The Infrared Camera and Spectrograph for the Subaru Telescope

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ABSTRACT

A 1–5 μm Infrared Camera and Spectrograph (IRCS) is described. The IRCS will be a facility instrument for the 8.2 m Subaru Telescope at Mauna Kea. It consists of two sections, a spectrograph and a camera section. The spectrograph is a cross-dispersed echelle that will provide a resolving power ($\lambda/\Delta\lambda$) of 20,000 with a slit width of 0.15 arcsec and two-pixel sampling. The camera section serves as a slit viewer and as a camera with two pixel scales, 0.022 arcsec/pixel and 0.060 arcsec/pixel. Grisms providing 400–1400 resolving power will be available. Each section will utilize an ALADDIN II 1024×1024 InSb array. The instrument specifications are optimized for 2.2 μm using the adaptive optics and the tip-tilt secondary systems of the Subaru Telescope.

Keywords: infrared, camera, spectrograph, Subaru Telescope

1. INTRODUCTION

The development of large aperture telescopes such as the Subaru Telescope[1] as well as the development of large-format infrared arrays such as the 1024×1024 pixel ALADDIN II[2] and HAWAII[3] arrays provides an unprecedented opportunity to achieve significantly greater sensitivity from the ground than is currently possible. This paper describes the Infrared Camera and Spectrograph (IRCS), a facility instrument for the Subaru Telescope, which is presently under construction at the Institute for Astronomy. The emphasis of this paper is on the optical and mechanical designs, as space does not allow for a complete description of the instrument. Various components of the IRCS are described elsewhere in these proceedings.

2. INSTRUMENT DESIGN DRIVERS

The specification and design of the IRCS are aimed at providing general purpose 1–5 μm infrared imaging and spectroscopy using the Adaptive Optics (AO) system[4] and the tip-tilt (TT) system on the Subaru Telescope. In developing the final specifications for the IRCS, we have kept in mind the following objectives:

- The instrument will use the 1024×1024 pixel ALADDIN II InSb array to obtain observations at 1–5.6 μm.
- Optimization at 2.2 μm is a priority because we expect to see deepest into space at this wavelength (highest sensitivity compared to longer wavelengths and lowest extinction compared to shorter wavelengths). We optimized one of our camera pixel scales for the AO system (0.022″/pixel) and a second camera pixel scale for the TT system (0.060″/pixel).

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- The spectrograph section will provide 20,000 resolving power with the largest possible spectral range and will be designed for use with the AO system.

The pixel scales of the IRCS will complement other Subaru instruments, the Coronagraphic Imager with Adaptive Optics (CIAO), which has pixel scales of 0.012 and 0.024″/pixel, and the Cooled Infrared Spectrograph and Camera for OHS (CISCO), which has a pixel scale of 0.2″/pixel.[5]

2.1. Rationale for Combining Imaging and Spectroscopy

In the original concept, the IRCS consisted of a spectrograph section with moderate resolution and a simple slit viewer. However it was recognized that high spectral resolution spectroscopy would be very desirable and that low-to-moderate resolving power could be achieved with grisms. The design was therefore modified to include both a high-resolution spectrograph with a camera section with two pixel scales and grisms. The camera section functions as a slit viewer when needed. A significant advantage of this concept is the ability to switch between the spectroscopic and imaging modes very quickly. This will allow observing flexibility to take full advantage of the weather, seeing conditions, or time-critical events. In addition, both low and high spectral resolution observations can be made over the entire 1–5.6 μm spectral range. This provides an exceedingly powerful observing capability.

2.2. Choice of Pixel Scales

Detailed image-quality simulations were made to verify that the pixel scales chosen were reasonable. The AO group at the National Astronomical Observatory of Japan simulated the image quality we can expect to have as a function of the brightness of the guide star. The simulation assumed an AO system using the curvature sensing technique,[4] 36 deformable mirror elements, a system capable of 200 corrections/sec, an atmosphere with a single turbulent layer and a Kolmogorov power spectrum, an operating wavelength range of 0.6-0.8 μm, 20% throughput, and the use of avalanche photodiodes for the wave-front sensor.

2.2.1. Spectrograph section

In evaluating the suitability of the pixel scales and slit widths, we were primarily concerned with the energy through the slit and the predicted image profile. For the AO case, we concluded that to get at least 50% of the light through the slit at 1.25–3.5 μm under conditions of good seeing and a bright reference star, we need a slit that is at least 0.1″, thus leading to a pixel scale of 0.05″/pixel for Nyquist sampling. For the TT case, a slit width of 0.3″ gives us at least 50% of the light under conditions of normal seeing at 1.25–3.5 μm, thus leading to a pixel scale of 0.15″/pixel for Nyquist sampling. As a compromise between these two cases, a pixel scale of 0.075″/pixel was chosen. Both the energy through the slit and the image profile are functions of the wavelength, and therefore the tradeoff between the slit width and energy through the slit is a complicated one. A slit width of 0.075″/pixel should be satisfactory in most cases.

2.2.2. Camera section

The camera serves four functions:

1. Infrared imaging mode

   Proper sampling of point sources at 2.2 μm is required for imaging. Since the diffraction-limited size of the core at K is 0.069″ (1.22 λ/D), we choose a pixel scale of 0.069″/3 $\simeq$ 0.022″/pixel. The larger pixel scale, 0.060″/pixel, gives us 2.5 pixels across the diffraction-limited core at 4.8 μm as well as a reasonably large field of view (61″).

2. Slit viewing mode

   For good sampling of the slit image and positioning of objects on the slit, we estimate that the sampling should be $\geq$4 pixels across the slit. In the case of the 0.15″ slit (AO with good seeing), this leads to 0.019″/pixel. In the case of the 0.3″ slit (TT with normal seeing), this leads to 0.0375″/pixel. We will use the 0.022″/pixel scale for slit viewing as a compromise. For larger slits, we will use the 0.060″/pixel scale.

3. TT sensor mode

   In some cases, such as observing in dark clouds, it will be necessary to use the infrared camera as a TT sensor because no stars will be detectable at 0.8 μm. There are two basic methods for TT operation: peak detection (shift-and-add) and center-of-light detection (centroiding). In the case of peak detection, we would expect to use the small pixel scale (0.022″/pixel) and to work with bright stars. In the case of center-of-light detection, we expect to use the large pixel scale (0.060″/pixel) and to work with faint guide stars.

4. Grism spectroscopy mode

   The larger pixel scale, 0.060″/pixel, can be used for the grism spectroscopy modes with the slit widths from 0.15″ (2.5 pixels across the slit) to 0.9″ (15 pixels across the slit). The widest slit is used to take data in the cases where the object is extended or limited by seeing (no AO and TT) and for observations at wavelengths longer than 2.5 μm. In cases where high spatial resolution in the slit direction is needed, the smaller pixel scale, 0.022″/pixel, is used with slit widths from 0.1″ (~4 pixels across the slit) to 0.15″ (~7 pixels across the slit).

2.3. Use of ALADDIN II Arrays

The IRCS will employ two ALADDIN II arrays, one for the spectrograph section and one for the camera section. This allows for real-time guiding of objects in the slit-viewing mode and complete separation of the spectrograph and camera sections. The ALADDIN II array was chosen because of its large format and because the InSb material allows full coverage of the 1–5.6 μm spectral range. The L-band spectral region (2.8–4.1 μm) is one of the most important spectral regions for the Subaru Telescope, and therefore the use of an InSb detector is necessary. Its relatively high quantum efficiency and low dark current make it suitable for both the spectrograph and camera sections.

3. OPTICAL DESIGN

The IRCS consists of 3 sections: the fore-optics, the spectrograph, and the camera. The IRCS will be located at the Cassegrain focus, and it will use the infrared secondary, which has a focal ratio of 12.37. Since the infrared secondary is undersized, the effective aperture of the Subaru Telescope is 8.08 m with this secondary.

3.1. Fore-optics

A layout of the fore-optics is shown in Fig. 1.

3.1.1. Beamsplitter

The beamsplitter reflects light shortward of 1 μm to the Wave-Front Sensor for the AO system, while transmitting the infrared to the IRCS. CaF_2 was chosen as the substrate for the beamsplitter, since this material has the best combination of required low dispersion at 1–5 μm, is sufficiently stiff, can be polished to the required smoothness, is suitable for coating, and is available in the required size and thickness for a reasonable cost. A compensator will be used to minimize the astigmatism caused by the beamsplitter. It is a flat identical to the beamsplitter, but rotated along the optical axis by 90°.

3.1.2. Offner relay

The Offner relay is a 1:1 relay, and it consists of two mirrors with spherical surfaces. It serves two purposes: (1) It creates a cold pupil stop at which we can baffle against stray thermal light. This will significantly improve the sensitivity of the spectrograph at 3–5 μm. (2) It moves the telescope focal plane to a more convenient position. The Offner relay has a focal length of 650 mm, and it will be fabricated out of aluminum by Applied Physics Specialties (Don Mills, Ontario, Canada).

3.2. Spectrograph Optics

Having decided that all of the low- and moderate-resolution spectroscopy could be done with grisms in the camera section, we set as a goal the design of a high-resolution spectrograph with a resolving power of at least 20,000. In our initial attempt, we tried to find a solution that would allow us to observe the entire K window at a resolving power of 20,000. This requires an echelle with a 18 grooves/mm, which cannot be made by standard techniques. Therefore we sought an optical solution using commercially available replica gratings. After several iterations, we settled on the design shown in Fig. 2. Light from the slit goes to a folding flat, which sends the light to the collimator (an off-axis parabola). The collimated light goes to the echelle to be dispersed, and then to the cross-dispersing grating. An all metal four-mirror anastigmat focuses the spectrum on the array. The design and tradeoffs that were finally accepted were done by D. Warren.[6] Replica gratings on aluminum substrates were made by Hyperfine, Inc. (Boulder, Colorado).

The specifications of the optics are

- Collimator: off-axis parabola, focal length = 320 mm, collimated beam diameter = 25.9 mm.
- Echelle: 31.6 grooves/mm replica grating, 63.5° blaze angle.
- Cross-disperser: 42.2 grooves/mm replica grating, 24° blaze angle, first-order blaze wavelength = 6.6 μm.
- Camera: Four-Mirror Anastigmat, effective focal length = 315 mm.

3.2.1. Slit width

The smallest slit width of 0.15″ is used to obtain a spectral resolution of 20,000 (with 0.075″/pixel). This requires the use of the AO system. We would prefer to have at least 3 pixels across the slit, but this would require decreasing the spectral coverage per exposure. A range of slits, up to 0.60″/pixel, will be provided to accommodate observing modes without the AO system as well as extended objects and observations at wavelengths longer than 2.5 μm.

3.2.2. Placement of the orders on the array

Our design permits us to obtain about 70% of the K band (2.2 μm) in a single exposure at a resolving power of 20,000 and with two pixels per resolution element. For the H band (1.6 μm), we shall be able to obtain about 80% of the H band in a single exposure. For the J band (1.25 μm), we will need two exposures to avoid overlapping orders, but the echelle and cross-disperser do not have to move (see Fig. 3). Instead, the order-sorting filters are changed.

3.2.3. Four-mirror anastigmat (FMA)

Several design studies were conducted to determine the best type of camera optics for the spectrograph, including an all-refractive design and a three-mirror anastigmat. A final solution using an FMA was developed by SSG, Inc. (Wilmington, Massachusetts). The four-mirror design allowed for the internal pupil image to be accessible and separated from the mirror surfaces. Although more expensive than a solution using lenses, the advantages of the FMA are (1) there are fewer surfaces, (2) an all-reflection design eliminates chromatic aberration, (3) for 1–5 μm an all-reflective design has significantly better performance than antireflection coated lenses, and (4) there are no ghost images caused by reflections between surfaces of the lenses. The FMA will be fabricated out of aluminum by SSG, Inc. High-performance overcoated silver coatings will be used on the mirrors. Ray-trace analysis of the FMA shows that 65% of the energy from a point source at 2 μm will be within one pixel, compared with 75% in the diffraction-limited case. This is sufficient since one resolution element of the spectrograph is 2×2 pixels. At 1 μm 70% of the energy falls on a single pixel compared with 87% for the diffraction-limited case, and at 5 μm it is 21% compared with 23% for the diffraction-limited case.

3.3. Camera Optics

The design approach for the camera optics follows that of the Gemini Near-Infrared Imager (NIRI,[7] also being constructed at the Institute for Astronomy), and all of the lenses have spherical surfaces. To achieve this relative simplicity, the infrared array will have to be refocussed at different wavelengths. The camera optics consists of a "collimator" section and a "camera" section. The collimator section is the same for both pixel scales, but the camera section has two "flip" mirrors to change the camera pixel scale as shown in Fig. 4. Various factors were taken into consideration for the final design of the camera optics, including minimizing the size of the camera lenses and pupil image, minimizing the total number of optical elements, and providing space for the filter wheels and mechanisms. The lenses will be made out of BaF_2, LiF, ZnSe, and ZnS to avoid materials difficult to work with. Ray-trace analysis shows that $\geq$90% of the energy from a point source falls within a single pixel. Therefore the optics should provide diffraction-limited imaging at 1–5 μm. The final optical design and optimization was done by J. Hora.

Light to the camera section is reflected off the slit substrate (or off a mirror for imaging alone). The slits are tilted by 15° to allow light to clear the camera optics. The collimator has an effective focal length of 346 mm, and it forms an image of the pupil that is 28 mm in diameter. The camera section has 3 identical filter wheels that can hold up to 30 filters and 6 grisms. The IRCS will have the standard photometric broad-band filters as well as a number of narrow-band filters centered on important emission lines, such as hydrogen recombination lines, molecular hydrogen, helium, iron, etc.

3.3.1. Grism mode

We are planning to have four grisms as specified below:

- 1–2.5 μm; 0.022″/pixel; 20 lines/mm; 14.75° prism angle.
- 1–2.5 μm; 0.060″/pixel; 40 lines/mm; 30.5° prism angle.
- 1–2.5 μm; 0.060″/pixel; 75 lines/mm; 12.5° prism angle.
- 2.8–4 μm; 0.060″/pixel; 54.25 lines/mm; 7.85° prism angle.

The 1–2.5 μm grisms will be fabricated by Richardson Grating Laboratory (Rochester, New York) on an ULTRAN30 substrate with a replica grating attached with epoxy. The 2.8–4 μm grism will be fabricated on KRS-5 and will be a custom-ruled grism fabricated by Carl-Zeiss (Jena, Germany).

3.4. Summary of Instrument Modes

3.4.1. Spectroscopy

Spectroscopic capability consists of a cross-dispersed echelle for the spectrographic section, and of grisms in the camera section. These are summarized in Tables 1 and 2.

Table 1. Spectroscopic modes and maximum resolving powers.

mode	wavelength range	resolving power	slit width
grism, 0.060 ″/pix	1.0–2.5 μm	400	0.15″
grism, 0.060 ″/pix	2.8–4.2 μm	850	0.15″
grism, 0.022 ″/pix	1.0–2.5 μm	900	0.10″
grism, 0.060 ″/pix	1.0–2.5 μm	1,400	0.15″
cross-dispersed echelle, 0.075 ″/pix	1.0–5.6 μm	20,000	0.15″

Table 2. Slit width and length.

mode	pixel scale	slit width	slit length
grism	0.022 ″/pix	0.10–0.90″	23″
grism	0.060 ″/pix	0.15–0.90″	20″
echelle	0.075 ″/pix	0.15–0.60″	3.9–10.5″

The slits required for the IRCS are complicated because we need two types of slits, transmitting for the spectrograph section and reflecting for the grisms in the camera section, and we need different slit lengths for different orders of the cross-dispersed spectrum. Table 3 shows the required slits.

The transmitting slits require 13 positions on the slit wheel. An additional position is required for a mirror to allow imaging with the camera section. These slits will be made by laser cutting a copper substrate by National Aperture (Salem, New Hampshire). In the case of reflecting slits, 2 or 3 slit widths will be provided on a single substrate, each with a slit length given in Table 3. We will fabricate reflective slits out of polished tungsten carbide which is cut by electron discharge machining. The details of the slit fabrication is discussed elsewhere in these proceedings.[8]

Six order-sorting filters are required for the spectrograph section, and 7 order-sorting filters are required for the camera section.

Table 3. Transmitting and reflecting slits.

Transmitting slits for the echelle spectrograph		Reflecting slits for the camera grisms	
width (arcsec)	length (arcsec)	width (arcsec)	length (arcsec)
0.15	3.9	0.10, 0.15	23
0.15	5.8	0.30, 0.60, 0.90	20
0.15	7.5		
0.30	3.9		
0.30	5.8		
0.30	7.5		
0.30	10.5		
0.60	3.9		
0.60	5.8		
0.60	7.5		
0.60	10.5		

3.4.2. Imaging

The camera section will have two pixel scales, $0.022''$/pixel and $0.060''$/pixel. This section serves as an imager and a slit viewer. High-speed readout electronics allow for use of the array as a TT sensor as well. This allows the camera to be used in areas where there are no suitable guide stars for the AO system, and for occultation studies.

4. MECHANICAL DESIGN

4.1. Cryostat Design

4.1.1. Cryostat design approach

Our approach toward achieving a very stiff optical mounting structure is shown in Fig. 5. A vertical plate of dimensions 700 mm $\times$ 700 mm $\times$ 40 mm provides the main support of the optics. This vertical plate is rigidly attached to the vacuum jacket with 4 trusses that hold the edge of the vertical plate. The trusses will be made out of titanium for low thermal conductivity and stiffness. The vacuum jacket is made up of three sections: the central section, front cover, and back cover. All three sections were fabricated from forged 6061 T-6 aluminum slabs. The center section will hold all components, including the closed-cycle cooler, array electronic boxes, and electrical connectors. This permits the covers to be removed for access to the optics.

4.1.2. Flexure requirements

The instrument should be rigid enough that the image does not move significantly on the array while integrating. In order for the image motion to be insignificant, the image should not move by more than 0.1–0.2 pixels during the integration. If we assume that a typical long integration is 20 minutes, then this leads to a flexure requirement of less than 0.2 pixel motion (≤ 6 μm) in 20 minutes. Finite element analysis was used to verify that the structure can meet this requirement.

4.1.3. Cooling system

A single closed-cycle cooler (CCC) will be used to keep the instrument cold at the telescope. Based on the expected heat loading, we plan to use a Sumitomo RDK-210W cooler, which provides 53 watts of cooling at 55 K. This is about twice the expected heat loading. An antivibration mount will be used to suppress vibrations from the CCC. The second-stage of the CCC will be used to cool the infrared arrays to approximately 35 K. Since the ALADDIN II detector is sensitive to 5.6 μm, we will need to cool the optical components to 65 K to keep the background emission from the cooled optics below the detector dark current. We plan to have a liquid nitrogen heat exchanger attached to the cold optics plate to provide the initial cooldown of the instrument. After cooling down the instrument, the CCC will keep the instrument stabilized at 65 K.

4.1.4. Cryostat radiation shields

There are two photon shields, one on each side of the cold support plate plate. The purpose of the photon shields is to provide a light-tight enclosure. They will be cooled to 65 K (same temperature as the optics) so that they do not contribute any background emission to the detector. The outer surface will be polished and gold-plated to reduce the heat load on the cold support plate, while the inside will be painted black to suppress scattered light. A thermally isolated radiation shield will enclose the photon shield to reduce the heat load on the 65 K surface.

4.1.5. Interface to the Instrument Container

The IRCS will be installed in a standard Subaru Telescope "Instrument Container." The Instrument Container will provide a standard interface to the telescope for all Subaru instruments. The size of the Instrument Container will be 2 m $\times$ 2 m $\times$ 2 m. It will be capable of holding a maximum instrument weight of 2 metric tons, will be mounted to the telescope automatically with electrically driven screws, and will include automatic connectors for electrical cables, fluids, and compressed gas. Our plan is to mount the IRCS to the Instrument Container with supporting braces as shown in Fig. 6. These supporting braces will have provision for x-y adjustment and tilt.

4.2. Mechanisms

The number of mechanisms in the IRCS is large for a cryogenic instrument. Our approach is to use cryogenic motors wherever possible. This will eliminate mechanical feedthroughs that are subject to failure and vacuum leaks. The mechanisms are slit wheel (1), filter wheels (4), echelle grating tilter (1), cross-disperser grating tilter (1), flip mirrors for changing the camera pixel scale (2), and array focus mechanism (1), a total of 10 mechanisms. Cryogenic motors made by Phytron Inc. (Waltham, Massachusetts) with a torque rating of 310 N mm at 2 kHz will be used. Hall effect sensors will be used to determine the zero position.

The filter and slit wheels will employ a Geneva-type mechanism to ensure good positioning repeatability.[9] The mirror flip mirrors are two-position, spring-loaded mechanisms. The springs are used to keep the mirrors against a hard stop at all times to ensure repeatability. The grating tilters consist of a linear ball screw that pushes a grating mount. The grating mount pivots along an axis located near the surface of the grating. The focus mechanism for the camera detector is described in these proceedings.[10]

5. ELECTRONICS

The electronics will provide (1) analog signal amplification and digitization for two 1024$\times$1024 ALADDIN II infrared arrays, (2) suitable interfaces to the array readout electronics and array clock signals, (3) stepper motor drivers, (4) readout of position sensors, (5) temperature control and temperature sensors, (6) real-time self-diagnostic functions for troubleshooting, (7) computer control during laboratory testing and troubleshooting capability at the telescope focal plane, and (8) power supplies for all devices, microprocessors, and interface electronics. The ALADDIN II controller for the IRCS is described elsewhere in these proceedings.[11]

Cooling fluid provided by the telescope is used to remove heat generated by the electronics. Air will be circulated through the electronics, and a simple heat exchanger will remove the heat.

6. SOFTWARE

The software will provide the following functions: (1) infrared array control (integration time, co-addition of frames, coordination between the camera and spectrograph infrared arrays); (2) mechanism control; (3) power control (motors, array electronics, sensors); (4) user interface; (5) observatory interface (data transfer, telescope control, telescope autoguider, etc.); (6) tip-tilt and adaptive optics control; and (7) troubleshooting (basic hardware checks, stand-alone control, internal viewing CCD).

We also require stand-alone operation for the laboratory and for troubleshooting at the telescope.

7. STATUS AND FUTURE PLANS

At the time this paper was being prepared, the cryostat was in preparation for vacuum testing and all of the major components had been ordered or fabricated. The first science-grade ALADDIN II array had been delivered to the Institute for Astronomy, and it was under test.[11] Delivery of the instrument to the Subaru Telescope facility in Hilo, Hawaii, is scheduled for January 1999. The first installation of the instrument on the telescope is planned for about July 1999.

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REFERENCES

1. N. Kaifu, “Subaru Telescope,” in *Advanced Technology Optical/IR Telescopes VI*, L. M. Stepp, ed., *Proc. SPIE* **3352**, submitted, 1998.
2. J. D. Garnett, S. L. Solomon, A. W. Hoffman, J. P. Rosebeck, N. A. Lum, M. S. Smith, A. D. Estrada, and A. J. Tribble, “InSb arrays for ground-based and space-based astronomy,” in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, submitted, 1998.
3. L. J. Kozlowski, K. Vural, S. A. Cabelli, A. C. Chen, D. E. Cooper, G. L. Bostrup, C. Cabelli, K. Hodapp, D. N. Hall, and W. E. Kleinhans, “HgCdTe 2048x2048 FPA for infrared astronomy: Development status,” in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, submitted, 1998.
4. H. Takami, N. Takato, M. Otsubo, T. Kanzawa, Y. Kamata, K. Nakashima, and M. Iye, “Adaptive optics system for Cassegrain focus of Subaru 8.2-m telescope,” in *Adaptive Optical System Technologies*, D. Bonaccini, ed., *Proc. SPIE* **3353**, submitted, 1998.
5. Information on these instruments can be found at http://www.subaru.nao.ac.jp/
6. D. W. Warren, “Baseline design for the high resolution section of the Subaru Infrared Camera and Spectrograph,” Aerospace Report No. ATR–96(7418)–1, The Aerospace Corp., El Segundo, California, 1996.
7. K. Hodapp, J. L. Hora, T. T. Young, E. M. Irwin, H. Yamada, J. Douglass, J. Bell, and D. Neill, “Gemini near-infrared imager (NIRI),” in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, submitted, 1998.
8. T. T. Young, A. T. Tokunaga, J. L. Hora, L. Robertson, and N. Kobayashi, “Precision slit design and fabrication for Subaru IRCS instrument,” in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, submitted, 1998.
9. J. Bell, J. Douglass, K. Hodapp, L. Robertson, A. T. Tokunaga, and T. T. Young, “Design of the wheel mechanisms for IRCS and NIRI,” in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, submitted, 1998.
10. J. Douglass, T. T. Young, K. Hodapp, and L. Robertson, “Design review of flexure-based focus stages for Gemini NIRI and Subaru IRCS,” in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, submitted, 1998.
11. P. M. Onaka, A. T. Tokunaga, N. Kobayashi, M. Weber, “Test and selection of Aladdin II arrays for IRCS: Redline array control electronics for IRCS,” in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, submitted, 1998.

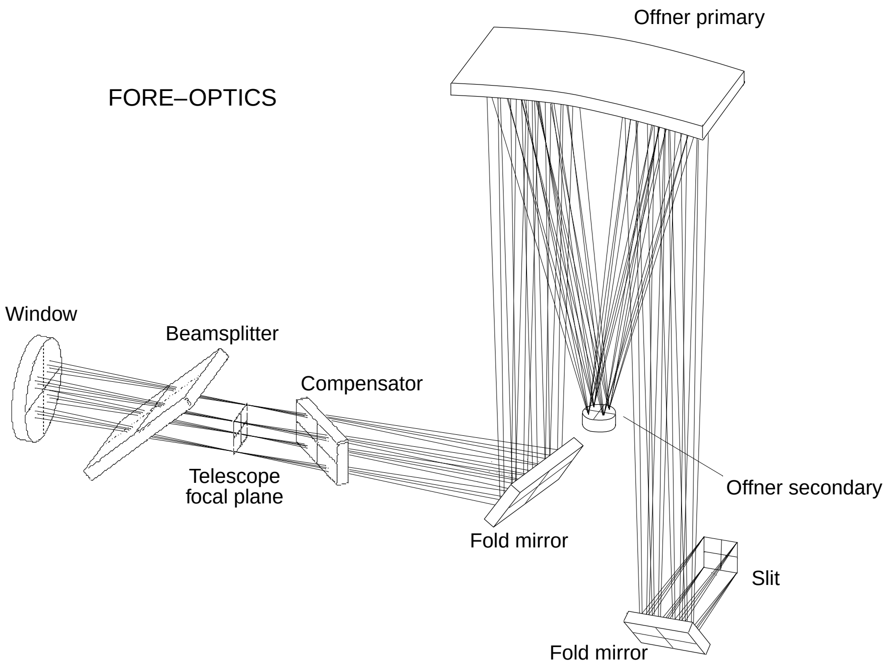


Figure 1. Optical layout of the fore-optics section. The Offner relay has a magnification of 1:1, and it is fabricated from post-polished aluminum optics.

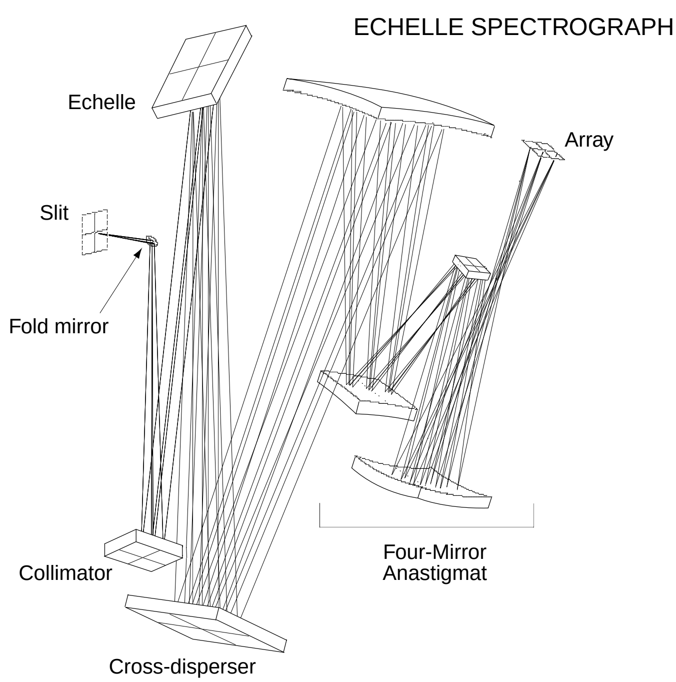
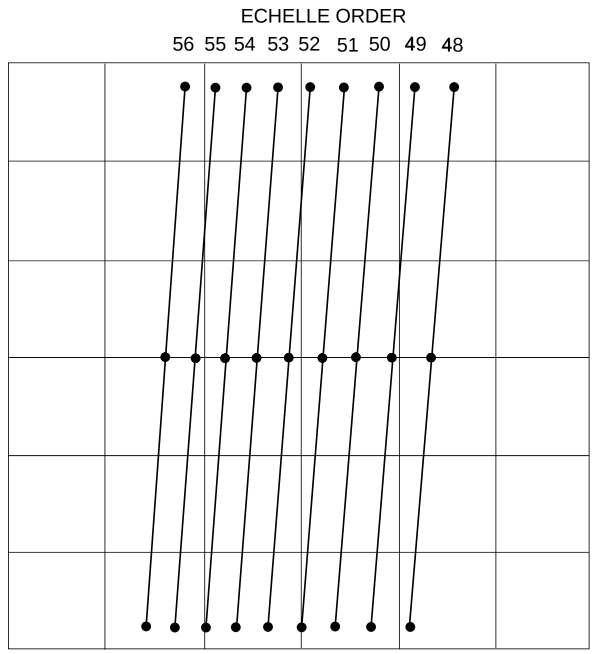
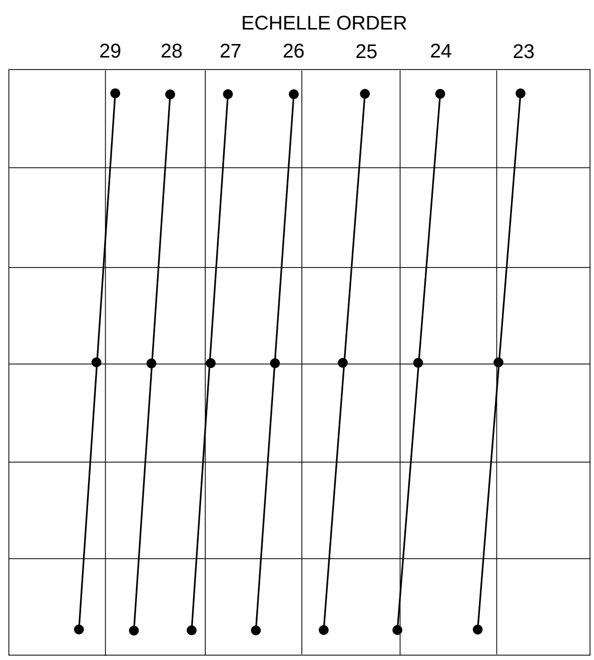


Figure 2. Optical layout of the spectrograph section. The off-axis collimator and four-mirror anastigmat are post-polished aluminum optics.



Echelle orders projected onto the array. 0.996 to 1.191 microns

Figure 3(a). Schematic of the spectral orders in the J band (1.25 μm) superimposed on the infrared array. The wavelengths range from 0.996 to 1.191 μm in orders 56–48. A second exposure with a different order-sorting filter is required to observe the spectral range 1.187–1.361 μm in orders 47–42.



Echelle orders projected onto the array. 1.940 to 2.506 microns

Figure 3(b). Schematic of the spectral orders in the K band (2.2 μm) superimposed on the infrared array. The wavelengths range from 1.941 to 2.506 μm in orders 29–23. Two echelle grating positions are needed to cover the entire K band.

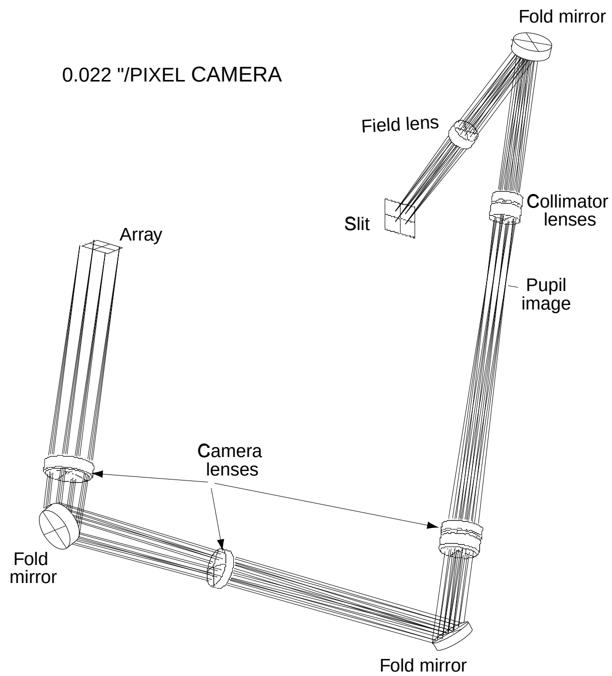


Figure 4(a). Optical layout for the 0.022″/pixel scale of the camera section. The filter wheels are located at the pupil image location. A cold pupil baffle is placed at the position of the pupil image.

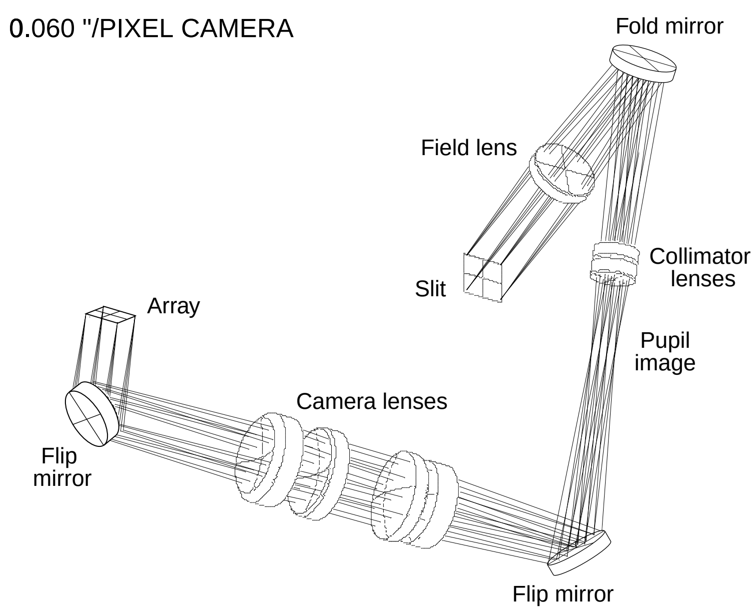


Figure 4(b). Optical layout for the 0.060″/pixel scale of the camera section. The flip mirrors are placed in the light path of the 0.022″/pixel scale to change the pixel scale to 0.060″/pixel.

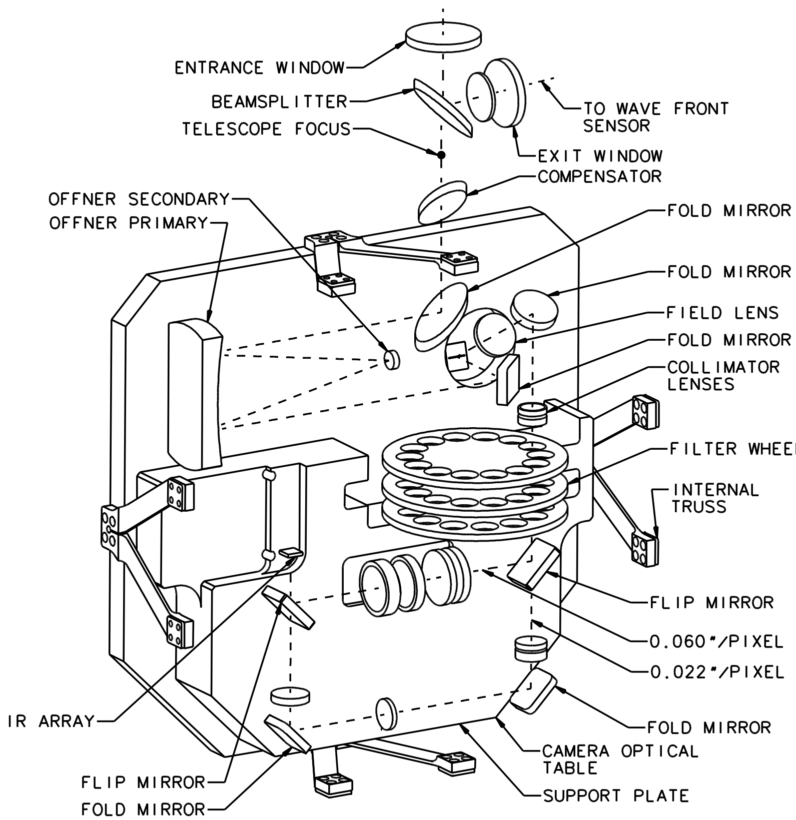


Figure 5(a). Layout of the fore-optics and camera sections. Four internal trusses, fabricated out of titanium, attach the main support plate to the inner wall of the cryostat.

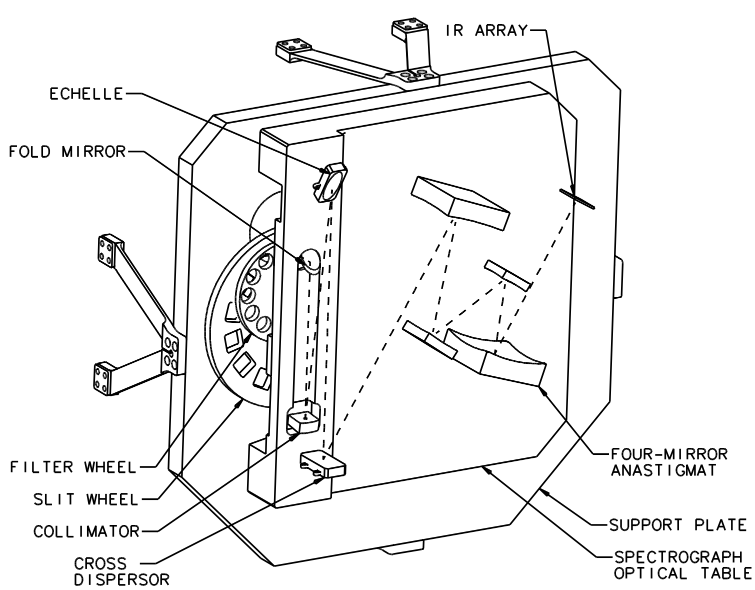


Figure 5(b). Layout of the spectrograph section. The optics are mounted on the opposite side of the main support plate shown in Fig. 5(a).

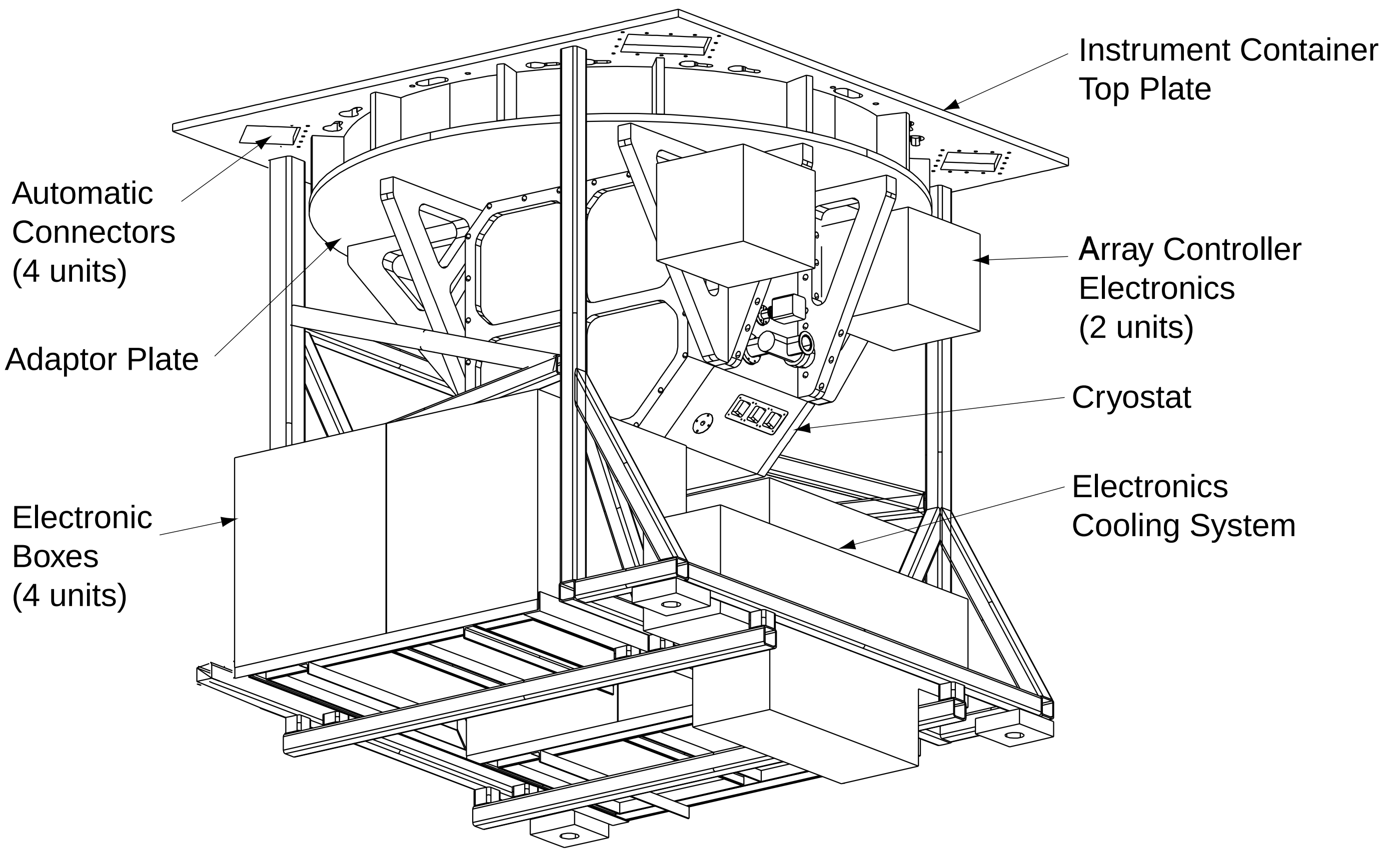


Figure 6. Mechanical layout of the cryostat, instrument container, and electronic boxes. The entire structure will be covered by aluminum panels to keep heat from leaking into the dome. The Wave-Front Sensor for the AO system is mounted on the top side of the adaptor plate, and it is hidden in this view. The automatic connectors on the instrument container top plate will provide electrical, high-pressure helium, and cooling fluid connections to the telescope. The instrument container will fit onto a cart which is used for moving the instrument on the observing floor. The overall size of the structure is 2 m $\times$ 2 m $\times$ 2 m.