To fully take advantage of NIRES' capabilities of simultaneous JHK spectroscopic observations, the Keck Observatory worked in partnership with staff from Canada France Hawaii Telescope (CFHT) to convert the SVC into an infrared guider so that scientists could easily position the telescope on targets without an optical counterpart.

The software delivered with the instrument allowed for full frame readouts of both the science and slit-viewing cameras using Leach generation III electronics. The older array (Rockwell Hawaii-1) for the SVC resulted in some challenges in implementing sub-arrays with the camera so that a suitable guide box of over 5 arcsecond on a side could be used to isolate the guide star emission and increase the readout efficiency. Originally, the frame period in the SVC was limited to 6.3 s due to the full frame reset for the CDS readout time of the Hawaii-1 array.

CFHT had implemented sub-array control for their H2RG detectors using Leach electronics, and due to their relative proximity in Waimea and on the summit, they were natural partners to pursue this upgrade. While CFHT staff implemented sub-array control for the NIRES Hawaii-1 detector, WMKO staff implemented the slit-viewing guider high-level software that telescope operators use for initial acquisition, target identification, and guiding (see Figure 3). CFHT dovetailed the existing code with sub-array developed in-house. WMKO staff implemented a remote power cycling capability for the hardware to assist in CFHT troubleshooting and for additional improvements including on-sky recovery. CFHT updated and tested the DSP code in the lab and on the deployed Leach controllers on site. As a result of this development, a 64×64 pix region of interest (ROI) can now be acquired in correlated double sampling (CDS) readout mode with a frame rate near 2 Hz and a 300 ms integration time. The ROI is static and fixed to the slit area.

Sub-array readout of the Hawaii-1 multiplexer had been demonstrated by Hodapp et al. (1996). Unlike the HxRG multiplexers, the Hawaii-1 does not have a separate column/row select mechanism for sub-array readout. Instead, accessing a subregion involves implementing



File dh0001.fits
Object UTR_Test_1024
Value 17692
WCS
Physical x 519.944 y 513
Image x 519.944 y 513
Frame 1 x 1.44 0 °

FIGURE 2 One of the first images taken with the NIRC2 detector connected to the new Archon controller in February 2023. The image was taken in multiple correlated double sampling (MCDS) mode using the Brγ filter. The bright light source in the middle of the image corresponds to the fiber source in the Keck-II AO bench, which is normally used to calibrate the AO system.

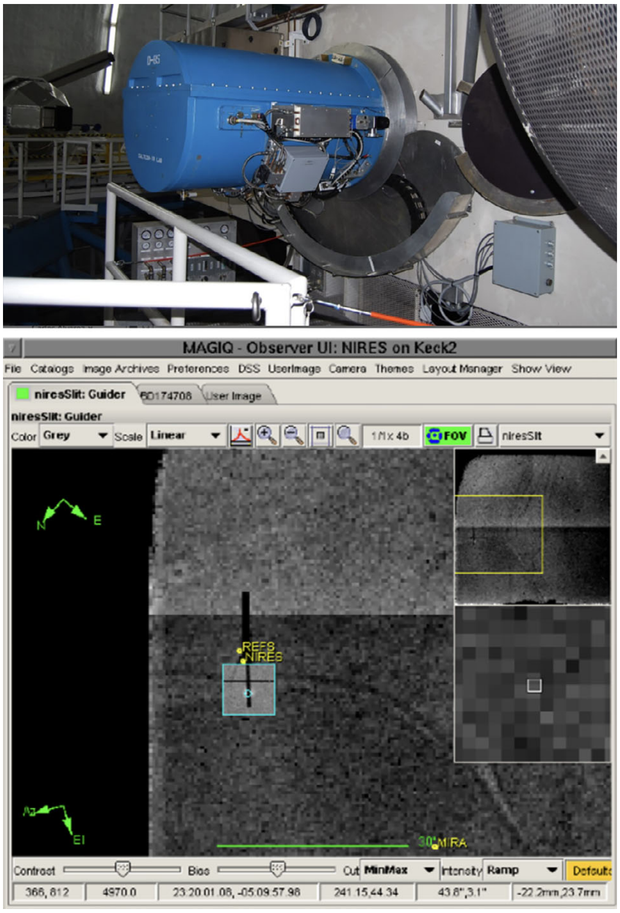
logic similar to the readout of a CCD subregion, where each row and column must be clocked up to the ROI, saving time by not sampling the signal outside the ROI. This significantly limits the readout rate possible from a Hawaii-1 sub-window compared with the HxRG variants. For simplicity, in NIRES the sub-array dimensions and corner coordinates are limited to even numbers (see Figure 4). This avoids having to implement separate logic to account for the fact that the Hawaii-1 uses both the rising and falling edges of the clocks applied to the horizontal and vertical scanners.

TABLE 2 NIRES detector systems.

NIRES	Current	Upgrade
Detector science	Teledyne 2K × 2K H2RG	
Detector SVC	Rockwell 1K × 1K Hawaii-1	
Controller	ARC Gen-III	
Guiding	Optical guider	SVC guider
Motivation	Increase observing efficiency On-source guiding	
Team	CFHT and WMKO	
Status	Released for science operations	

4 | DEIMOS THROUGHPUT UPGRADE

DEIMOS (DEep Imaging Multi-Object Spectrograph) was purpose-built (Faber et al. 2003) for the groundbreaking DEEP2 redshift survey (Davis et al. 2003), but it has facilitated revolutions in many areas of astronomy in its more than 20 years of operations. DEIMOS made possible the discovery of the enormous reservoirs of dark matter in Milky Way dwarf satellite galaxies (Simon & Geha 2007), and it was used by Kirby et al. (2011, 2013) to establish



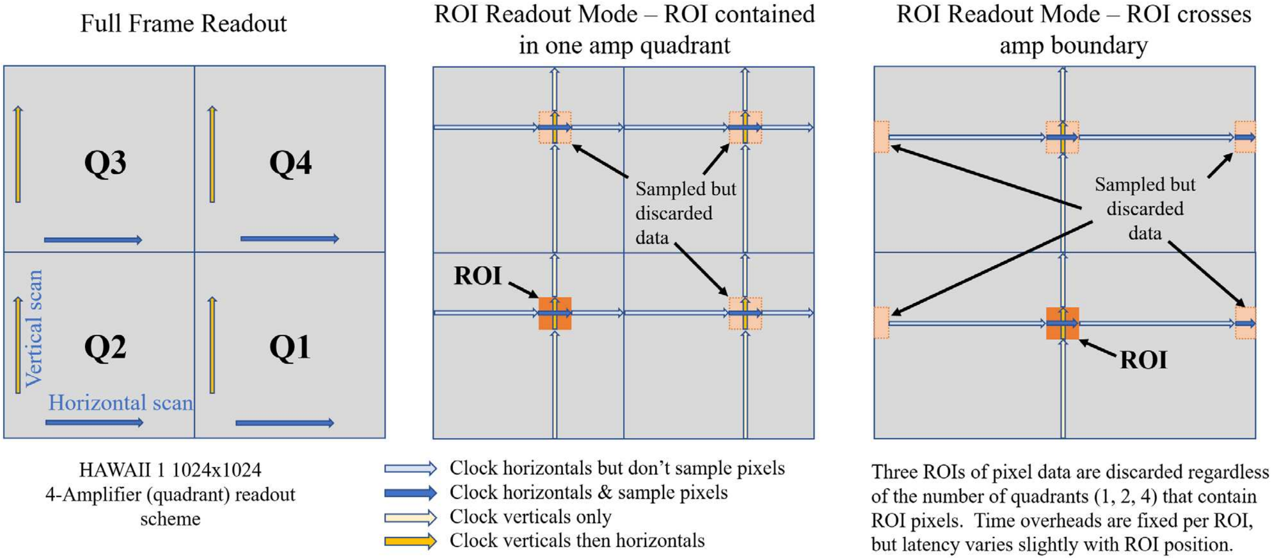
Color Grey
Scale Linear
Cut MinMax
Intensity Ramp

FIGURE 3 Top: NIRES located at the right-bent Cassegrain port on the Keck II telescope. Bottom: Guider image display showing the full frame of the SVC and the ROI for the on-slit guiding that was implemented.

the universal stellar mass-metallicity relation for dwarf galaxies and to measure detailed abundances for thousands of stars. DEIMOS has made possible 878 refereed papers with 67,000 citations. At WMKO, DEIMOS remains the workhorse multi-object spectrograph in the visible for Keck II, with the rate of citations continuing to increase.

DEIMOS' optical efficiency is no longer world-class not due to any degradation in the optical system, but rather due to technological advances in image sensors that result in the current DEIMOS detector mosaic quantum efficiency (QE) to be below modern CCDs. The current detector system is populated by a 2×4 mosaic of 2048×4096 MIT/Lincoln Labs CCID20 CCDs for the science data and two 1200×600 Orbit Semi CCDs for the Flexure Compensation System (FCS). The current science detector QE peaks at 87% at 780 nm and is down to 60% at 420 nm and 920 nm (blue and red ends of the DEIMOS spectral range). The development team investigated off-the-shelf detectors as well as custom solutions to replace the current detector mosaic. The Teledyne/e2v CCCD261-84 detectors were selected for the upgrade (see Table 3) as a result of the investigation because they fulfilled the science requirements in terms of throughput and detector gap size. The CCD261-84 detectors have a QE greater than 90% over the desired scientific spectral range of DEIMOS (see Figure 5). The higher QE is achieved because the new devices are 200 μm thick (currently 40 μm) and are coated with e2v's proprietary broadband Multi-2 anti-reflection coating.

In addition to improving the QE another motivation for the upgrade is to tackle obsolescence. The current DEIMOS detector system is aging and difficult to source spare parts, which incurs high maintenance costs. The



HAWAII 1 1024x1024
4-Amplifier (quadrant) readout scheme

Three ROIs of pixel data are discarded regardless of the number of quadrants (1, 2, 4) that contain ROI pixels. Time overheads are fixed per ROI, but latency varies slightly with ROI position.

FIGURE 4 Readout scheme for a subframe ROI in the Hawaii-1 array used for guiding on the NIRES SVC. Three quarters of the sampled data are discarded regardless of the ROI position. The entire frame is clocked to ensure that the readout time is invariant with ROI position.

TABLE 3 DEIMOS detector systems.

DEIMOS	Current	Upgrade
Detector science	2 × 4 mosaic of 2K × 4K MIT/LL CCID20 CCDs	2 × 4 mosaic of 2K × 4K Teledyne/e2v CCD261-84 CCDs
Detector FCS	Two 1200 × 600 Orbit Semi CCDs	Two 2K × 4K SITe ST-002A CCDs
Controller	Based on SDSU-2	STA Archon
Motivation	Increase throughput Tackle obsolescence	
Team	Notre Dame, Caltech, WMKO	
Status	Detailed Design phase; 2 yr for release	

detector system has experienced intermittent episodes of low performance in recent years ranging from CCDs with elevated noise to complete insensitivity to light. As a result, the DEIMOS upgrade development team proposed an overhaul of the detector system coupled with upgrades to the optical path to make DEIMOS' optical efficiency on par with modern instruments. The team determined that replacing the entire cryostat and the detector controllers was less risky than replacing detectors in the current cryostat.

The preliminary design of the upgrade system components is shown in Figure 6. The detector mosaic mount is supported by three thermally isolating bipods that connect to the detector enclosure. The mount assembly will be cooled via a pair of thermal links that connect to the LN2 tank cold plate. The new design incorporates a modern vacuum interface board (VIB) that collects signals from CCDs and routes them on internal layers to conventional connectors on the atmospheric side of the vacuum wall. Each science CCD has a pin grid array (PGA) at the edge of the detector package. The CCD is inserted into a custom zero insertion force (ZIF) socket, which will be soldered to an adapter board and flex cable plugged into the VIB. The VIB removes the need for hermetic connectors and allows us to outsource cables. WMKO initiated a contract with Teledyne to secure the detectors and an engineering device currently available at Caltech is being used for initial testing and development. The new controller is the STA Archon that is now in use at WMKO with KCWI, KPF, LRIS, and soon with NIRC2. The spare parts situation for these instruments is greatly improved by having the same CCD controller deployed with all of these instruments.

The development team is working toward a drop-in replacement dewar with a new FCS that relies on a hexapod for high-precision motion control (see Figure 6). The simpler electronic interface and the elimination of cryogenic stages greatly simplify the dewar design relative to the currently deployed DEIMOS system. The current dewar is split into (a) a vessel for the detector, electronics, and two motors with cryogenic couplings, and (b) a separate nitrogen reservoir that provides cooling for the detector via a cold finger enclosed in its own vacuum chamber. The hexapod will eliminate the need for motors with cryogenic couplings, freeing space to relocate the nitrogen inside the dewar. With this concept, the entire dewar is articulated for focus and flexure compensation instead of having internal cryogenic stages. This solution also allows us to maintain the required precision for instrument focus and flexure compensation while allowing new degrees of freedom to correct rotation and focus tilt.

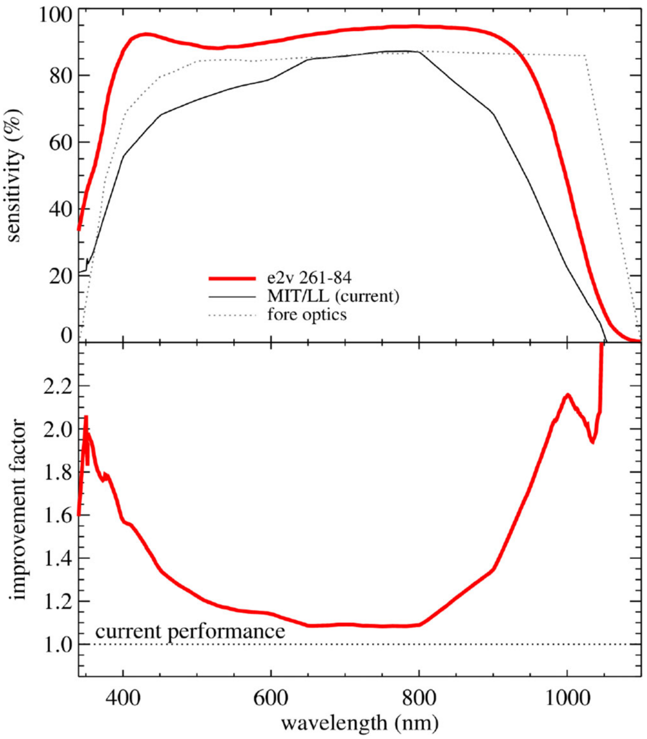


FIGURE 5 Top: Sensitivity of the new detectors compared with the current detectors. The dotted line shows the transmissivity of the camera lenses, which limit the instrument below 400 nm. Bottom: Fractional improvement of the instrument response.

An additional advantage of the drop-in replacement dewar and hexapod is the reduction of commissioning

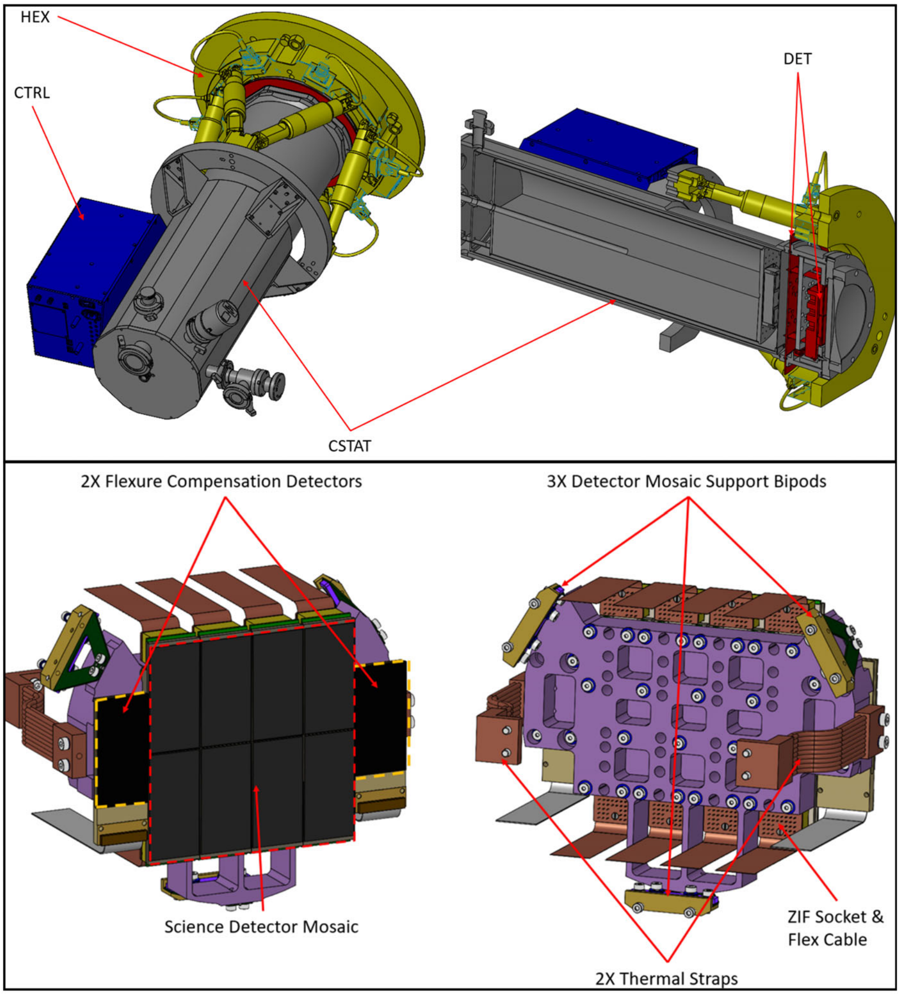


FIGURE 6 Preliminary design of the new detector system. Top: DEIMOS detector system upgrade components including cryostat, hexapod, detector, and controller. Bottom: Layout of the detector mosaic assembly.

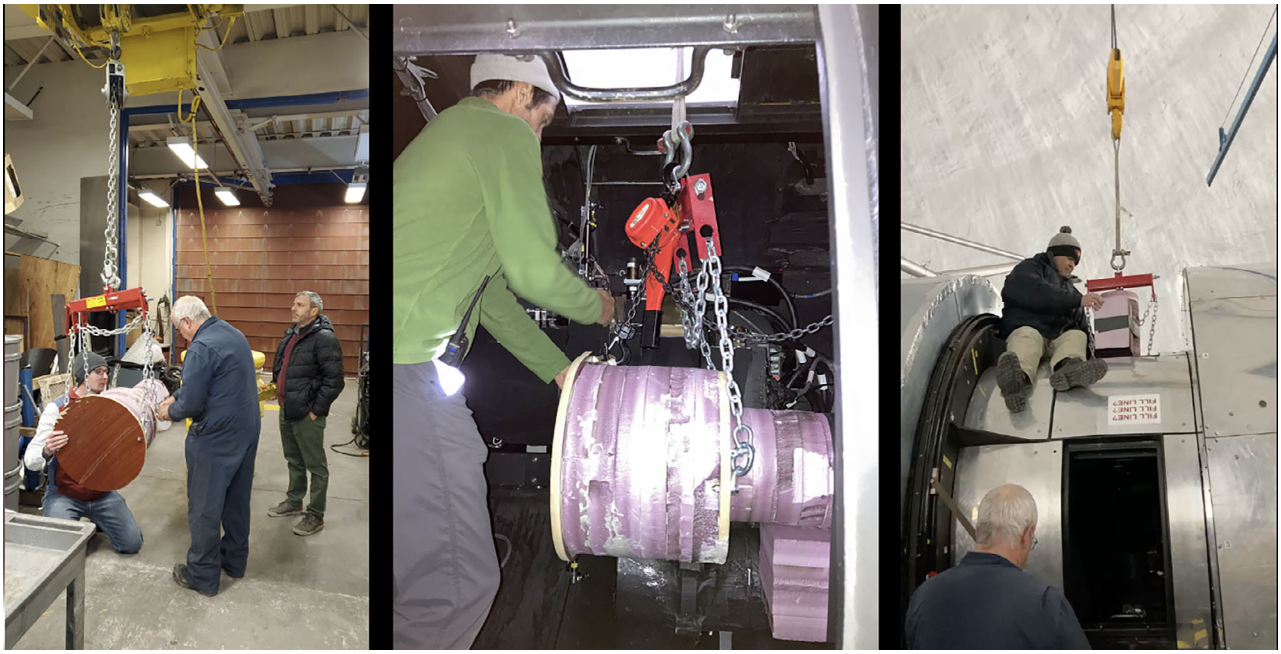


FIGURE 7 The development team test fitting and determining the appropriate rigging for a mock-up dewar. Left: Joshua Holewczynski and David Cavalieri from the U. of Notre Dame with observatory staff Mike Dahler working on the initial rigging setup. Middle: Carlos Alvarez positioning the mock-up inside the DEIMOS instrument rotating barrel. Right: Installation into DEIMOS using the dome crane with observatory staff Dwight Chan and Mike Dahler.

time. Reusing the existing dewar would have required DEIMOS to be off-sky for many months. With our planned system, the development team will be able to swap the dewars in a time frame of up to two months. There is an established precedent at WMKO for this kind of work: The LRIS red detector upgrade was completed in a single lunation in 2009 and later in 2019.

The development team is currently finalizing the procurement details for the hexapod, and exploring different handling and rigging options to install the new system in the instrument (see Figure 7).

5 | CONCLUSIONS

We have presented three examples of cost-effective detector system upgrades to instruments that either were designed or started science operations on the Keck Observatory nearly two decades ago. These upgrades tackle obsolescence in aging instruments, improve observing efficiency, and open the possibility to explore new science cases.

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