Iao: The new adaptive optics visible imaging and photometric system for AEOS

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The Iao camera is a totally new camera system that will be replacing the existing visible imager (VisIM) camera. It functions as the science camera, and is capable of collecting uncompensated, as well as adaptive-optics compensated images. Iao offers a number of improvements over the existing system, including higher speed, greater sensitivity, as well as improved flexibility in control of the imaging system. We describe the Iao camera system, the current state of progress, as well as the plans for integration of the new system into AEOS.

Topics: Instrumentation, Astronomy, or Adaptive Optics

1. Motivation and requirements

The Visible Imager's primary task is to serve as the science camera behind the AEOS Telescope's high-order adaptive optics (AO) system [1]. In this role it takes high spatial resolution imagery of resolved targets. These targets are primarily low Earth orbiting satellites acquired for the Department of Defense and other branches of the U.S. government. In addition it supports many astronomical observation programs. These have included observations of binary stars, asteroids and planets such as Mercury and Mars [2,3,4].

The Visible Imager is also used to take time resolved photometry of spatially unresolved objects. These are primarily objects which are too small to be resolved by the AO system or too faint for AO compensation [5]. In this case data are collected on the object and the brightness of each image is measured. These data are then calibrated using standard astronomical techniques that have been shown to be accurate to 1%. For most programs (both resolved and unresolved), these data sets have been collected at wavelengths longer than 700nm, but there is interest in collecting data at shorter wavelengths.

While the Visible Imager has served the site well, it has several limitations: it is only a 12-bit camera, which limits the dynamic range it can capture in a single image. The reported integration time is not the true integration time, which makes analysis of photometric images when the exposure changes difficult. The camera has a maximum frame rate of 3.5 frames per second. The dark current is rather high, which is fine for short exposures, but is problematic for longer exposures. The camera has been showing its age, and there are frequent maintenance issues, which lower the observing efficiency.

In order to correct these shortcomings and to add additional capabilities, a new camera was designed and built. The goals were to increase the frame rate, lower the operating temperature (to decrease the dark current), increase the read-out resolution, and upgrade the various electronic elements, to increase reliability and data storage. Ideally, the CCD sensor would also be improved over the current device, with higher quantum efficiency, and few bad pixels and columns. The need is to keep all of the existing system capabilities, but to expand on the existing camera's performance. The existing VisIM camera was designed to support the following missions:

- Adaptive Optics (AO) imagery

- Photometry (with or without the use of adaptive optics) [5]

- Wide Field Imagery of extended objects

While at the same time increasing the following performance areas:

- Higher sensor quantum efficiency (QE)

- Lower system noise

- Higher read-out frame rates

The increased frame rate of Iao, compared to the VisIm, will increase the capabilities of the AEOS AO system. Depending on conditions, the AO system is able to produce highly compensated images, but even in the best conditions the images are not perfect. The performance is limited by target brightness and atmospheric seeing. The seeing on Haleakala is quite good, but it has its share of poor nights. Also, the telescope is often used to observe objects far from zenith (through high air mass), which degrades the effective seeing. In addition, in all seeing conditions, the AO system is only able to correct spatial frequencies up to the spatial frequency of the deformable mirror actuators. Above this spatial frequency the images are effectively uncompensated.

The AEOS AO system is unable to compensate for targets dimmer than 8th visual magnitude, and on large objects that fill the field of view of the individual lenslets in the wavefront sensor. For these objects, the AO system can only correct the tip/tilt of the object. With Iao, we will be able to post process these images, with techniques that have been successfully applied to the GEMINI imaging system on the MSSS 1.6m [6,7,8].

The high frame rates of Iao, will allow post processing algorithms to improve the image quality. These algorithms require frame rates that image the object several times before the point spread function changes significantly [9,10].

A design-and-build effort has been underway at AMOS for the past ~2 years to construct such a new visible imaging system, and the result is known as the Iao camera. The system is a combination of some custom-off-the-shelf (COTS) components, coupled with some custom components (some built in-house, others acquired from outside vendors). Some are re-use from the existing VisIM camera system, but many are new. We are in the final integration and testing phases for this project, and have acquired all the necessary components, which have been assembled in our sensor laboratory (as of this writing), with plans to integrate the new system into the AEOS telescope this year.

Implementation The Iao camera system (see Fig. 1) includes a new sensor (a CCD), mounted inside of a new vacuum dewar (to allow cooling of the chip to -75 C) (see Fig. 2), as well as new sensor control/read-out electronics, which include two computers to operate the camera and a large amount of hard-disk RAID storage. Additionally, new optics and optic actuator systems have been procured.
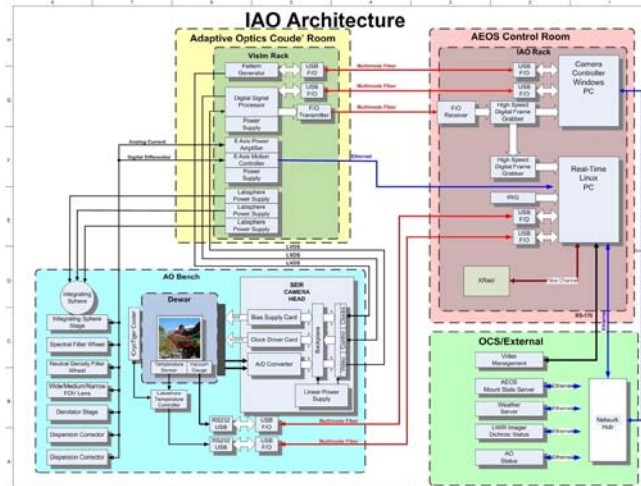
Fig. 1 shows the architecture of the Iao camera system. The sensor and the optics will be integrated onto the Adaptive Optics (AO) optics bench. In close proximity (but not on the bench) will be the control and read-out electronics, as well as the camera chiller system. Computers controlling the camera and optics actuators will reside in the telescope control room. Meta-information is imported via connections to external data servers, to allow for accurate time-stamps, mount state information, etc.
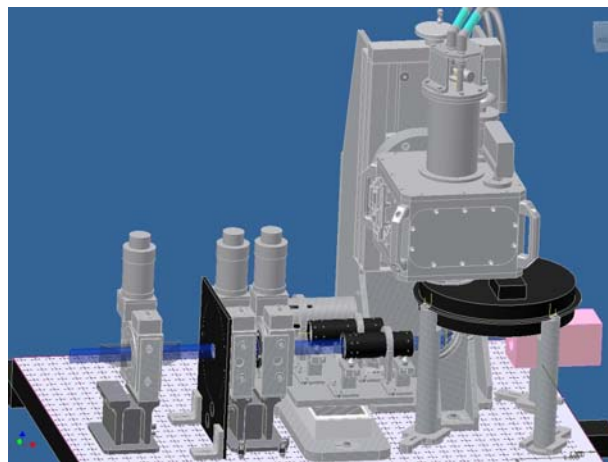

Fig. 2 shows the camera and optical elements mounted on the AO bench. Following the beam path from the left, the first element is a Dove prism, followed by a field stop (black plate), then the Risley prisms, next the three lens barrels (allows the three selectable fields of view). The visible light is then reflected up-wards, passing through a filter wheel (black cylinder), and entering the Iao camera vacuum dewar. Space has been provided for the possible future installation of a dichroic, which would allow wavelengths longer than 1 µm to pass to the right, into a near-IR camera (shown here as a notional pink box). Not shown is an enclosure that mounts over the optics and camera dewar.

2. CCD

The single most important element of the Iao camera system is the sensor that converts incoming photons into a measurable electronic signal. Various trade studies were conducted to chose the sensor for the camera, given the various requirements that the camera would need to fulfill, as well as the available budget, and a charged coupled device (CCD) from E2V was chosen as the best sensor available for the camera at this time. Some important features are compared between the existing sensor and the Iao camera in Table 1. Key areas that dictated camera performance include:

- o Being able to observe from the blue cutoff of the AEOS optics out to 1 μm of wavelength coverage
- o Over 99.8% of the sensor pixels will be operable and there will be no clumps of 3 or more dead pixels
- o A maximum read-out rate of 50 frames/second with 2x2 pixel binning
- o Selectable region of interest, variable in size and position, to be read-out
- o Variable speed readout of the device:
    - ▪ Readout rate controlled by waveform file logic and selected clock speed
    - ▪ Allows for a limited set of read-out speeds
    - ▪ An "as fast as possible" (50 frames per second) read-out rate
    - ▪ A "standard rate" (compromise between low-noise and fast frame rate)
    - ▪ A lowest-noise (~50 kilopixels per second) read-out rate
    - ▪ Variable integration time
    - ▪ Ability to digitize or skip reference pixels or rows

Table 1. compares the existing sensor in use in the VisIM camera with the expected performance (per E2V) of the Iao sensor. The readnoise of the Iao sensor is quoted for its maximum read-out rate, and has not been measured at any lower rate (e.g., 500 KHz), but is expected to be much lower.

	Visible Imager	Iao
Read Noise	16 e⁻ (at ~500 KHz)	35 e⁻ (at 10 MHz)
Quantum Efficiency	0.45	0.70
Dark Current	22 e⁻/s (at -20° C)	0.1 e⁻/s (at -75° C)

The CCD selected was a CCD 48-20 from E2V. This device is a 1024 x 1024 pixel (plus reference rows and columns; see Fig. 3) back-illuminated frame transfer device, with two 10 MHz read-out taps, and 13 μm square pixels. It has a mid-band optical coating to optimize the QE across our bandpass of interest, ~500 nm to 1 μm (see Fig. 4). We have on hand two working devices (in addition to a mechanical fit check dummy device); one "science" grade (grade "0"), and one "engineering" device (of lesser quality, although it is actually a grade "1" device) for routine integration and test work (Fig. 5). See table 2 for a description of the CCD grading scheme.

Table 2. Criteria used to grade CCDs by the foundry (E2V) for blemishes and flaws. The Iao camera project has on-hand two CCDs; a grade 0 and a grade 1. Initial testing will be only with the grade 1 device. Grade 5 is actually an engineering grade. Grades 1-2 are science grades. Our engineering grade detector was the 'worst' detector from the wafer they cut apart. It just happens to be a pretty good one, and is actually grade 1.

Grade	0[a]	1[b]	2
Column Defects	0	2	6
Black Spots	50	100	200
Traps >200	2	5	12
White Spots	50	80	100

A: Grade 0 = 99.99% operable
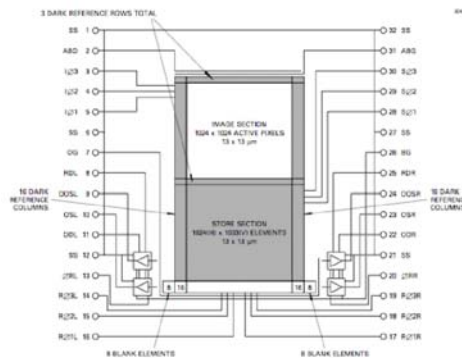B: Grade 1 = 99.77% operable

Fig. 3. shows the E2V 48-20 schematic chip lay-out and pin-out configuration. The chip includes, in addition to the active pixels, a number of reference rows and columns, as well as blank pixels, for bias and read-noise estimation. The serial register is split in the middle, reading to the outside of the device, to the two output amplifiers. In addition to each output amplifier is a dummy load amplifier, which can be utilized for differential mode read-out, useful in situations with high external noise (e.g., radio frequency noise).
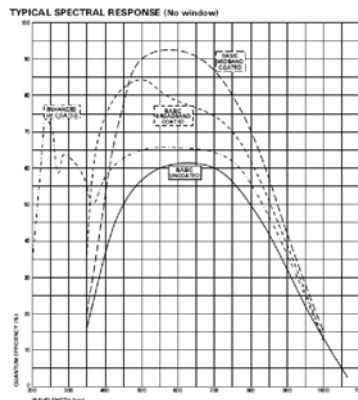
Fig. 4, showing typical quantum efficiency for E2V 48-20 BI CCDs. Our devices have the midband coating. Device QE peaks at about 92% at 600 nm, and is still about 15% at 1 μm. Note, these QE curves are only for the CCD, and do not include any contributions from the optics.
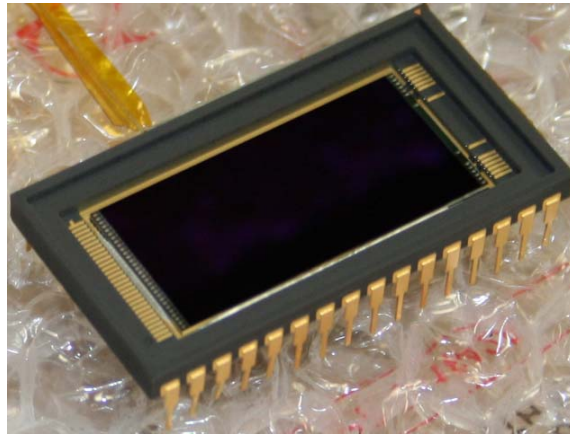

Fig. 5 is a photograph of the Iao "engineering" CCD prior to initial integration and test in the Iao camera dewar. The lack of metallization over the frame-store region requires the use of an external mask to shield this area of the chip from stray light.

Dewar

The vacuum dewar for the Iao camera was acquired from GL Scientific. It is a very close copy of one built for a Massachusetts Institute of Technology Lincoln Laboratory telescope camera system (Fig. 6). It provides a clear entrance window, to allow optical photons onto the CCD, as well as a Beryllium window to allow soft (5.9 keV) X-rays from an ^{55}Fe source to enter the dewar for specialized testing (Fig. 7). Electrical signals pass to/from the CCD via a potted-in-place flex print circuit. A CryoTiger closed-cycle chiller allows cooling of the CCD to temperatures of less than -75° C, with a Lake Shore temperature read-out and thermal control system for CCD temperature regulation. The dewar also contains a vacuum gauge, a vacuum valve, and a vacuum getter (see figures 8, 9, and 10). During normal use, after using a turbo pump to evacuate the dewar to less than two millitorr, and cooling the sensor to -75° C, the vacuum valve is closed, and the vacuum pump is disconnected. The getter and the cyro-pumping action of the cooling system are sufficient to maintain a pressure inside the dewar of less than 3 millitorr.
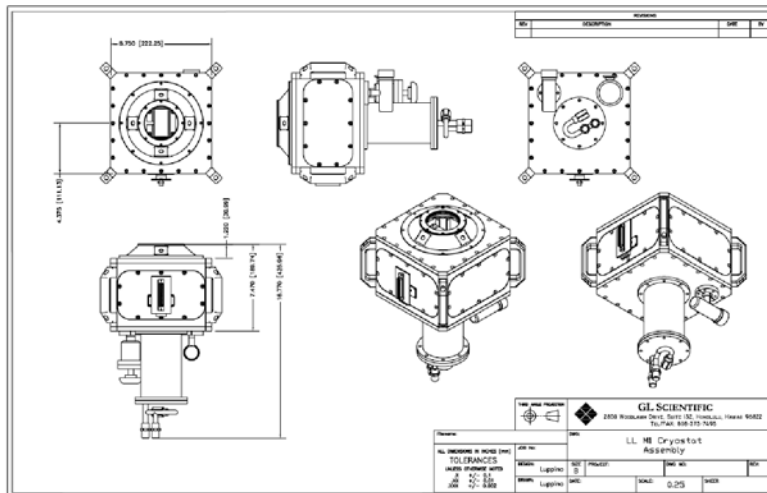
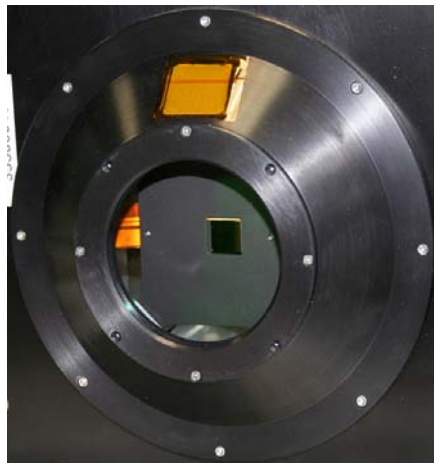Fig. 6 shows schematic views of the Iao camera vacuum dewar.

Fig. 7 shows the front aperture of the camera. The frame-store region of the CCD is masked; only the image area is visible. The Beryllium window can be seen above the entrance window of the dewar, covered in kapton tape.
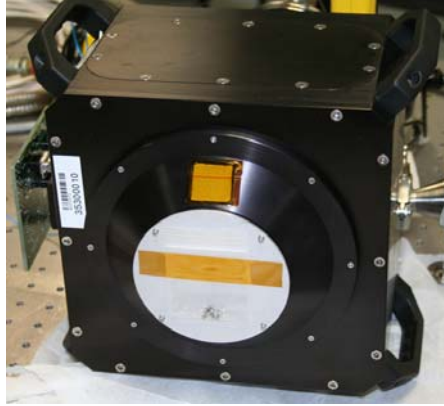
Fig. 8 showing the front of the Iao camera vacuum dewar. The entrance window is covered with a removable aluminum plate that protects the window as well as allows for provision of darkness inside the dewar. The electrical signals are brought via flex-print through the left-hand side of the dewar (in this picture), where an interface card has provision for external connectors.
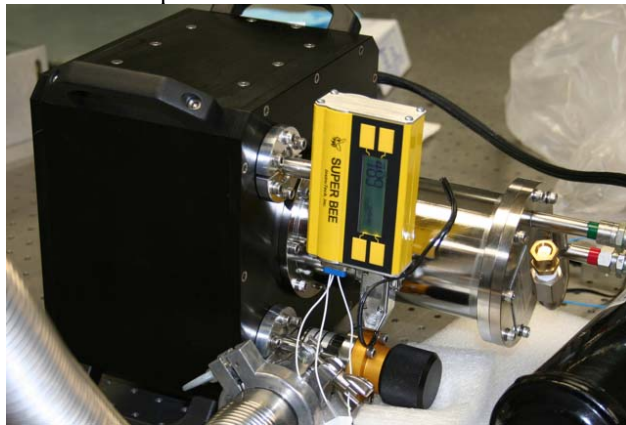

Fig. 9 shows the rear of the dewar, which contains the vacuum valve, vacuum sensor and read-out, and thermal cooling circuit hook-up.
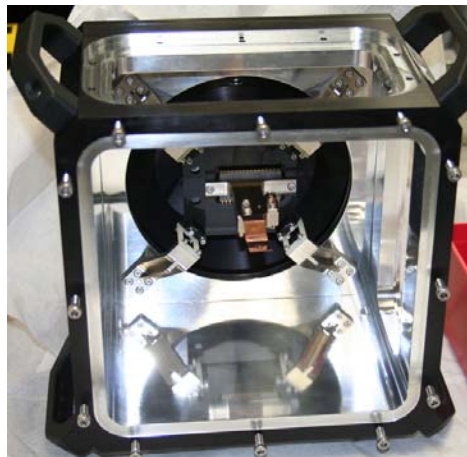

Fig. 10 shows the inside of the dewar with the rear-panel removed, as well as the flex print. The two rows of pins on the CCD can be seen pointing towards the rear of the dewar; the CCD is held in alignment by a cold-finger, which connects to the thermal cooling circuit by a flexible copper multi-layer strap.

Balance of System

In addition to the sensor and the dewar (including thermal control system), the camera includes SEIR-provided read-out electronics, camera control and data collection computers, RAID data storage. Also, there are provisions for

controlling optical elements (field of view settings, filters, dispersion correctors, etc.). The Iao camera system also has to tie into the Observatory Control system for control and data collection. Various elements of the system are dispersed throughout the AEOS observatory.

Status

First light in Lab
Initial camera set-up and testing has occurred at our Kihei facility. Fig. 11 shows the laboratory "first light" image. As of this writing, we have demonstrated basic camera functionality. Integration, check-out, first-light, and testing at the AEOS facility will occur in the latter half of this year.
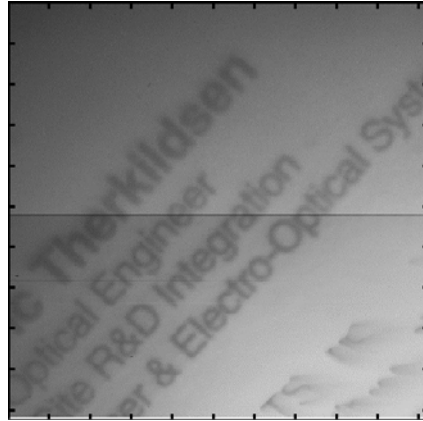

Fig. 11 is the "first light" (in the laboratory) image saved during testing. A number of artifacts are apparent; the horizontal line across the center (and the white line at the bottom) are due to a "counting" issue (since corrected). The lines across the lower half of the image are column problems inherent in this grade of CCD, along with several problem pixels. The bottom right hand corner is smeared due to too much light. The "frame" around the outside of the image is from an image capture program, and is not in the data.

Conclusion

The Iao camera system is poised to begin its operational life at AEOS. It offers significantly upgraded capabilities from the existing Visible Imager, in read-out rate, quantum efficiency, system noise, image bit-wise resolution, maintainability, and various other factors. Iao was also designed with upgradeability in mind; our camera electronics can accommodate a CCD with twice the number of read-out ports that the current Iao CCD has. Implementing a CCD with this capability would double the read-out rate, while utilizing the rest of the existing Iao system without change. Discussions are underway with CCD foundries to acquire such a sensor.

Acknowledgements

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