# HiCIAO – The High-Contrast Coronographic Imager for Adaptive Optics
# A New Instrument for the Subaru Telescope

Klaus W. Hodapp[a], Motohide Tamura[b], Ryuji Suzuki[b], Shane Jacobson[a], Vern Stahlberger[a],
Hubert Yamada[a], Hideki Takami[c], Olivier Guyon[c], Lyu Abe[b]

[a]Institute for Astronomy, 640 North A'ohoku Place, Hilo, HI 96720, USA
[b]National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan
[c]Subaru Telescope, 650 North A'ohoku Place, Hilo, HI 96720, USA

## ABSTRACT

HiCIAO, the High-Contrast Coronographic Imager for Adaptive Optics, is a coronographic simultaneous differential imager for the Subaru Telescope Nasmyth focus. It is designed primarily to search for faint companions, brown dwarves and young giant planets around nearby stars, but will also allow observations of disks around young stars and of emission line regions near other bright central sources. HiCIAO will work in conjunction with the new Subaru Telescope 188 actuator adaptive optics system. It is designed as a flexible, experimental instrument that will grow from the initial, simple coronographic system into more complex, innovative coronographic optics as these technologies become available. The main component of HiCIAO is an infrared camera optimized for spectral simultaneous differential imaging that uses a 2.5 μm HAWAII-2RG detector array operated by a Rockwell Sidecar ASIC.

**Keywords:** Optical design, infrared cameras, coronographs

## 1. INTRODUCTION

The High-Contrast Coronographic Imager for Adaptive Optics (HiCIAO) is a new instrument [1] being designed for the Japanese National Observatory Subaru Telescope. The new HiCIAO will supercede the capabilities of the existing CIAO [2] (Coronographic Imager for Adaptive Optics) on Subaru. HiCIAO will be used behind the new, high order, curvature sensing and bimorph mirror adaptive optics system [3] that is currently being built for the Subaru Telescope. This new laser guide star adaptive optics system with its 188 actuators will be superior to the current generation of adaptive optics systems with typically 85 actuators, and will therefore allow higher contrast coronographic observations. HiCIAO is the coronographic system and infrared camera to be used with this new adaptive optics system. The overall project, including its scientific goals and performance predictions, is described in [1]. This contribution describes the coronographic foreoptics and the infrared camera design of HiCIAO. These components are being designed and built at the Institute for Astronomy, University of Hawaii under contract from the National Astronomical Observatory of Japan. HiCIAO is designed as an experimental system and will be modified over the coming years to incorporate more advanced coronographic techniques and upgrades to its adaptive optics capabilities.

## 2. CORONOGRAPH AND CAMERA OPTICS DESIGN

The first light configuration of HiCIAO consists of a fairly simple classical Lyot coronograph and an infrared camera designed for a 2040×2040 pixels HAWAII-2RG 2.5μm HgCdTe detector array. As shown in Fig. 1, the coronographic foreoptics consist of a field lens with the occulting spot deposited on its flat front surface, a doublet collimator, and a doublet camera lens.

The coronographic foreoptics require several motion stages to select one of several field masks, occulting spots, and beamsplitting elements. Since the instrument is designed for the Nasmyth focus of the Subaru Telescope, the pupil mask needs to rotate against the field. Finally, all coronographic components can be fine adjusted on these high precision motorized stages to allow a precise centering of the coronograph relative to the adaptive optics system. Due to this complexity of the required motions, but also due to the difficulties of fabricating high quality cryogenic Wollaston prisms and finally, because of the relatively lower priority of the K band for the scientific goals of HiCIAO, it was decided to design the coronographic foreoptics for ambient temperature operation. A more detailed discussion of the thermal background on HiCIAO will be given below.

The camera lens is a $BaF_2$ / fused-silica doublet operating at ambient temperature. This is a less than ideal combination of optical materials, but it was chosen so that the mechanically robust fused silica lens can also be used as the cryostat window. The most important limitations to the performance of a spectral simultaneous differential imager (SSDI) are optical aberration differentials between the four beams that limit the ability to match and subtract the speckle cloud. To minimize these differential-path aberrations, the infrared camera lens is placed as close as is mechanically possible to the beamsplitting Wollaston prism. The first cryogenic optical element is the common-path filter, which is used for direct imaging and dual-beam polarimetric imaging. For use in quadruple-beam imaging, which is the mode of operation for spectral simultaneous differential imaging, the four individual filters (one for each of the four beams generated by the double Wollaston prism) are placed as close as possible to the detector, to minimize the impact of any surface imperfections on the wavefront in each of the channels.

The coronographic foreoptics deliver a collimated beam to the infrared camera. Therefore, the mechanical coupling between the foreoptics and the camera is not very critical. This is an important aspect of our design, since the foreoptics and the camera will be separately mounted on the Subaru Telescope Nasmyth platform, which is not of the same rigidity as an optical bench.

### 2.1 Modes of Operation

The HiCIAO camera is designed as a flexible system that can be configured into different modes of operation in an optical bench environment at the Subaru Telescope Nasmyth focus. The most basic mode of operation is direct imaging at the AO focus, with or without a coronographic occulting spot.

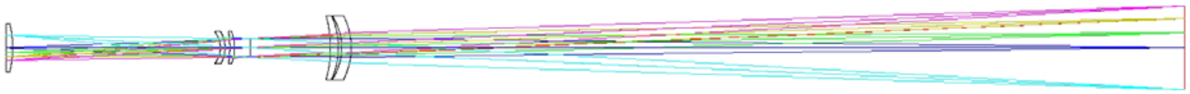


Figure 1: Raytrace of the HiCIAO infrared camera in simple imaging mode

The HiCIAO infrared camera offers two simultaneous differential imaging modes. For polarimetric simultaneous differential imaging (PSDI) mode, a single Wollaston prism splits up the image into two orthogonally polarized images. In conjunction with a rotating waveplate, this can be used to obtain imaging polarimetry. In particular, the polarization of an object near a bright star, for example a scattering dust cloud or a dust condensation in a protostellar disk, can be used to distinguish the object from the less polarized residual speckles of the bright star.

For spectral simultaneous differential imaging [4] , we will use a set of two Wollaston prisms (material YLF, angles 27° and 38°), with their optical axes at 45° relative to each other, to produce the four images of the object. Each of these images is recorded through individual filters, designed to match a spectral feature in the object, for example, the Methane absorption band in brown dwarves and young gas giant planets. The quadruple imaging mode is particularly powerful when the two or four sub-images are recorded simultaneously, so that residual speckles from the atmosphere, the telescope, and from common instrument optics are identical (but scaled by wavelength).

This method has been successfully used [4] to distinguish objects with Methane absorption in their spectrum from the cloud of residual speckles that, being scattered light from the star, do not show this feature.

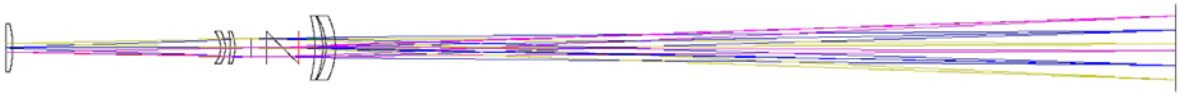


Figure 2: Raytrace of the HiCIAO infrared camera in single Wollaston (polarimetric) mode.

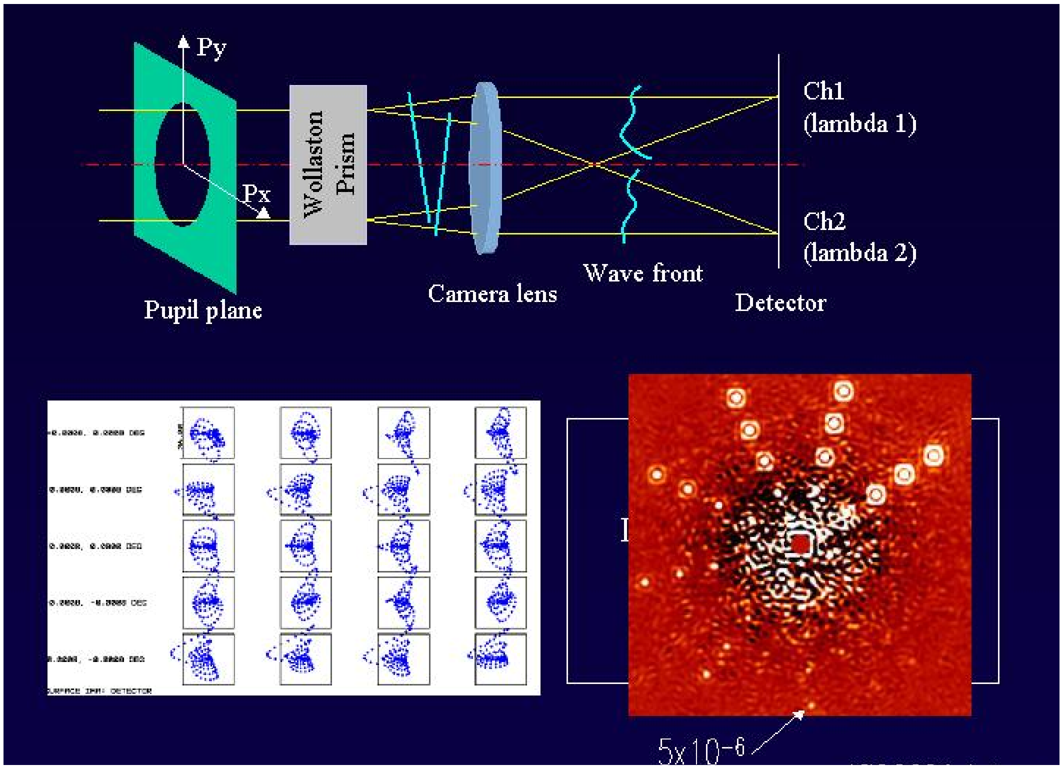


Figure 3: Basis principle of operation of a spectral simultaneous differential imager (SSDI).

Figure 3 illustrates the principle of operation of the spectral differential imaging. Even after adaptive optics correction and coronographic masking of the bright star, this bright star is surrounded by a halo of speckles of scattered light. A faint companion or planet can be distinguished from these scattered light speckles if the companion object has spectral features different from the central star. The most promising spectral feature used for this purpose is the methane band around 1.5 μm, which is present in low temperature companion objects but absent in stellar atmospheres. By scaling and subtracting the scattered light speckle pattern, this scattered light can be strongly suppressed, if the wavefront at both wavelengths is closely identical. The key performance characteristic of a simultaneous differential imager is therefore the residual level of differential path wavefront errors. The simulation shows a best estimate of the expected performance of HiCIAO. Around the central star, a pattern of simulated companion objects is shown, with different levels of contrast.

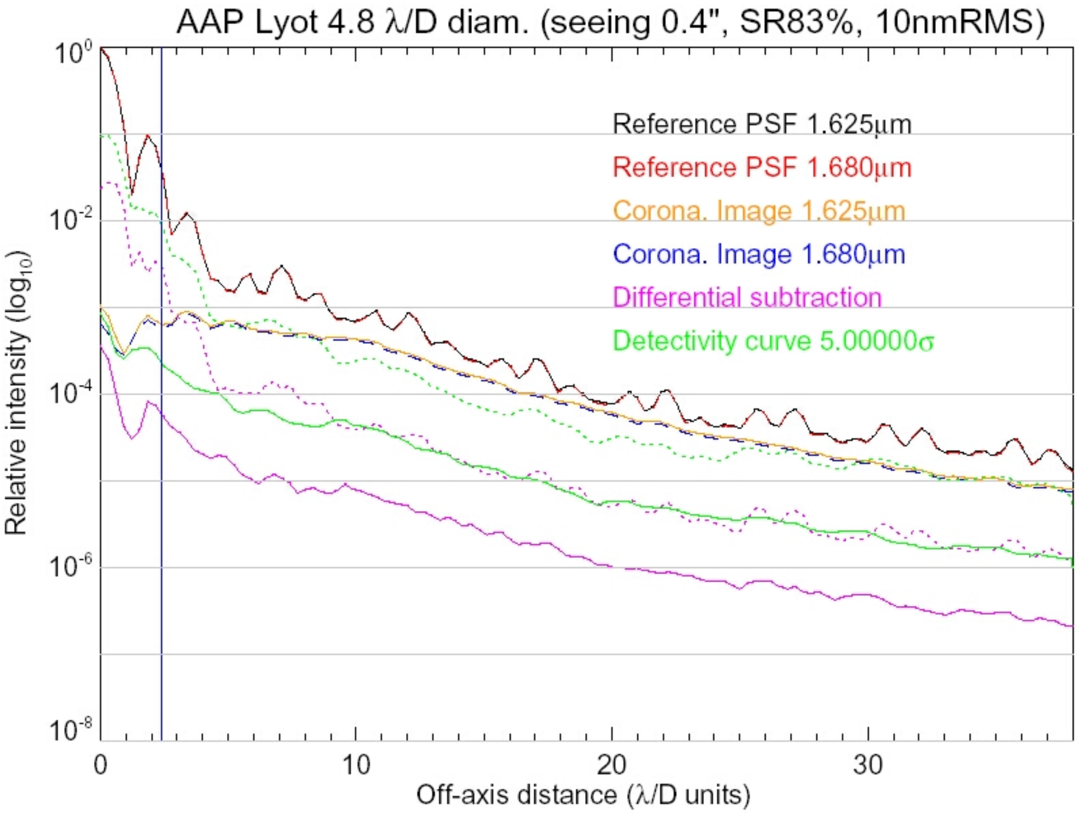


Figure 4: Predicted performance of the HiCIAO system under conditions of 0.4" (visual) seeing, 83% Strehl ratio, and 10 nm rms differential path errors.

### 2.2 Wollaston Prism Design

By far the best birefringent material for use in the H band is $\mathrm{LiYF_4}$, commonly referred to as YLF, due to its very low chromatic effects [5]. Wollaston prisms have been made from YLF for use at ambient temperatures. The chromatic effects in YLF are about a factor of 36 (in the H band) lower than in the more commonly used Calcite. In the J band, Calcite is about a factor of 5 worse than YLF, and in the K band, Calcite is not usable due to its absorption. YLF also has the advantages of reasonable cost and low anisotropy in its thermal expansion, leading to a relative insensitivity of the optical components to temperature changes. The two Wollaston prisms required for HiCIAO (the single Wollaston prism and the double prism) will therefore be fabricated out of YLF.

### 2.3 Filters

The common path filter wheel, used for direct imaging and single-Wollaston polarimetric observations, will have space for 11 filters and will carry the common J, H, and K broad band filters, and the selected narrow-band filters listed in Table I below. The differential path filter wheel has space for 3 sets of filters with 4 filters in each set, plus an open position. At this time, we have only decided that one of these filter sets must be chosen for detection of the H-window Methane absorption band in brown dwarfs and hot young Jupiter-sized planets. One of the filters in that set will also be used to observe the [FeII] line at 1.644μm, which is characteristic of high-excitation shocks in young stellar outflows.

### 2.4 Thermal Background

The HiCIAO foreoptics operate at ambient temperature. This will lead to a higher background when observing in the K band, but this is an acceptable restriction, given that most of our science will be done at shorter wavelengths. We are using background reduction mirrors that reflect the low thermal background of the inside of the cryostat back into the optical path. This technique limits the thermal background to acceptable levels in the K band.

## 3. MECHANICAL DESIGN

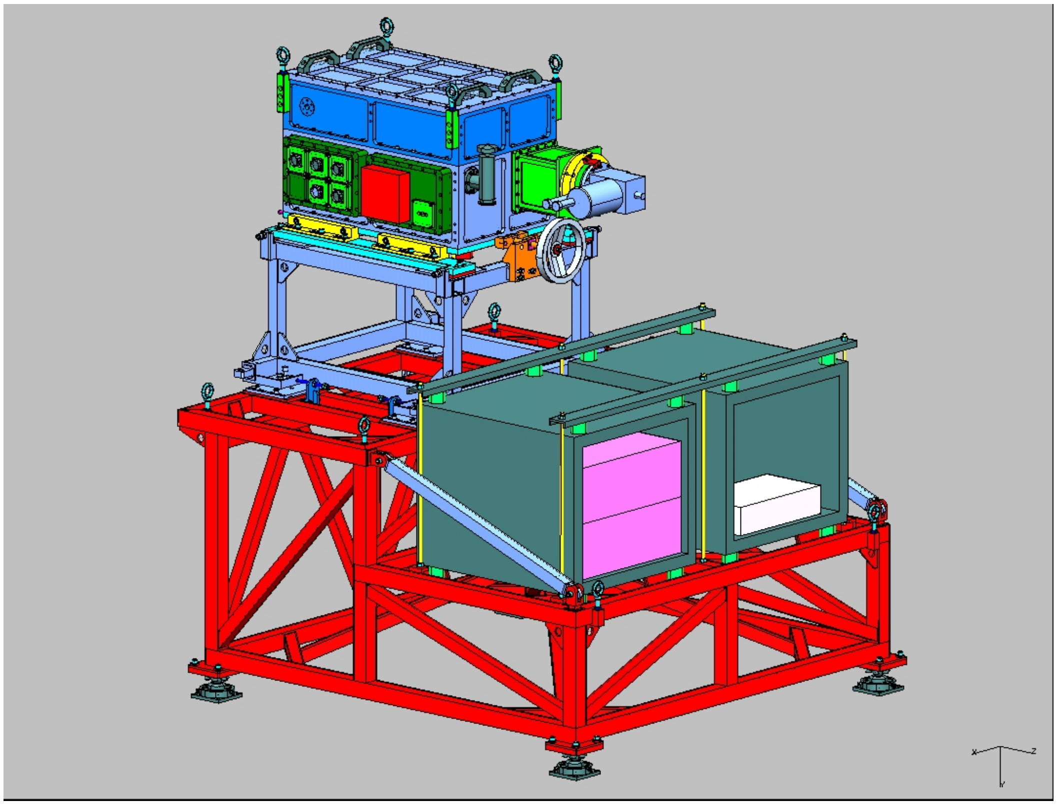


Figure 5: View of the HiCIAO cryostat on its adjustable support frame. Not shown here are the coronographic foreoptics mounted separately on the AO optical table. The camera support frame allows movement along the optical axis for installation and reproducible fine adjustment of the camera position and tilt.

### 3.1 HiCIAO Warm (external) fore-optics mounts

The warm fore-optics are designed as a separate unit that will be mounted onto a interface bracket that is directly bolted to the AO optical bench.  The HiCIAO infrared camera will sit on its own support system on the Nasmyth platform. The foreoptics interface is also designed to allow the use of the Subaru IRCS spectrograph at the AO focus, taking the place of the HiCIAO camera. For IRCS, a system of mirrors directs the AO system output past the coronographic foreoptics to a different focus location. The IRCS cryostat uses the same attachement points to the Nasmyth platform as HiCAIO. The changeover between these two instruments will take several hours and is a daytime task.

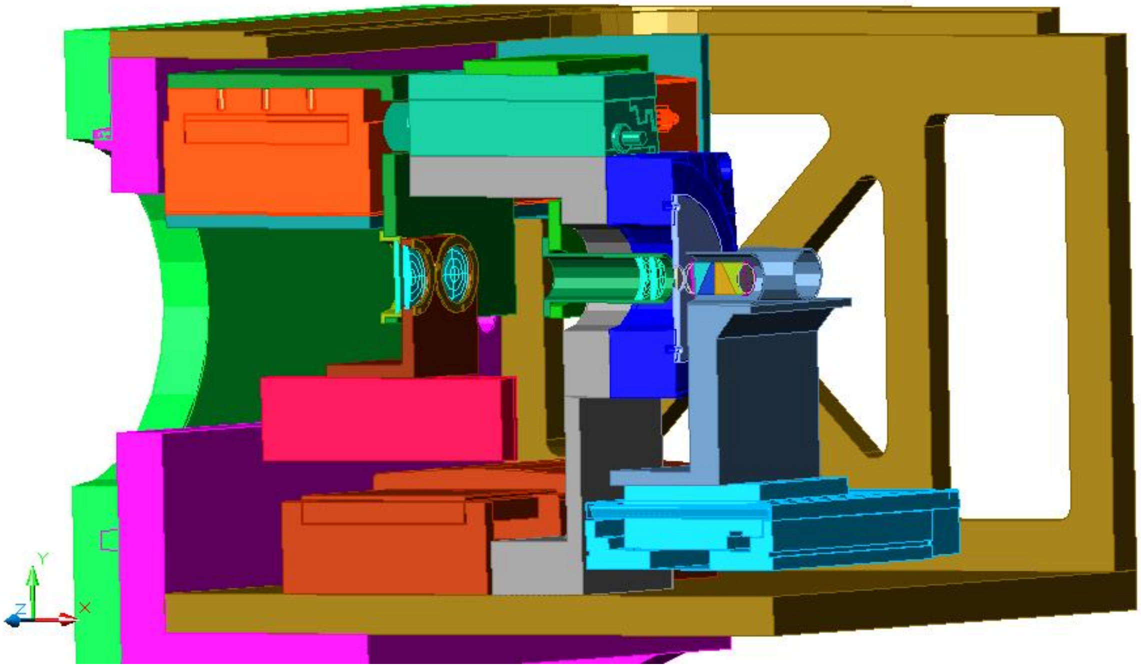


Figure 6: Cross-sectional cut through the foreoptics of HiCIAO, illustrating the position of the optical elements. From left to right (in direction of light), there are the field background reduction mirror and field mask, the field lens with the occulting spot, the collimator, the Lyot pupil stop, and the Wollaston prism.

The coronographic foreoptics are all mounted on Newport motion stages, first to align the components properly, and second to exchange components (field lenses, Wollaston prisms).

### 3.2 Cryostat

The Vacuum Jacket has two main frame components and top and bottom plates that are constructed from solid plates of aluminum 6061-T6. The Vacuum Jacket is designed to allow easy access to the internal components of the instrument. The internal surfaces of all sections of the Vacuum Jacket will be post-processed to a very shiny finish; the outside will be anodized. Handles and utility tapped holes are provided at various places for the handling of the instrument.

HiCIAO will be used at the Nasmyth Focus of the Subaru Telescope. This means that the Instrument will remain stationary in a horizontal plane and will only rotate about an axis perpendicular to this plane. This relaxes and simplifies the structural aspects of the design, in that no rotating gravity vector has to be considered.

The HiCIAO instrument contains three almost identical rotary mechanisms: The Common Path Filter Wheel, the Pupil Wheel and the Differential Path Filter Wheel. The basic design is that of a modified Geneva intermittent motion mechanism that includes a spring-operated detent mechanism. Our design has a Geneva wheel with 48 slots. The two-pin driver is located at the periphery of the Geneva wheel and advances the Geneva wheel by 2 slots for every 360° turn. The driver also is coupled to a cam, the function of which is to lift/lower the detent in/out of the detent groove in the Geneva wheel as it is being turned. The nominal filter positions are defined by the position of the detent arm and are accurate to approximately 50 arc-seconds. The mechanism is driven with a Phytron cryogenic stepper motor coupled to the driver with a flexible coupling. A move between adjacent filters will take 1-2 seconds.

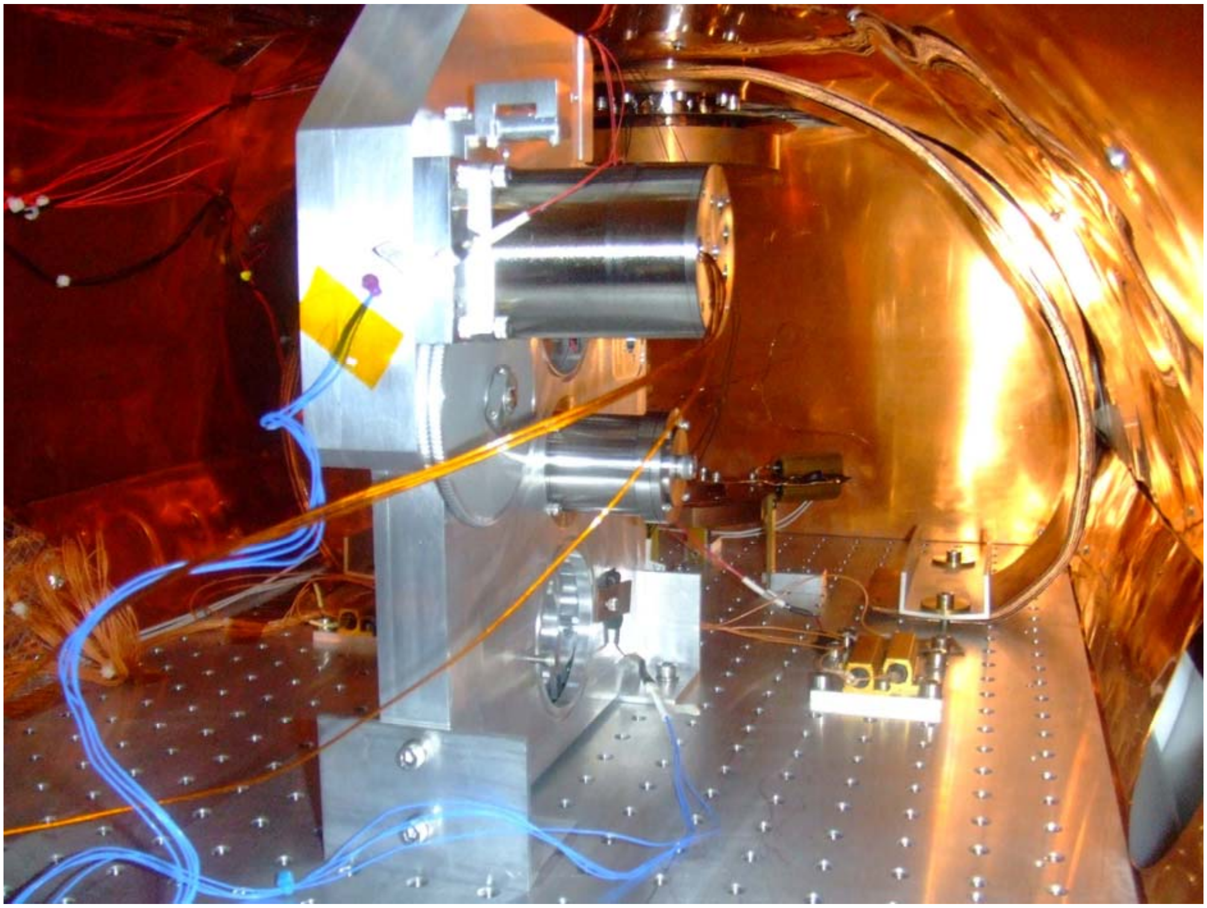


Figure 7: Common Path Filter Wheel assembly during cold testing

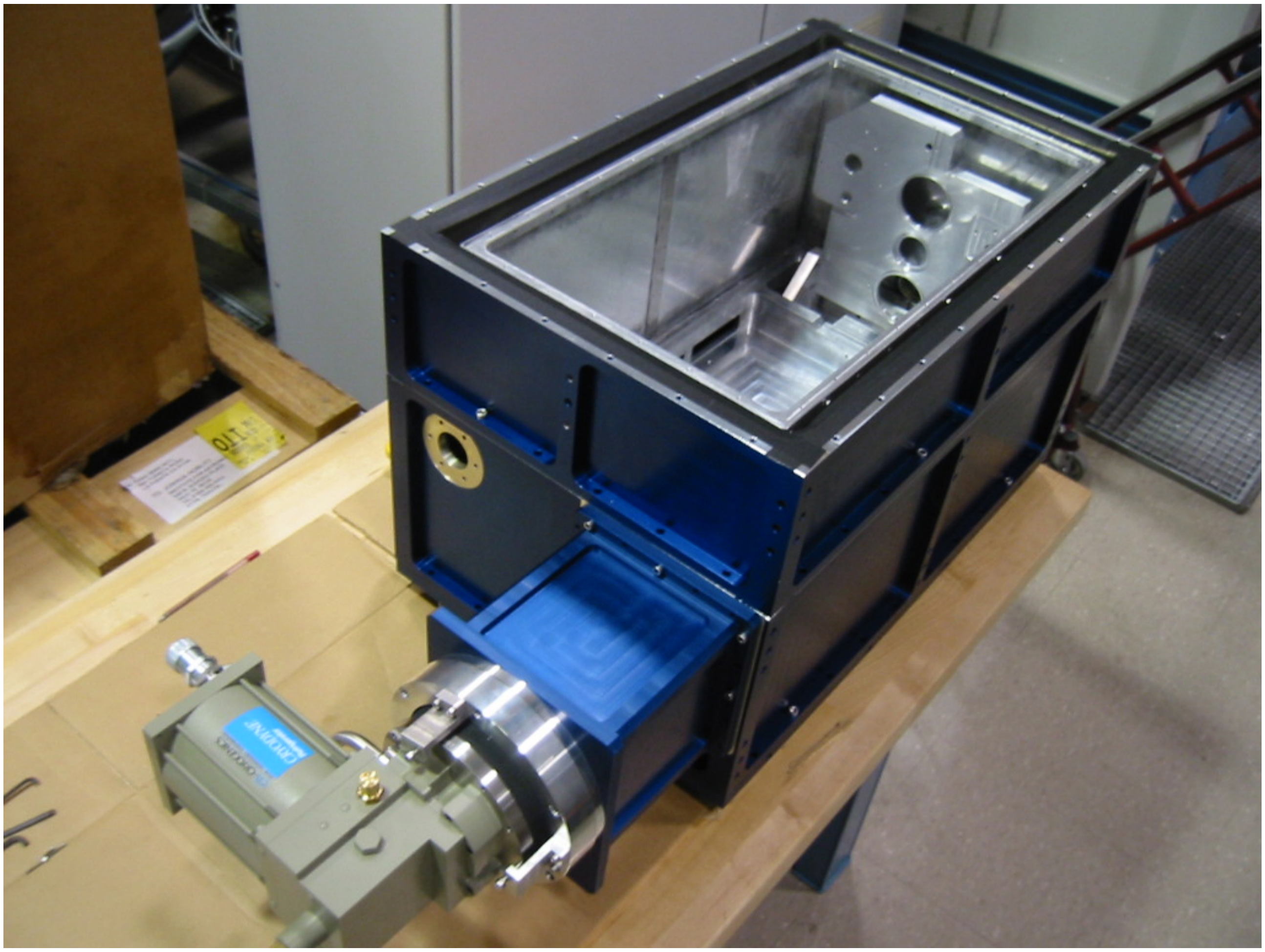
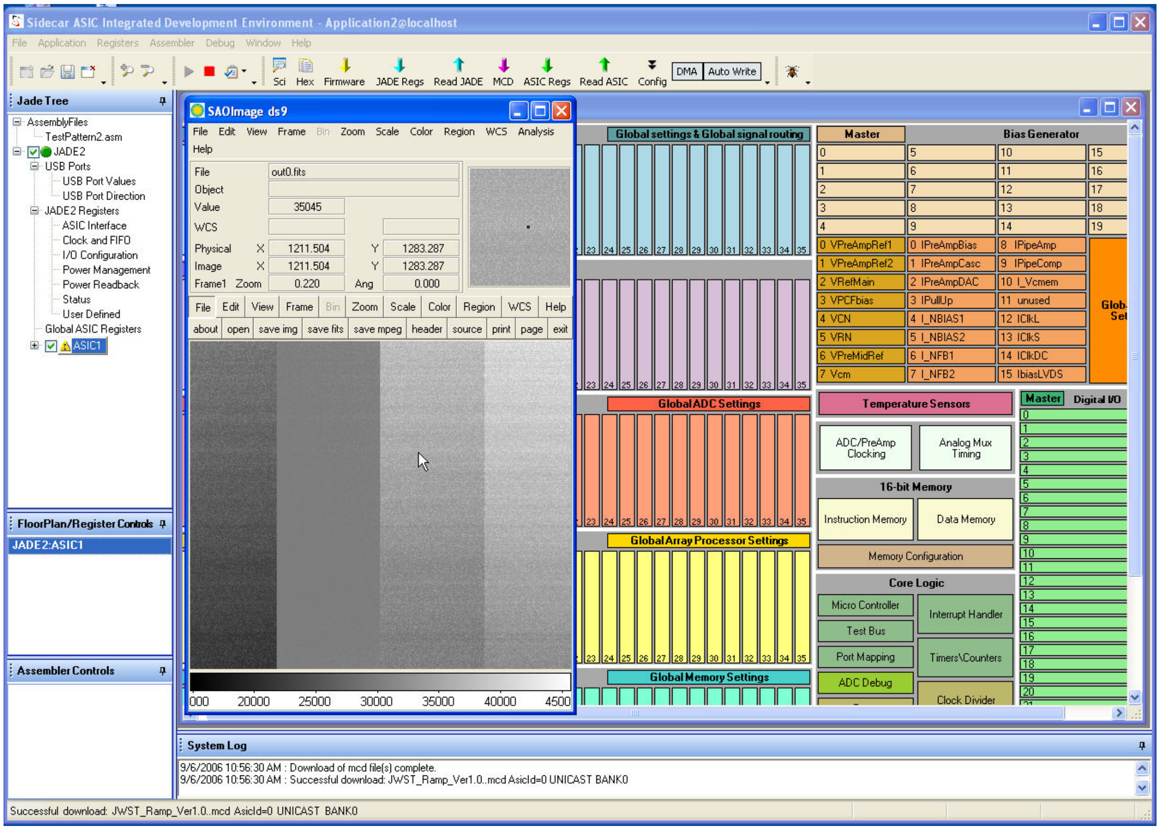


Figure 8: HiCIAO cryostat during first assembly test.

## 4. Detector Array

The detector array used in HiCIAO will be an engineering-grade HAWAII-2RG [6] sensor chip assembly that Subaru has already purchased. It will be controlled with the “Sidecar” ASIC [7] (Rockwell’s tradename for the ASIC). Reversible shift registers give flexibility in reading out various portions of the detector array.The ASIC will take the place of conventional controller electronics. The ASIC contains 36 16-bit ADCs, 36 12-bit ADCs, 36 1K word Dual Port Data Memory, 36 preamps, Bias Generators, Digital I/O, Clock Generators/Timers, 16K Program Memory, and of course, the 16-bit microcontroller [7]. In comparison with a conventional external detector array controller, the ASIC offers the advantage of a much smaller and more integrated detector control system. The ASIC offers 36 Analog-to-Digital converters with up to 400 kHz speed and therefore allows the implementation of fast, low-noise readout modes. All ASIC functions relevant for HiCIAO have been tested as part of the characterization effort for the JWST NIRCam instrument [6]. To speed up the development schedule, we have decided to initially operate the ASIC at ambient temperatures outside of the cryostat, and to use the available detector-to-ASIC cables used for the JWST detectors. This configuration will allow a relatively slow readout of the detector through 4 amplifiers. This readout mode is sufficient for the initial scientific use of HiCIAO. Later upgrades to a cryogenic ASIC, resulting in better stability, and to more output amplifiers, resulting in higher readout speed, will be possible. The interface between the ASIC and the data acquisition computer is provided by a JADE-2 card from Rockwell that delivers the data to a USB-2 port in a PC running under Windows.

Figure 9: Ambient temperature ASIC board and JADE-2 interface board.



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| 5 VRN | 5 I_NBIAS2 | 13 IClkS | |
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Figure 10: IDL engineering interface to Rockwell Sidecar ASIC, showing input noise from 4 different input channels.

## 5. Instrument Status

HiCIAO has passed the mid-fabrication milestone in mid-August 2006. The first cold test is expected in December 2006 and the first use at the Subaru telescope will be in March 2007.

## REFERENCES

1. Tamura, M. et al., 2006, "Concept and science of HiCIAO: high contrast instrument for next generation adaptive optics", Proceedings of SPIE, 6269, 123

2. Murakawa, K., Suto, H., Tamura, M., Kaifu, N., Takami, H., Takato, N., Oya, S., Hayano, Y., Gaessler, W., Kamata, Y., *"CIAO: Coronographic Imager with Adaptive Optics on the Subaru Telescope"*, PASJ 56, pp. 509-519, 2004

3. Takami, H., et al., "Status of Subaru laser guide star AO system", Proceedings of SPIE, 6272, 133

4. Lenzen, R., Close, Brandner, L. W., Biller, B., and Hartung, M., *"A novel simultaneous differential imager for the direct imaging of giant planets"*, Proc. SPIE, Vol. 5492, pp. 970-977, 2004

5. Oliva, E., Gennari, S., Vanzi, L., Caruso, A., and Ciofini, M., A&A Suppl. 123, 179, 1997

6. Garnett, J. D., Farris, M. C., Wong, S. S., Zandian, M., Hall, D. N. B., Jacobson, S., Luppino, G. , Parker, S., Dorn, D., Franka, S., Freymiller, E., and McMuldroch, S., *"2K X 2K molecular beam epitaxy HgCdTe detectors for the James Webb Space Telescope NIRCam instrument"*, Proc. SPIE 5499, pp. 35-46, 2004

7. Loose, M. et al. 2002, *"SIDECAR low-power control ASIC for focal plane arrays including A/D conversion and bias generation"*, Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, Proc. SPIE, Vol. 4841, pp. 782-794, 2002