

KALI Camera - Mid-infrared camera for the Keck Interferometer Nuller

Michelle J. Creech-Eakman^a, James Moore^a, Dean L. Palmer^a and Eugene Serabyn^a

^aJet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

ABSTRACT

We present a brief overview of the KALI Camera, the mid-infrared camera for the Keck Interferometer Nulling Project, built at the Jet Propulsion Laboratory. The instrument utilizes mainly transmissive optics in four identical beam paths to spatially and spectrally filter, polarize, spectrally disperse and image the incoming 7-14 micron light from the four outputs of the Keck Nulling Beam Combiner onto a custom Boeing/DRS High Flux 128X128 BIB array. The electronics use a combination of JPL and Wallace Instruments boards to interface the array readout with the existing real-time control system of the Keck Interferometer. The cryogenic dewar, built by IR Laboratories, uses liquid nitrogen and liquid helium to cool the optics and the array, and includes six externally motorized mechanisms for aperture and pinhole control, focus, and optical component selection. The instrument will be assembled and tested through the summer of 2002, and is planned to be deployed as part of the Keck Interferometer Nulling experiment in 2003.

Keywords: mid-infrared, cryogenic, instrumentation, nulling, interferometry

1. INTRODUCTION

One of the three key projects for the Keck Interferometer is the detection and quantification of dust, called exozodiacal dust, in nearby stellar systems, which serves as a tracer for the possible presence of planets. This will be accomplished through an interferometric technique called “nulling”.¹ It is advantageous to carry-out this search at mid-infrared wavelengths because the contrast between the stellar flux and dust emission is much smaller than at optical or near-infrared wavelengths, which makes detectability with shallower nulls possible. For the purposes of this effort, we have built a mid-infrared camera with low-resolution spectroscopic capabilities which will serve as the detector for the Keck Interferometer Nulling experiment.

The optical layout of the Keck Interferometer, up to and including the Nulling Beam Combiner, is briefly described in several different documents,^{1, 2, 3} Briefly, the starlight is collected by the two Keck telescopes and is corrected for atmospheric effects via adaptive optics (AO) systems at the back of each telescope. Each Keck aperture is then subdivided into two elliptical beams and sent to the long delay lines in the Keck basement via a modified version of the dual-star modules directly behind the AO benches. Star tracking and fringe tracking are accomplished in the near-infrared at 1.2 μm and 2.2 μm respectively, using the existing cameras (KAT (Keck Angle Tracker) and FATCAT (Fringe Tracking Camera)), and the fringe position information is fed-forward to the nulling experiment. Corrections to the fringe position are made via fast delay lines, atmospheric dispersion is compensated using Atmospheric Dispersion Compensators (ADCs)⁴ and then the four beams are combined for nulling. One subaperture beam from each Keck is combined with its paired beam on a modified Mach-Zehnder interferometric beam combiner. The outputs of each beam combiner consist of two “bright” and two “nulled” combinations. The “nulled” combinations are then further combined using a traditional Michelson combiner, and the four resultant nulled outputs are sent to the mid-infrared camera for detection and measurement. For full details please see Serabyn.¹

Once the four nulled beams are brought into the camera, all functions are performed in a cryogenic environment. These functions include aperture definition, spatial filtering, bandwidth and spectral dispersion

Further author information: (Send correspondence to M. J. C-E.)

M J C-E: E-mail: mce@huey.jpl.nasa.gov, Telephone: 1 818 354 2853

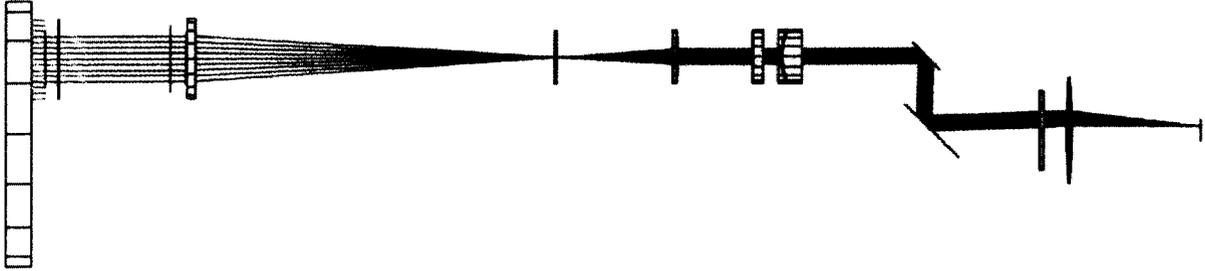


Figure 1. This is the Zemax optical design of the primary beam layout including (from left to right) the window, assorted beam defining stops, the aperture, focusing lens, pinhole plate, recollimating lens, a filter, direct view prism doublet, 45 degree mirror, face of the pyramidal mirror, final bandpass filter, final focusing lens, and focal plane array. See text for details.

selections, and polarization control. In order to reach the detection limit of an exozodiacal dust signature corresponding to ten times that of the zodiacal dust present in our solar system (i.e. 10 exozodis) around a nearby star (approximately 10 pc away) it is necessary to reach stable null depths of 1000:1 with the Keck Interferometer. The identification and quantification of exozodiacal dust signatures around nearby stars will be the first step toward continued nulling experiments on space-based interferometers, such as the Terrestrial Planet Finder Mission⁵. Below we describe the optical layout, array and electronics, dewar and control mechanisms for the Keck Interferometer Nulling Camera and, briefly, how it will be implemented in practice at the Keck Interferometer.

2. OPTICAL LAYOUT

The optical layout of the KALI (*Keck Aperture nuLLing Interferometer*) camera is designed to accomplish several functions simultaneously on the four incoming beams from the Keck Nulling Beam Combiner³ (Fig. 1). These functions are to define the aperture of the system at a cold Lyot stop, spatially filter the incident radiation, perform polarization and bandpass filtering, and to spectrally disperse the light (in a number of operational modes) for readout onto the array. The camera can also perform the added function of pupil reimaging of each of the four incoming beams so that adjustments can be made to the external mirrors or other optics for beam shear that might occur prior to the camera. The optics are discussed below in the order in which they occur in the system.

All functions are performed in a cryostat, consisting of a liquid-helium and liquid-nitrogen cooled dewar. The liquid helium is used principally to cool only the detector array, final lens and a bandpass filter. The remainder of the optics will be cooled by liquid Nitrogen. Selection of the optical mode, and control of the optics' positions, are accomplished via motorized stages and wheels, connected to six external motors operated outside the cryogenic environment, which will be discussed in more detail in Section 4.

2.1. Window and Feed Mirror

The four beams from the Nulling Beam Combiner are directed into the KALI camera via periscopes which translate the light onto a 191 mm diameter gold-coated pyrex mirror mounted at 45 degrees prior to the

entrance window. The beams are configured with their centers on the vertices of a ~~50.8 mm square~~ at the entrance to the KALI camera's window. The mirror was specified to have a ~~0.05 λ~~ surface at HeNe wavelengths before overcoating with bare gold and was manufactured by Harold Johnson Optical Laboratories (HJOL), CA. Zygo Interferometer tests supplied from HJOL confirm that these specifications were met. The entrance window, manufactured by International Scientific Products (ISP), CA, is a ~~127 mm diameter, 12 mm~~ thick ZnSe substrate with a 5 arc minute wedge, anti-reflection (AR) coated for the ~~8-13.5 μm~~ region. The surface quality of the window was specified to be ~~0.05 λ~~ at 10.6 μm . We tested the window with an optical Zygo Interferometer and found it to have surface effects less than 0.5 λ peak-to-valley (PV) at HeNe on each side in reflection.

2.2. Apertures

The four beams incident on the camera from the Nulling Beam Combiner are simply diffracted geometric images of the subapertures on the primaries of each Keck telescope approximately 24X12 mm elliptically in size. They are also not circular and their footprints rotate versus position on the sky. To optimize the beam aperture for given astronomical observations, weather conditions and instrumental configurations, a selection of cold aperture stops is provided immediately after the first light baffles. Five individual circular apertures (for each of the four beams) are selectable via a common filter wheel assembly and span the range of 35 to 25 mm in diameter (Fig. 2).

2.3. Powered Optics

The system's main powered optics are all transmissive to maintain simplicity in the design of four beams heading toward a common array. They consist of four focusing lenses, four recollimating lenses and a single common focusing lens prior to the array. All these lenses are manufactured by II-VI Inc., PA, out of Ge and AR coated to reduce transmission losses. The plano-convex focusing lenses are 38 mm in diameter, and focus the subaperture beams at F7 onto the spatial filters (Section 2.4). After spatial filtering, the beams are recollimated at F7 by 25 mm diameter plano-convex lenses. The initial focusing and recollimating lenses are all on focusing stages that will operate under cryogenic conditions to give ± 2.5 mm control of the optimal position for these lenses (Section 4.2). After a variety of bandpass filtering, polarization and dispersing functions are performed, the final beams are brought closer together via a reflecting pyramidal periscope assembly (Section 2.8) onto a common 50 mm diameter single, biconvex focusing lens. The incoming individual beams are directed nearly parallel to the optical axis of this lens with about a 2 mm beam-edge-to-edge separation, and focused onto the array at

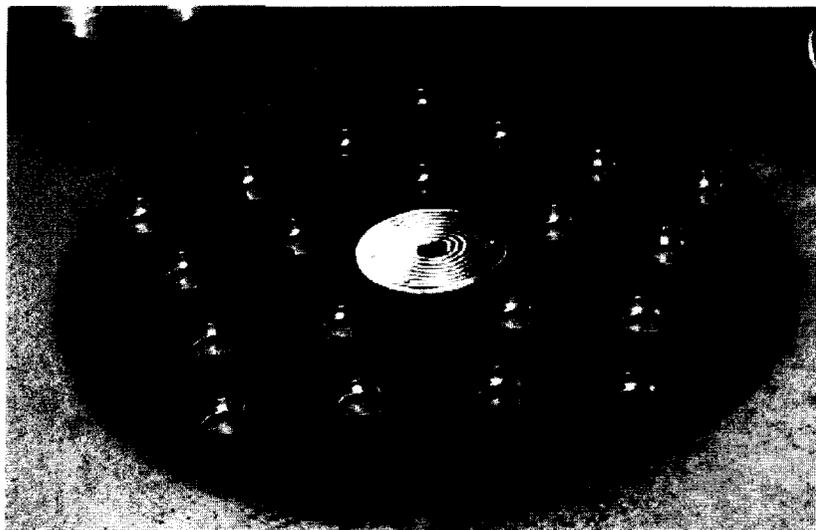


Figure 2. This is a picture of the aperture wheel, which will house five individual sets of four apertures between 35 and 25 mm in diameter to help define the beams coming from the Keck subapertures.

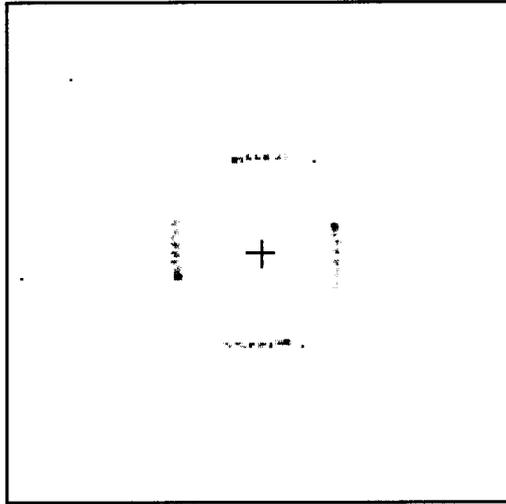


Figure 3. This Zemax layout depicts the low-dispersion rays on the array substrate for the four beams. The colors are indicative of 8-13.5 μm light dispersed over about 15 pixels, with beam lines across from each other separated by about 50 pixels.

roughly F6 for each individual beam to allow approximately 50 pixels between beam across from each other, with the entire spectrum from 8-13.5 μm dispersed across approximately 15 pixels in the low dispersion mode (Fig. 3)

All these lenses were manufactured to specifications of one fringe at HeNe and the nominal effective focal length (ranging from $55.9\text{-}372.4 \pm 0.2$ mm) to high accuracy from stock test-plates at II-VI. We have tested all the optics using an optical Zygo Interferometer in reflectance for wavefront quality and curvature and find that they have surface qualities measured at HeNe of $< 0.3 \lambda$ PV. Based on refractive index and thermal coefficient data obtained from Hawkins⁶, calculations were performed which show that the focal length will change less than 2.3% down to 80 K and less than 5.2% down to 4 K for the final lens, which is larger than the depth of focus for each of these optics, but within our focus stage correction capabilities. We anticipate that warm alignment using a mid-infrared source will render the system very close to the optimal focus for cryogenic operation, and only small adjustments will be necessary to bring the system back into focus. The focusing capability via stages will also be used if gross movements occur during cool down of the optical plates which shift the system radically, and for adjusting the focus when operating in reimaging mode (Section 2.9).

2.4. Spatial Filters

The spatial filters for this system are integral to cleaning up the beams in order to attain the required null depths of 1000:1 that are the requirement for Keck Interferometer Nulling Key project.¹ Unfortunately, single-mode mid-infrared fibers, with low losses that are operable under cryogenic conditions, do not exist. Therefore, in the KALI Camera simple spatial filtering is done via precision pinholes. The current design includes a pinhole plate which contains three pinhole sizes for each of the four beams, and an open, a block and a position for a reimaging lens. Because the pinhole selection and associated theoretical best null-depth is wavelength and waveband dependent, eight different plates with pinholes ranging from 25 to 250 μm in diameter will be available for actual operation, although only one will be installed in the camera at any given time. The plates are being micro-electron discharge machined (micro-EDMed) by Optimization's Burr-Free Microholes Division, UT. The substrate for the pinholes is stainless steel, as is the mounting plate that the pinholes are attached to. Each plate will be painted with Lord Corporation's Z306 Aeroglaze paint (Section 4.3) to minimize scattering of stray light.

2.5. Bandpass Filters

The mid-infrared bandpass filters for the KALI camera were all stock filters from Optical Coating Laboratories Inc. (OCLI), CA. We purchased six filter sets (six each), all 25 mm diameter on Ge substrates, spanning the atmospheric window of approximately 7-14 μm and ranging in bandwidth from 1 to about 7 μm (Table 1). Each filter bandpass was targeted to take advantage of the natural atmospheric windows in this region while avoiding by as much as possible certain telluric spectral features like CH_4 (7-7.5 μm) and O_3 (9.5-10 μm). The principle filter uses are: 1) to limit the radiation incident on the array, which is sensitive over a wide range of wavelengths (see Section 3.1); 2) to limit the bandwidths for narrow-band (a few micron) spectrally dispersed nulls; and 3) to utilize very narrow bandwidths (one micron or less) for pupil-reimaging modes or simple narrowband nulling-imaging modes. The filters were tested with an optical Zygo Interferometer and found to have surface wavefronts at HeNe ranging from 0.1 to 8.6 λ PV, and generally 0.7-1.0 λ root-mean-square (RMS), varying widely by bandpass. Also, each filter's transmission curve was verified at ambient temperatures using a Nexus 670 infrared FT-IR Spectrometer (FTS) over the 1-20 μm region. The transmission curves were found to be very uniform throughout the sets and to match the character and transmissivity of the cold transmission curves supplied by OCLI for the filters, except for the expected wavelength shift due to cooling. In principle, only 2 to 3 bandpasses will be available in the KALI camera at any given time.

Table 1. Tabulation of the filter bandpasses (half-power points indicated) currently available for the KALI camera. Note that a short-pass blocker is included for use with filters which leak beyond 14.5 μm , but likely won't be needed as the other optics in the system will serve the same purpose.

Filter	Type	HPP Cut-On (μm)	HPP Cut-Off (μm)	Bandpass (μm)	T (%)
L06882-8	Long	7.0	15.8	8.8	75
W10561-8	Wide	7.7	13.5	5.8	75
W08775-9	Narrow	9.1	9.8	0.7	80
W11779-9	Wide	9.5	14.3	4.8	80
W11102-9X	Wide	9.8	13.0	3.2	70
Astro. Sil.	Narrow	11.2	12.3	1.1	80
Blocker	Short	<1	14.5	+13.5	70

2.6. Polarizers

Our first choice mid-infrared polarizers are those manufactured by Leonard Research Corporation, OH. The polarizers are made through a proprietary process in which a uniform grid is etched into a photo-resistive layer on ZnSe and then coated with gold. The polarizers for use in the KALI camera will be AR coated on substrates approximately 2 mm thick, 25 mm in diameter with 10 arc second parallelism. However, due to manufacturing delays, we have not received these polarizers yet. The contrast ratio of these polarizers is expected to be \simeq 1000:1 range, which is sufficient for routine polarization diagnostics and control of the incoming Keck beams. While we have not yet tested any of these polarizers for wavefront quality or cryogenic survivability, there are reports of their use at Lawrence Livermore National Labs under cryogenic conditions.⁷ As part of the Keck Interferometer Project, these and two other commercially available polarizers have been tested at ambient temperatures in our labs at JPL, and a paper produced summarizing the results of these tests is published in these proceedings.⁸

2.7. Direct View Prisms

Spectral dispersion in the KALI camera will be accomplished using direct-view prism doublets. The prisms are made of ZnSe and ZnS, and two pairs with different dispersions will be available in practice. The resolving power of the lower-dispersion pair, manufactured by Janos, VT is approximately 30 at 10 μm . The higher-dispersion

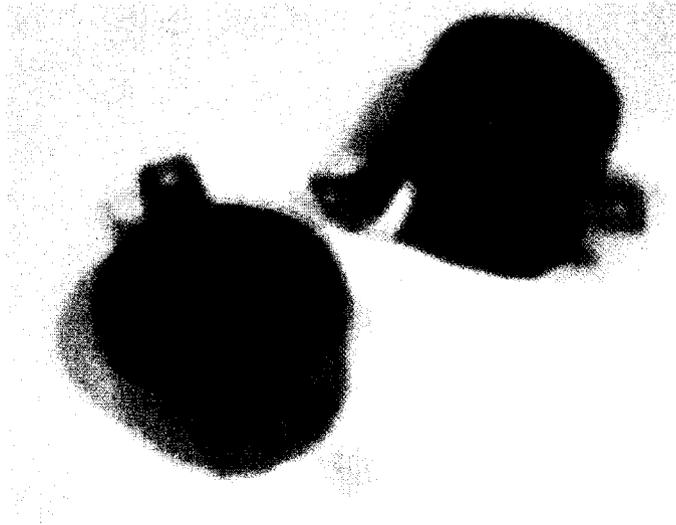


Figure 4. The figure depicts the layout of the polarization experiment for a pair of crossed polarizers. Details of the experimental setup can be found in the text.

pair, manufactured by ISP is 40 at $10\ \mu\text{m}$. The prisms will be mounted in specially designed titanium cells, with precision spacers to maintain the wedge spacings to 1 mm (absolute) at the optical axis. Finally, stainless steel clips will hold them in place but allow for clocking the prisms with respect to each other during alignment. Titanium was chosen because its coefficient of thermal (linear) expansion (α), and $\delta\alpha/\delta T$ (T = temperature) curve most closely matches that of ZnSe and ZnS over the expected temperature range of operations (ambient to 80 K)⁶⁹ (Fig. 4).

Specifications for the prisms were for a $0.5\ \lambda$ wavefront at HeNe wavelengths, with angles matching the specified values to within 1 arc minute and AR coated for the 8-13.5 μm region. The tight tolerance on the wedge angle arises from the need to maintain both dispersion and deviation on the array to within a few pixels of the nominal positions at which the beams are initially placed. All the individual low-dispersion prisms were tested with a Zygo Interferometer at JPL in reflection on each face and were found to have wavefront errors at HeNe $< 0.4\ \lambda$ PV. ISP supplied Zygo tests of all the high-dispersion prisms, and these were shown to have wavefront errors at HeNe $< 0.34\ \lambda$ PV. Assembly and alignment of the prism doublets is ongoing, and then tests for deviation, dispersion and transmissivity in the 7-14 μm range will be conducted on the prism pairs as units.

2.8. Periscope and Pyramid

The four light beams, as described above, are brought closer together for final focusing onto the array via a periscope and pyramid assembly. The periscope consists of four individual 25 mm diameter fused silica substrates, overcoated with bare gold. The surface wavefront was specified to be $0.05\ \lambda$ at HeNe before gold coating. The mirrors were purchased from HJOL. After Zygo Interferometer testing, we found that the wavefront at HeNe was $< 0.09\ \lambda$ PV for all mirrors, post coating. Each of the mirrors is mounted at an angle slightly less than 45 degrees to allow separation of the four focused spots onto the array. The pyramid, off of which the four light beams emerge nearly parallel to the optical axis, is a perfect right-angle pyramid with four faces. The base is 30 mm square and the optic is 15 mm tall, made of cryogenically destressed aluminum by II-VI Incorporated's diamond turning division.¹⁰ The surface was specified to 100 \AA roughness before an overcoating of bare gold was applied. The mounting bracket for the optic, a nearly separated pedestal in the monolithic substrate, was manufactured as part of the entire optic to avoid applying any stress to the faces of the optical surface when in use (Fig. 5). The four silica mirrors and aluminum pyramid are housed in an aluminum mounting bracket which can be separately assembled and aligned, and then placed within the dewar housing.

2.9. Pupil Reimaging Optics

The pupil reimaging system consists of two ZnSe lenses used in conjunction with the three Ge lenses that each beam already traverses. This combination of optics form an image roughly 15 pixels square on the array of each beam aperture. The lenses consist of a 13 mm diameter plano-convex lens located directly behind the pinhole plate assembly, and a 25 mm diameter plano-concave lens located in the last wheel assembly before the periscope and pyramid mirrors. These lenses were manufactured by Janos Technology, VT from existing test-plates. The plano-convex lenses were specified to have an effective focal length of 26.9 ± 0.2 mm, and the plano-concave lenses to have a radius of curvature of 1200 mm. Both sets of lenses are AR coated for the 8-13.5 μm region.

3. ARRAY AND ELECTRONICS

The detection of light levels from an exozodiacal source, above the considerable mid-infrared backgrounds, and in the presence of factors of one-thousand or more times that in stellar radiation, is the ultimate goal of the Keck Interferometer Nulling experiment. To accomplish this goal, it quickly became clear that the very best detector technology, capable of high-dynamic range, stable read-out at high frame rates (to allow for real-time operation on time scales coincident with normal interferometric operations) is absolutely necessary. In this sense, the focal plane array and associated electronics are the heart of the KALI camera. Much work has gone into identifying, procuring, and optimizing an optimal system for the KALI camera, which we describe below.

3.1. Focal Plane Array

The infrared focal plane array for the KALI camera was purchased from Boeing's array division, now part of DRS Technologies, CA (Fig. 6). While larger format Blocked Impurity Band (BIB) arrays are available, the anticipated high backgrounds at mid-infrared wavelengths, due to the large number of optics upstream of the Nulling experiment, necessitate the ability to read out whatever array is used very quickly, in real-time operations. The DRS High-Flux 128X128 array is capable of operating at 4.1 kHz full-frame rates (4.2 MHz pixel rates). It is an Si:As BIB High-Flux detector on a 128X128 multiplexer with 16 outputs.¹¹ The particular array to be used in the KALI camera was manufactured in a special run in order that we could take advantage of recently available, cleaner doped materials and to apply a single-layer ZnS AR coating to provide a peak

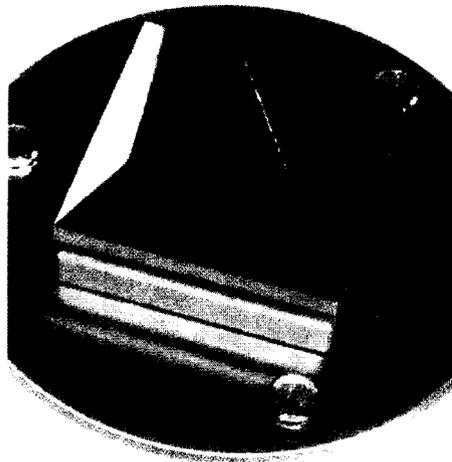


Figure 5. This is a picture of the gold coated pyramid that will bring the four beams together onto the final focusing lens. Note how the back of the monolithic piece of aluminum is a nearly separated pedestal, to avoid stressing the optical face.

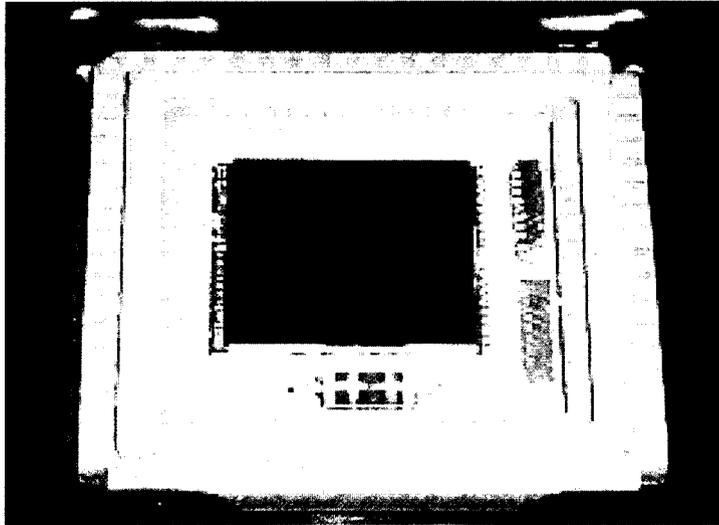


Figure 6. This is a picture of the Si:As focal plane array to be used in the KALI camera. The physical scale of the substrate is about 1 cm square.

quantum efficiency near $12\ \mu\text{m}$ of 80%. The pixel pitch for this array is $75\ \mu\text{m}$ and the measured responsivity is principally from $5\text{-}28\ \mu\text{m}$. These arrays work best in the 6-12 K range. We are currently testing process evaluation chips of Si:As single element detectors to determine in practice at what temperature to operate the KALI camera array for maximum sensitivity. The read-noise for our array (as tested by Boeing once they have corrected for the read-noise of their system) is 640 electrons RMS per read, tested at 10 K, 1.5 V bias and a 4.1 kHz frame rate. The well-depth of the array is approximately 2.1×10^7 electrons with dark currents ranging from $3 \times 10^1\text{-}1 \times 10^9$ electrons per second. The array response is linear from 5%-90% full well capacity.

While we currently do not anticipate needing to read out and process data from full frames near 4.1 kHz (full frame), readout rates near 1 kHz are anticipated. As part of the “array package”, an engineering grade focal plane array and a bare multiplexer, sensitive to HeNe light, were also purchased so that both ambient and cryogenic tests could be run on the system without risking the integrity of the science grade focal plane array. These tests are anticipated to begin shortly.

3.2. Electronics

The electronics for the KALI camera are being built as a cooperative effort between Wallace Instruments, WI and the Jet Propulsion Laboratory (Fig. 7). The electronics built by Wallace Instruments will be used to drive, clock, amplify and read-out and digitize the analog signals from the array. The JPL electronics will interface the real-time signals from the interferometer software for array operations, and return digitized camera “pictures” to the same system for integration into the real-time control of the Nuller and Interferometer. Wallace Instruments uses 14 bit analog-to-digital (A/D) converters capable of operating at the full-frame rate of the array with ultra-low noise (below the read-noise of the array). Currently, three clocks will be used to operate the array; however, the Wallace Instruments boards are capable of operating arrays needing as many as five clocks. Two bias boards and four four-channel preamps are also part of Wallace’s supplied package.

The JPL electronics are very similar in function to those electronics already being used for the Keck Interferometer for the KAT and FATCAT cameras¹² so that interfacing with the real-time operations system of the interferometer are simplified via the reuse of existing software and hardware components. Two significant changes required for the operation of the KALI camera are the use of four camera boards to read out the array, instead of only one which is used for the KAT and FATCAT cameras (using Hawaii arrays), due to the number of outputs (16) and the inability to “window” the BIB arrays. Also, to preserve the capability to read

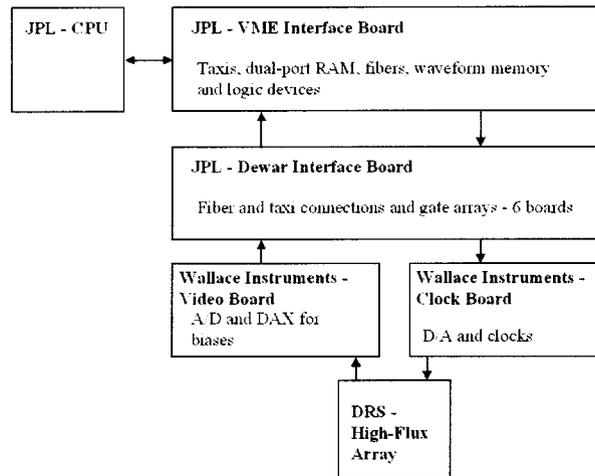


Figure 7. This block diagram depicts the interfacing between the JPL and Wallace Instrument electronics. See the text for details.

the BIB array close to its full-frame rate, the taxis on the JPL boards had to be upgraded. Specifically, the JPL electronics for the KALI camera consist of six camera interface boards (VME based) connected by fiber to six infrared focal-plane array (IRFPA) interface boards local to the camera: one VME board outputs the clocking patterns (from its local SRAM) to its associated IRFPA board; four VME boards receive pixel data from their associated IRFPA boards; and the last VME board handles low-speed utility functions. The pixel data is captured into dual-port memory arranged as a double buffer so that one frame can be read while another is being received. It is anticipated the combination of Wallace Instruments and JPL boards will allow operation on the limited number of pixels (a few hundred) at up to 2 kHz frame rates.

4. DEWAR

The cryostat for the KALI camera is being designed and built at Infrared Laboratories, AZ (Fig. 8). This dewar will utilize liquid cryogenics for cooling the array and optics, and will have six external motors for control of wheels, focus stages and a pinhole slide. It utilizes a design to suppress vibrations from sources external to the dewar, which was verified through solid body modeling at JPL. Stray-light suppression will be accomplished via an intricate series of baffles (Fig. 9), and the use of infrared black paint capable of operating under vacuum and cryogenic conditions. Several housekeeping functions, including temperature and vacuum sensors, and sensors indicating the positions of various moving mechanisms are also included in the design. The dewar itself is large (about 1.25 meters tall, weighing approximately 100 kg) by standards of the Keck Interferometer cameras, and as such will be mounted on the basement floor of the beam combining room in order to facilitate cryogenic fills (Fig. 10). We anticipate delivery of the dewar in the very near future, at which time assembly of all the optics inside the cryostat will occur.

4.1. Cryogenics

Due to the calculated heat loads primarily from the array, wiring and window, and the requirement of at least 36 hour hold time at the summit of Mauna Kea, the KALI camera's dewar is designed for 16 liters of liquid Nitrogen and 19 liters of liquid Helium (Fig. 11). IR Laboratories, based on their mass estimates for the opto-mechanical components attached to each cold plate, have calculated that it will take 78 liters of liquid Nitrogen and 71 liters of liquid Helium over a 24-36 hour period to precool and fill the vessels for the initial cool down. Based on these values, a week-long run with the KALI camera will utilize nearly 200 liters of liquid Helium and 160 liters of liquid Nitrogen. The current plans include autofilling of the liquid-nitrogen vessel once

the dewar is initially cooled, however due to prohibitive cost and safety issues, the liquid Helium will always be filled manually.

4.2. Mechanics

There are six actuated systems in the KALI camera - three optical “filter” wheels, two focus stages and the pinhole plate. The wheels contain apertures, filters, direct view prisms, polarizers and reimaging lenses. As such, the repeatability of their placement is not crucial to system performance and placement to 9 arc minutes is adequate for operation of the system. The two focus stages hold common mounts which house the focusing and re-collimating Ge lenses. As the depth of focus is about 0.50 mm for these optics, and the focal lengths are only expected to be good to a similar level, the focusing stages require 5 mm of travel with a resolution of 100 μm per step. Finally, the pinhole slide, mounted on a crossed-roller bearing stage, is by far the most precisely positioned opto-mechanical component in the KALI camera. The requirement here stems from the need



Figure 8. This is a side-view of the autocad drawing of the dewar layout, with some parts labeled.



Figure 9. This is a picture of the main optical plate on which the focusing and reimaging lenses and the pinhole plate assembly will be registered. Note the intricate series of baffles for stray light suppression.



Figure 10. This is a picture of the outer vacuum shield and inner cryostats for the KALI camera's dewar. Note the human in frame for scale.

to reliably change from one pinhole to another on the pinhole slide, without returning to the home position or re-peaking on the beam in reimaging mode for each iteration. As such, the pinhole slide has a full 50 mm of travel with 25 μm repeatability and 10 μm resolution per motor step.

All the motorized stages are connected to motors external to the dewar via feed-thru mechanisms. The motors, produce by Cymatix Inc., CA, can operate up to 3000 rpm, with no backlash. The include 2×10^5 encoder positions (before gear reduction) and home switches, with a 10:1 gear reduction endemic to the motor itself. Further gear reduction, in particular for the pinhole slide, is necessary to reach the required levels of precision for the opto-mechanical positioning in the system.

4.3. Stray Light Suppression

The two main methods by which stray light is suppressed in the KALI camera are through careful baffling of the four light beams to minimize external sources of radiation leaking into the beam trains, and the utilization of infrared black paint on those surfaces “seen” by the beam train to minimize scattered light. A common baffle for all four beams exists beginning behind the entrance window and continuing up to the aperture wheel (Fig. 2 & 8). After the aperture wheel, each of the four beams is baffled individually via interlocking baffle tubes which have been tapped on the inside to avoid smooth, reflective surfaces. The individual baffles are maintained until the second optical wheel, at which point the four beams are baffled as a group until they reach the gold mirrors and pyramid assembly. It was calculated that separated baffles are necessary to avoid crosstalk between the beam trains, particularly in the vicinity of the pinholes. Once the beams are brought together on the pyramid, the baffling treats them as one large beam and continues to the entrance of the liquid-helium chamber (Fig. 11), housing the final optics and array.

After an extensive literature search and investigating suppliers in the US commercial market, it was determined that the best available paint for our application is Z306 Aeroglaze, now made by the Lord Corporation, Chemical Products Division, PA. We had considered other paint and anodizing processes, chiefly discussed in Ungar et al.¹³ and St. Clair Dinger,¹⁴ which had been studied for use with the Infrared Space Observatory and the Space Infrared Telescope Facility, however many of these paints and processes are no longer available in the commercial market. Z306 Aeroglaze has been recently studied by McCroskey et al.¹⁵ for use with the Space Based Infrared System program, specifically in regards to its outgassing properties. The Lord Corporation, however, has an internal memo from 1997 regarding specular and diffuse infrared reflectance tests of this paint performed at Optical Data Associates, AZ for use with the GOES satellites.¹⁶ These tests compare Z306 Aeroglaze with five other black anodizing and painting processes and show that Z306 Aeroglaze paint has specular infrared reflectance below 0.5% in the 2-15 μm region, and diffuse reflectance between 0 and 7% over the same waveband. For comparison, two different Speedring Corp. black anodize treatments, and “Anoblack” EC from Anoplate Corp. show specular reflectance between 1-16% over the same waveband, and diffuse reflectance between 10 and 70% from 2-10 μm and between 2 and 20% from 10-15 μm . The Z306 Aeroglaze has been shown to have low outgassing properties once the water has been baked or pumped out of it, and to withstand cryogenic environments without flaking.¹⁵ We will be using Aeroglaze 9947 chromate free primer with the painting process, which was not tested as part of this memo, and hence while we are expecting to have

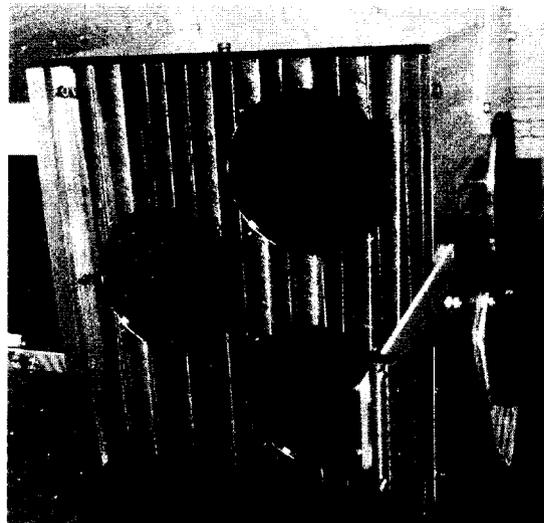


Figure 11. This is a picture of the liquid-helium cold plate and optical box that will house the final focusing lens, bandpass filter, and the array. The three openings toward the front of the photograph are for the feedthrus for the wiring harnesses that attach to the array.

similar performance, are not yet aware if there will be any implications due to our choice of primers. The paint and primer will be applied primarily to the inside of baffles, to mounts around optics and on the pinhole plate, where radiation may reflect directly into the beam path. Except for the pinhole plate, this paint will be applied through an air-brushing technique at JPL.

5. UPGRADE PATHS

Anticipating that technological advances will ultimately make it possible to improve the performance of the Keck Interferometer Nulling experiment, we have tried to design a system that can be readily retrofitted for these advances. The simplest upgrades, using existing optical solutions, would generally require different custom optics that are not part of the first-order instrument, including: 1) replacing the plano-convex Ge lenses with meniscus lenses, which should in principle produce much less aberrated focal-plane spots; 2) purchasing filter bandpasses specifically designed around the spectral signatures of the exozodiacal dust and telluric features; and 3) purchasing much higher-dispersion direct view prism doublets that would take advantage of these same exozodiacal and telluric features.

Future upgrades that depend entirely on technological advances not yet in-hand include new detectors and mid-infrared fibers. We have tried to anticipate, through extrapolation from what is currently available, the formats and electronics most likely to be utilized with the newer focal plane arrays, including high-speed taxis, more output lines and more clocking lines. These upgrade paths are all included in the current version of the electronics, focal plane mount, and cabling requirements. Mid-infrared fibers capable of operating under cryogenic conditions are somewhat harder to predict. However, extrapolating requirements such as length of fiber for multi-mode suppression, and likely numerical apertures, we have included adequate space in the cryostat to mount such fibers, if they should become available during the lifetime of the experiment.

ACKNOWLEDGMENTS

MJCE wishes to thank Jason Geis for all his work characterizing optics for the KALI camera. Also, we thank Robert Ligon and Steve Macenka for substantive discussions about the optical design. We would also like to particularly thank Mark Colavita for innumerable discussions with regard to hardware design, electronics and implementation of the system. Funding was provided by NASA through the Origins Program to the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

1. E. Serabyn, "Nulling Interferometry," *Proc. of SPIE: Interferometry for Optical Astronomy II* **4838**, 2002.
2. M.M. Colavita & P. Wizinowich, "Keck Interferometer Update," *Proc. of SPIE: Interferometry for Optical Astronomy II* **4838**, 2002.
3. C.D. Koresko et al., "Table-top mid-infrared nulling testbed for the Keck Interferometer and Terrestrial Planet Finder," *Proc. of SPIE: Interferometry for Optical Astronomy II* **4838**, 2002.
4. C.D. Koresko et al., "Longitudinal dispersion control for the Keck Interferometer nuller," *Proc. of SPIE: Interferometry for Optical Astronomy II* **4838**, 2002.
5. C. Beichman, "Terrestrial Planet Finder: The search for life-bearing planets around other stars," *Proc. of SPIE: Astronomical Interferometry* **3350**, 1998.
6. G.J. Hawkins, "Spectral Characterisation of Infrared Optical Materials and Filters," PhD Thesis, Univ. of Reading, UK, Dept. of Cybernetics, 1998.
7. "Leonard Research CRADA," <http://www.nawcupns.navy.mil/techtransfer/cradas/leonard.htm>, Rocketeer, China Lake Site, 1997.
8. M.J. Creech-Eakman et al., "Comparison of commercially available polarizing gratings for mid-infrared studies," *Proc. of SPIE: Polarimetry in Astronomy* **4843**, 2002.
9. "Thermal Contraction Data for Assorted Metals, Glasses and Plastics," p 318, Appendix, Table F.

10. "Aluminum prestressing script," Engineering Specification No. AOCC (Applied Optics Center Corporation)-0600S, as reprinted in M.J. Creech-Eakman, "Silicate Feature Variation in Long Period Variable Stars," PhD Thesis, Univ. of Denver, Dept. of Physics and Astronomy, 1997.
11. T. Herter et al., "Improved Si:As BIBIB (Back-Illuminated Blocked-Impurity-Band) hybrid arrays," *NASA, ARC, Proc. of the Third Infrared Detector Technology Workshop* 427-438, 1989.
12. G. Vasisht et al., "Performance and verification of the Keck Interferometer fringe detection and tracking system: FATCAT," *Proc. of SPIE: Interferometry for Optical Astronomy II* **4838**, 2002.
13. S. Ungar et al., "Infrared black paints for room and cryogenic temperatures," *Proc. of SPIE: Infrared Technology XV* **1157**, 369, 1989.
14. A. St. Clair Dinger, "The selection of infrared black(s) for SIRTf: A surface-by-surface performance comparison," *Proc. of SPIE: Stray Radiation in Optical Systems III* **2260**, 110, 1994.
15. D.M. McCroskey, G.C. Abell & M.H. Chidester, "A study of Aeroglaze Z306 Black Paint for Cryogenic Telescope Use - Outgassing and Water Vapor Regain," *Proc. of SPIE: Optical Systems Contamination and Degradation II* **4096**, 119, 2000.
16. D.R. Wickholm, "Technical Memo: Summary of ODA Paint Analysis for GOES NOPQ Secondary Mirror Baffle," Lord Corporation Chemical Division, to Scott Davis, March 7, 1997.