Gemini near-infrared integral field spectrograph (NIFS)*

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ABSTRACT

NIFS is a near-infrared integral field spectrograph designed for near diffraction-limited imaging spectroscopy with the ALTAIR facility adaptive optics system on Gemini North. NIFS is currently under construction at the Research School of Astronomy of the Australian National University. Commissioning is planned for 2003. NIFS uses a reflective concentric integral field unit to reformat its 3.0"×3.0" field-of-view into 29 slitlets each 0.1" wide with 0.04" sampling along each slitlet. The NIFS spectrograph has a resolving power of ~ 5300, which is large enough to significantly separate terrestrial airglow emission lines and resolve velocity structure in galaxies. The output format is matched to a 2048×2048 pixel Rockwell HAWAII-2 detector. The detector is read out through a SDSU-2 detector controller connected via a VME interface to the Gemini Data Handling System. NIFS is a fast-tracked instrument that reuses many of the designs of the Gemini Near-InfraRed Imager (NIRI); the cryostat, On-Instrument Wave Front Sensor, control system, and control software are largely duplicates.

Keywords: near-infrared, spectrograph, integral field unit

1. INSTRUMENT OVERVIEW

The Gemini 8 m telescopes are designed to achieve unprecedented ground-based image quality using adaptive optics techniques. The Gemini Near-infrared Integral Field Spectrograph (NIFS)[d] is a facility instrument that will be commissioned on the Gemini North 8 m telescope in 2003. It will be used with the ALTAIR adaptive optics system. NIFS combines an integral field unit (IFU) with a moderate resolution near-infrared spectrograph to perform near diffraction-limited imaging spectroscopy over a 3.0"×3.0" field-of-view with 0.1" sampling in the dispersion direction and 0.04" sampling in the spatial direction. The NIFS spatial sampling is chosen to sample at close to the Gemini diffraction limit while maintaining a modest field-of-view. NIFS operates in the wavelength range from 0.94 to 2.50 μm where ALTAIR delivers its greatest gains. The spectrograph uses a 2048×2048 pixel Rockwell HAWAII-2 detector with 2048 spectral pixels per spatial element. It produces a two-pixel spectral resolving power of ~ 5300, which allows each near-infrared photometric band to be recorded at a single grating setting. The spectral resolving power is sufficient to permit measurements between strong near-infrared OH airglow emission lines where the near-infrared sky background is low.

NIFS can also be used without ALTAIR for moderate resolving power near-infrared spectroscopy of extended objects through a 3.0"×3.0" aperture. These observations will benefit from the lower emissivity and higher throughput of the direct telescope beam, and from the large NIFS entrance aperture that will virtually eliminated slit losses, even in poor seeing conditions, while maintaining moderate spectral resolving power.

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[d] http://www.mso.anu.edu.au/nifs

The design, construction, and commissioning of NIFS have been fast-tracked by re-using many of the components designed for the Gemini Near-InfraRed Imager (NIRI)[1,2] by the Institute for Astronomy (IfA) of the University of Hawaii. The NIFS spectrograph will be mounted in a duplicate of the NIRI cryostat and use a duplicate of the NIRI On-Instrument Wave Front Sensor (OIWFS) to sense tip-tilt and focus corrections. The NIFS spectrograph will use the same mechanisms encoding architecture used in NIRI and will use the same cryogenic stepper motors adopted for NIRI. This commonality of mechanical designs means that the NIRI mechanism control system hardware and temperature control system hardware can also be duplicated for NIFS with minimal change. The EPICS Instrument Sequencer (IS), Components Controller (CC), and engineering interface software developed for NIRI and the CC for the OIWFS also have been re-used for NIFS with only minor modification. This fast-tracked approach has led to significant savings in schedule and budget.

2. SCIENTIFIC RATIONALE

The primary purpose of NIFS is to study moderate surface brightness structures around discrete objects that are revealed at high spatial resolution by ALTAIR. NIFS will address a wide range of science[3] from studies of star formation and the Galactic center in our galaxy to the nature of disk galaxies at $z \sim 1$. The main science drivers for high spatial resolution near-infrared spectroscopy are studies of:

- Massive black holes in nearby galactic nuclei
- Nearby active galactic nuclei
- Brown dwarfs and low mass binary stars
- Young star clusters
- YSO jet driving mechanism
- YSO jet-cloud interactions
- Late stages of stellar evolution
- Galactic center
- Nuclear stellar populations in Local Group galaxies
- Old stellar populations in nearby galaxies
- Nearby starburst galaxies and starburst regions
- Ultra-luminous infrared galaxies
- Dynamical evolution of high redshift galaxies
- Lyman break galaxies

Guide star availability imposes a strong selection on possible science targets. A guide star brighter the $R \sim 15$ mag is required within 20" of the science object for observations with the ALTAIR natural guide star system. A near-infrared OIWFS guide star is also required within the 120" diameter ALTAIR field and outside of the region vignetted by the NIFS pickoff probe. This vignetted region includes the region within 12.7" of the science field center, so the near-infrared image of the science target cannot be used for guiding. Typically only ~ 8% of extragalactic science targets and ~ 32% of Galactic science targets possess suitable combinations of guide stars. These requirements will be relaxed somewhat when the ALTAIR laser guide star system becomes available. An optical guide star brighter than $R \sim 17$-19 mag will then be required within ~ 35" of the science object for AO tip-tilt correction, and an OIWFS star will still be required for flexure monitoring. Typically 33% of extragalactic science targets and 69% of Galactic science targets possess suitable combinations of these guide stars.

3. SPECTROGRAPH OPTICAL DESIGN

The NIFS spectrograph optics are shown unfolded in Figure 1. ALTAIR passes a 120" diameter, f/16 field to its science instrument. A small pickoff mirror in the NIFS cryostat reflects the central 3.0"×3.0" field to the spectrograph. The remaining field not vignetted by this probe passes to the OIWFS, which monitors tip-tilt and focus variations due both to the atmosphere and to flexure between NIFS and ALTAIR. A focal plane mask wheel at the ALTAIR focal plane baffles the image and allows the insertion of occulting disks and calibration masks. The NIFS spectrograph uses a concentric IFU to reformat the input focal plane. The design of the concentric IFU is described elsewhere in this volume[4]. It is an evolution and simplification of a design by Content[5]. The IFU reimages the focal plane at enlarged scale onto a concave stack of 29 image slicer mirrors. These mirrors fan the IFU channels and form pupil images on an array of concave pupil mirrors. The pupil mirrors reimage the focal plane at a demagnified scale on an array of field mirrors where the input field has been reformatted as a long thin slit. The essential feature of the concentric IFU is that all the optical surfaces of the IFU and the spectrograph Bouwers collimator are concentric about a fanning axis through the central image slicer mirror. This means that all IFU channels operate as if they are on the optical axis, so off-axis aberrations are eliminated. The 418.32 mm focal length spectrograph collimator is an integral part of the IFU instrument, with coincident 25.8 mm diameter pupil images being formed on the IFU fanning axis at the location of the grating. Unlike the Content[5] design, the NIFS IFU reimages the focal plane at fixed scale on the image slicer. The geometry of the IFU and the anamorphic magnification of the grating then result in spatial pixels that are rectangular (0.10"×0.04") on the sky. The NIFS spectrograph uses a refractive five-element camera consisting of CaF_2, silica, ZnSe, CaF_2, and silica. The camera focal length is 286 mm.

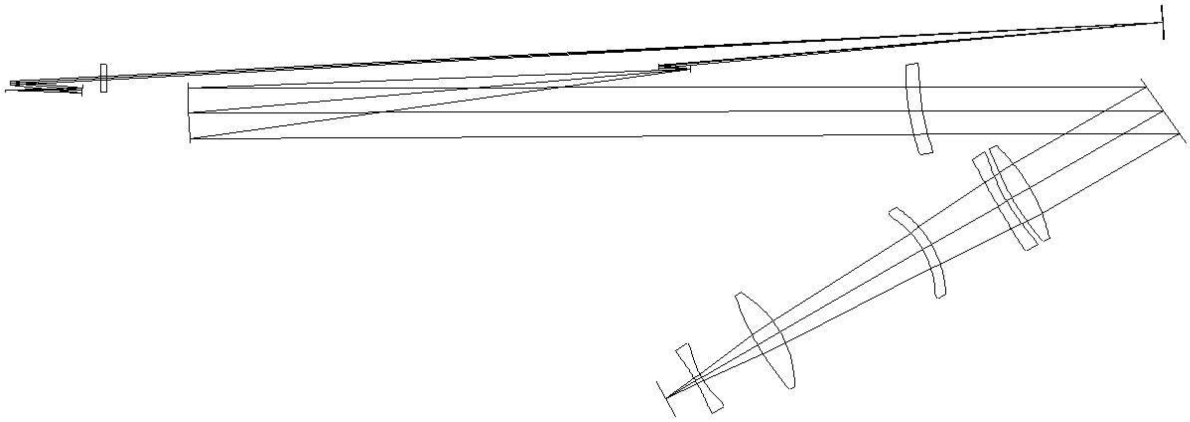

Figure 1: Optical layout of the NIFS spectrograph in side view with the fold mirrors omitted.

Diffraction effects at the 0.1" wide image slicer mirrors smear the pupil image in the dispersion direction at the IFU pupil mirrors and at the grating (Figure 2). These elements are made larger than the geometrical pupil by 60% to capture as much as is practical of this diffracted light. Nevertheless, the finite width of the grating will cause diffractive smearing of the slit image in dispersed light at the detector. One consequence of this will be to smear strong airglow emission lines into neighboring continuum regions, and hence compromise our ability to perform software rejection.

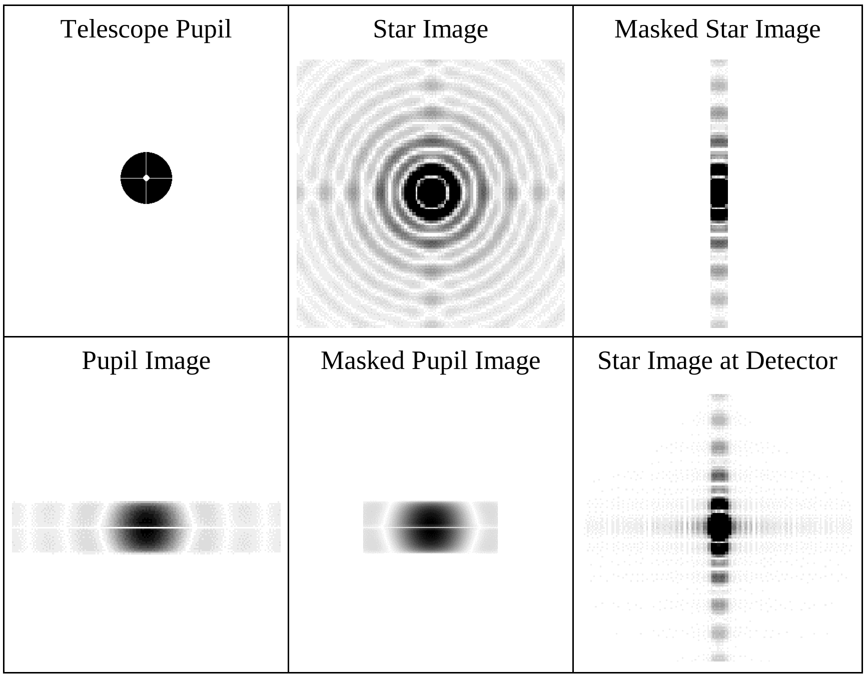

Figure 2: Diffraction effects at 2.2 μm caused by masking at field (slit) and pupil (grating) images.

The NIFS gratings operate at grating angles of ~ 20º to produce a two-pixel resolving power of R ~ 5300. The grating suite adopted is listed in Table 1. Rotating the grating away from the nominal grating angle accesses extreme wavelength ranges of the K band. A flip mirror can be positioned in front of the grating to permit field acquisition without moving the grating turret and losing wavelength calibration stability. OH airglow emission occupies ~ 7%, 11%, 13%, and 10 % of the *Z*, *J*, *H*, and *K* spectral bands at this resolving power.

Table 1: NIFS Grating Suite

Pass Band	Central Wavelength (μm)	Groove Density (g/mm)	Blaze Angle (deg)	Grating Angle (deg)	Resolving Power	Velocity Resolution (km/s)	Spectral Range (μm)
Z	1.05	600	17.5	19.1	4990	60.1	0.94 - 1.15
J	1.25	600	22.0	22.9	6050	49.6	1.15 - 1.35
H	1.649	400	18.6	20.043	5290	56.8	1.49 - 1.80
K	2.20	300	17.5	20.1	5290	56.7	1.99 - 2.40

4. MECHANICAL DESIGN

4.1 FOCAL PLANE UNIT

NIFS uses a duplicate of the NIRI cryostat, so externally looks similar to that instrument. The NIRI cryostat is a hexagonal cylinder divided internally by a cold work surface plate. The NIFS spectrograph mounts on one side of this plate (replacing the NIRI camera) and the duplicate OIWFS mounts on the other. A pickoff probe in the focal plane unit (Figure 3) extends into the ALTAIR beam below the cryostat window. A mirror on this probe reflects the spectrograph field to the focal plane wheel and then through the cold work surface plate to the f-converter mirror. The f-converter mirror re-images the ALTAIR exit pupil onto a 4.0 mm diameter reflective cold stop that baffles the input. The f-converter mirror also re-images the ALTAIR focal plane at f/256 onto the IFU image slicer.

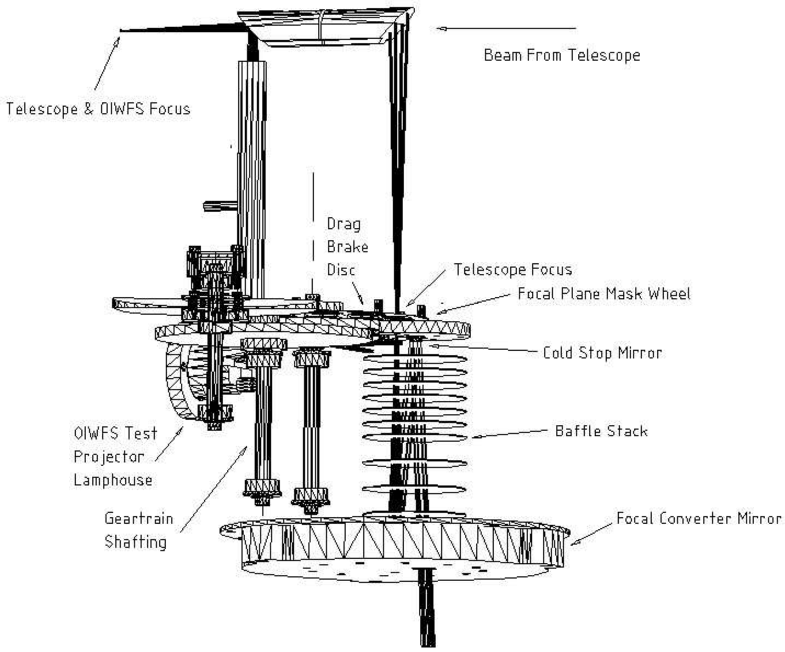

Figure 3: Focal plane unit internals showing pickoff probe at top, focal plane mask wheel, cold stop mirror, and f-converter mirror at bottom. The baffle stack prevents the spectrograph from bypassing the cold stop and looking out directly to the sky.

The decentered spherical f-converter mirror is diamond turned into a 114 mm diameter aluminum disk (Figure 3). The aluminum disk is mounted via a slightly larger flexure diaphragm to the focal plane unit housing. Three screws in the disk strain against the diaphragm and permit adjustment of the mirror in tip-tilt to align the system pupil onto the cold stop mirror. The cold stop mirror is mounted directly to the focal plane unit housing without adjustment. The mirror is diamond turned without edge chamfer to provide a sharp edge that cleanly baffles the telescope pupil. A black painted 1 mm wide cavity is formed in the housing around the 4 mm diameter cold stop mirror to provide a beam dump for rays outside the pupil image.

4.2 IFU AND COLLIMATOR

The rest of the spectrograph optics are mounted on the spectrograph side of the cold work surface plate (Figure 4) in a number of towers that are held between the cold work surface plate and the spectrograph cover to reduce their flexure. The beam first passes through an order blocking filter in the filter wheel and is then directed via two fold mirrors in the filter-fold tower to the tri-fold mirror and then to the image slicer in its tower. The fanned beams from the image slicer pass back to the pupil and field mirror arrays in the tri-fold tower, and then to the collimator mirror in its tower. The collimated beam is folded a third time at the tri-fold tower and then passes through the Bouwers collimator corrector lens to the grating.

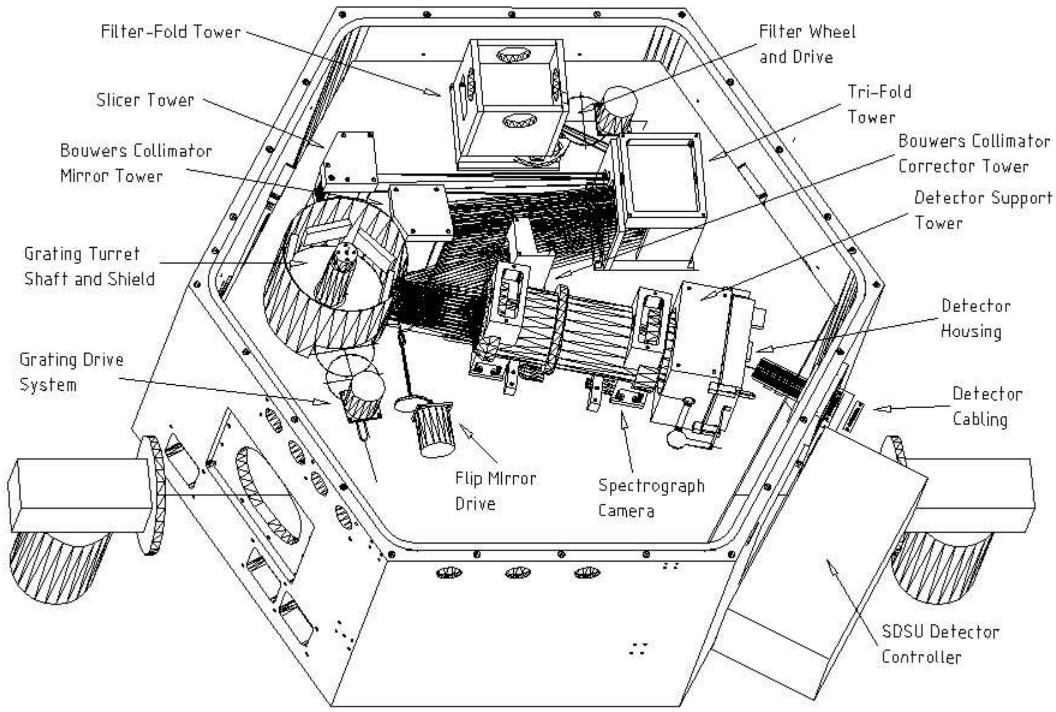

Figure 4: Spectrograph modules and towers mounted on cold work surface plate with baffling and spectrograph cover and skirt removed.

4.3 GRATING TURRET

The grating turret (Figure 5) is the dominant source of flexure in the NIFS spectrograph. It is required to be stable in angle to better than the 0.1 pixels per 15º change in orientation specifications, and to allow the gratings to be adjusted in tilt and rotation angle to accurately align the spectral image on the detector. One pixel at the detector corresponds to ~ 31.5 μrad (~ 6.5") tilt of the grating. The grating turret is mounted on a 33 mm diameter shaft by two angular contact bearings. The shaft is supported rigidly between the cold work surface plate and the spectrograph cover. The top bearing is held via two parallel spring diaphragms that preload the bearings with a light controlled force. The bearing support is athermalized via matching conical metal tapers. The apex of each cone is coincident with the center of the turret shaft so that the inner and outer cones slip relative to each other under differential contraction while the bearing support remains rigid. The turret is driven by a Phytron cryogenic stepper motor via a 1008:1 three-stage spur gear drive system. A belvel washer above the lower turret bearing provides a friction drag brake, which ensures that the grating turret does not move under gravitational load. Encoding is via a once per revolution Hall effect sensor on the stepper motor drive shaft. Other Hall effect sensors indicate which grating is selected at low grating angle resolution. A slipping clutch is incorporated into the axle of each drive gear to prevent gear train damage in the event of a system failure.

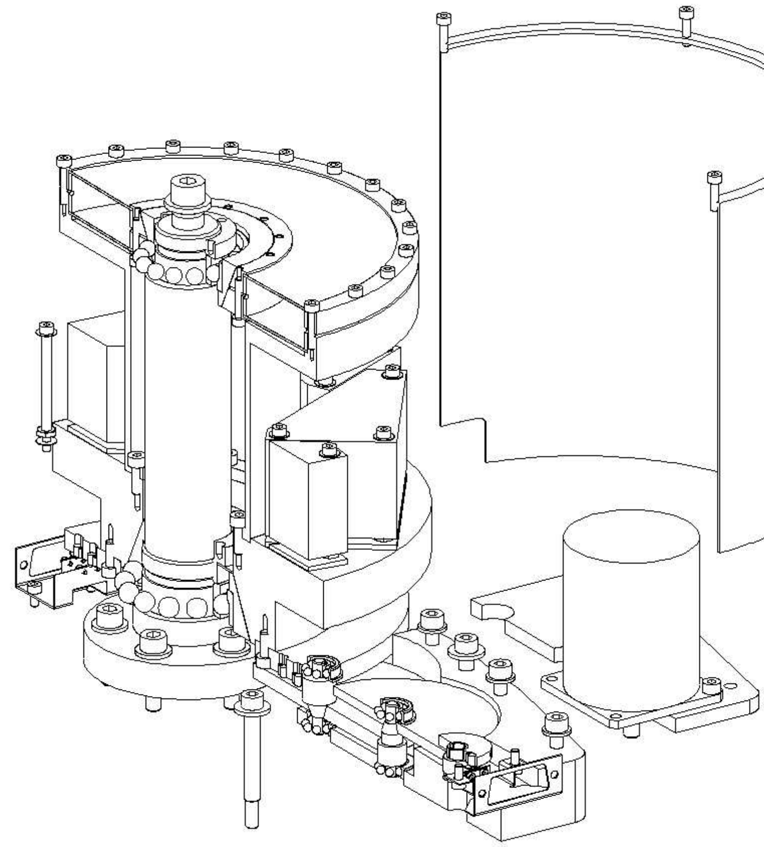

Figure 5: Cross-sectional view of the grating turret and drive system showing internal components.

The individual gratings are replicated on aluminum blanks. Each grating is mounted via three custom screws to the grating turret platform. These screws are preloaded with belvel washers so that the gratings can move within the over-sized clearance holes, but remain preloaded during adjustment. One front mounting screw adjusts grating rotation and the rear screw adjusts grating tilt.

4.4 CAMERA HOUSING

The refractive camera optics are held in a cylindrical camera housing (Figure 6). NIFS will operate initially at a temperature of 65 K. However, there is a possibility that a 5 μm cutoff HgCdTe/CdZnTe MBE detector might be installed at a later date. The detector should then be shielded from ambient thermal radiation from the camera. This is achieved by cooling the final silica camera lens to ~ 30 K by mounting it from the camera housing on a thin walled stainless steel tube and attaching it thermally to the spectrograph detector 20 K tie point.

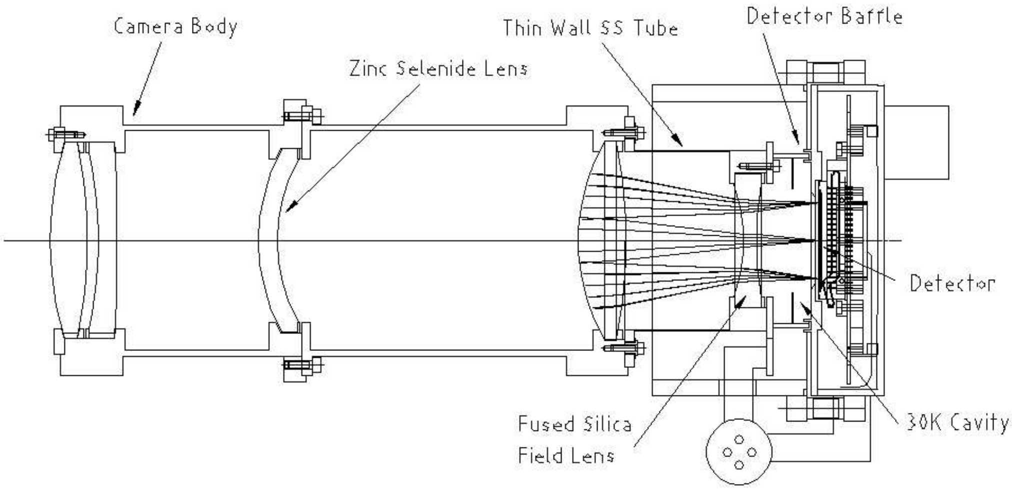

Figure 6: Camera cross section showing 30 K cavity and detector.

The individual ~ 100 mm diameter crystal camera lenses are axially located by pressing them against shoulders in the aluminum housing. Custom made wave springs manufactured from stainless steel shim are used to apply a force equal to about ten times the lens weight to ensure secure seating. All the lenses used in NIFS are radially located by mounting them in close fitting housing bores. In all cases the thermal contraction of the aluminum alloy housing is greater than that of the lens at operating temperature. The housing and lens tolerances are arranged so that the minimum clearance is zero under these conditions. The lens temperature will lag behind the housing temperature during the cooling process. It is therefore a concern that a transient interference condition may develop. This phenomenon has the potential to fracture lenses. The cooling rate of the cryostat is known so the temperature lag of the lenses can be calculated assuming that they cool by radiation alone. The clearances between lenses and housings have been determined from these temperatures using thermal strain relationships. From this, it appears that the CaF_2 first camera lens is the most adversely affected. It suffers a maximum compression relative to diameter of -20×10^{-5}. Increasing the lens clearance by 20 μm eliminates this compression.

5. SPECTROGRAPH DETECTOR SYSTEM

The NIFS spectrograph uses a 2048×2048 pixel Rockwell HAWAII-2 HgCdTe/PACE detector with 18 μm pixels. The detector temperature is controlled to ±1 mK to eliminate bias drifts. The detector is mounted in a Yamaichi NP89-44111-G4 Zero Insertion Force (ZIF) socket that is soldered to a flexi-rigid printed circuit board. The central 223 pins of the ZIF socket pass through the detector mounting board and are soldered to a 150 g copper block. This copper block is temperature controlled to the required 65 K ±1 mK using a Cernox CX-1080-LR-20L temperature sensor, a Vishay RTO series heater resistor, and a Lake Shore Model 340 temperature controller. The mass of the copper block has been chosen such that the expected 2 mW power dissipation of the detector over the 10 s read out burst does not increase the temperature of the block by more than 1 mK. The detector mounting board is mounted via a rotation adjustment ring and fiberglass standoffs to the inside of the detector housing (Figure 7). The flexible parts of the detector mounting board route signals to micro-D subminature connectors that are mounted on the back of the detector housing. A 0.6 mm thick aluminum cold strap connects the detector copper block thermally to the detector housing. Silpad and fiberglass washers are used at the detector housing end to electrically isolate the copper block. The detector housing is mounted via mechanically rigid but thermally and electrically insulating fiberglass strips to the detector support structure, which bolts to the 65 K cold work surface plate and the spectrograph cover. The detector housing is attached thermally to the spectrograph detector 20 K tie point through a brass strap that is electrically isolated from the detector housing at the housing end via Silpad strips and fiberglass washers. The detector housing temperature is controlled to ~ 60K ±20 mK. This provides a stable thermal environment with in which the more sensitive detector temperature is controlled. Two polymide flex circuits conduct signals from the detector housing micro-D subminature connectors via thermal shunts to Ceramaseal 25 pin feedthrough hermetic subminature D connectors on the cryostat vacuum jacket. One flex circuit carries the detector outputs and biases and the other carries clocks.

Low dark current operation with stable bias is essential in a spectroscopic application. The on-chip output amplifiers are disabled and the detector internal signal bus is fed to four JFET output amplifiers mounted on the thermally stabilized copper block. The reference channels of each quadrant of the HAWAII-2 detector are accessed through four separate matched JFET output amplifiers also mounted on the copper block. The amplifiers use Siliconix J270 *p*-channel JFETs in a source follower configuration as proposed by Klaus Hodapp. The reference outputs are enabled after each row is read out, i.e., on the 1025th horizontal clock cycle. These reference outputs are sampled 32 times.

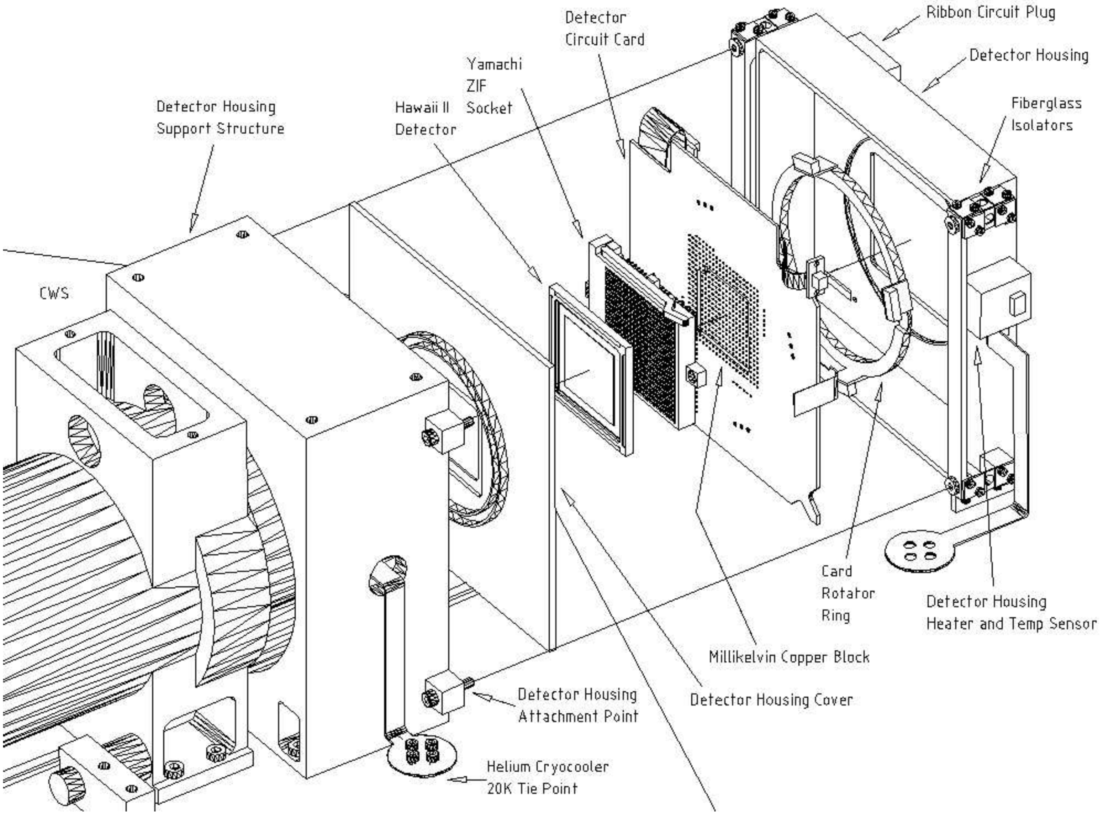

Figure 7: Exploded view of the detector housing showing the detector and associated components.

A SDSU-2 detector controller drives the spectrograph detector. The SDSU-2 is configured with a Quad Channel Coadder IR Video Board, an IR Clock Driver Board, a Fiber Optic Timing Board, and a custom Video Switch Board. The Quad Channel Coadder IR Video Board is configured for a full gain of ×24 provided by the first (×2) and second (×12) stages of the video chain. The inputs to the video chain are configured as differential amplifiers. The detector signals are fed into the inverting inputs and offset signals are fed into the non-inverting inputs. The IR Clock Driver Board is a standard SDSU-2 board providing 24 clock drivers, except that the clock drivers (normally Analog Devices AD829) for the horizontal register clocks CLK1, CLK2, CLKB1, and CLKB2 have been replaced with faster rise-time devices (Analog Devices AD811). The Fiber Optic Timing Board provides the timing sequencer and the communication hub. The Video Switch Board plugs into the SDSU-2 controller housing and uses two Analog Devices ADG713 quad analog switch integrated circuits to allow the analog inputs to the Quad Channel Coadder IR Video Board to be switched between signal and reference channels to monitor signal drift. The 10 kΩ source resistors of the detector external output amplifiers are located on this board before the analog switches. If fast subtraction of different signal and reference channel offsets is needed, one of the clocks can be routed through this board and fed to the non-inverting inputs of the differential amplifiers in the video chain. This clock will be switched at the same time as the signal inputs. The low voltage level of the clock is set to the signal offset and the high voltage level is set to the reference offset. The controller interfaces through a VME interface board to the Gemini standard Detector Controller (DC) Input-Output Controller (IOC), which in turn transmit data to the Gemini Data Handling System (DHS). The detector is read out through four amplifiers using a single correlated double sample in 10 s. Fowler sampling[6] or linear fitting[7] read out methods can be used to reduce read noise. The SDSU-2 controller is temperature stabilized by water-cooling using a custom water jacket. The fan unit has been moved further from the SDSU-2 housing to reduce pickup.

6. CONTROL SOFTWARE

Major savings in cost and schedule have been realized by requiring that all new mechanisms in the NIFS spectrograph interface to the instrument control hardware in a similar way to the original NIRI mechanisms. This has meant that it has been possible to duplicate the NIRI instrument control system with only minor modifications. All the NIFS mechanisms use Phytron stepper motors and the Hall effect sensor encoding philosophy developed for NIRI, and the NIFS temperature control system is largely a duplicate of the NIRI system. This has meant that the NIRI Instrument Sequencer, Components Controller, and engineering interface software have re-used with minimal modification. These modifications have mainly been due to the addition of the Lake Shore Model 340 detector temperature controller and the need to single-step the grating turret and the focal plane mask wheel to random positions.

The spectrograph Detector Controller (DC) IOC software is unique to NIFS because no other Gemini near-infrared instrument has used an SDSU-2 controller. Development of this software has been fast-tracked by implemented a thin EPICS layer on largely C code developed for the SDSU-2 controller by RSAA in its CICADA environment. The DC architecture uses *Control* tasks written as EPICS SNL code to interface to Gemini systems using EPICS channel access. Progress is monitored through the use of an interrupt service routine (ISR) that is executed in response to an interrupt generated by the SDSU-2 VME Interface Board. A *Data* task transfers image data to the Gemini DHS for storage and quick look display. The EPICS layer simply passes parameters and commands, gets back status, and does nothing else. Operational parameters are moved to a lower level shared memory area after they are modified. This is done using CAD SNAM subroutines. This shared memory area is then accessed by the lower level tasks during operation of the NIFS detector.

The DC is implemented using a Synergy SVGM5 single processor VME card using a 400 MHz MPPC7400 with Altivec extensions and 512 Mb of memory. The Altivec extensions are no used currently, but offer potential processing speed gains.

7. STATUS

NIFS was proposed in August 1999 and completed its Conceptual Design Review in March 2000 and its Critical Design Review in April 2001. The spectrograph and OIWFS mechanisms successfully underwent their first cool down and test in June 2002. Completion of the optics is expected by mid August 2002. The first full cool down with the optics and the engineering detector is scheduled for October 2002. Delivery of the science grade detector is expected in September 2002. If all goes well, NIFS will be commissioned on Gemini North in mid-2003 and will be available to the Gemini community with the ALTAIR natural guide star system in late 2003.

8. CONCLUSIONS

Adaptive optics systems on ground-based 8 m class telescopes have clearly demonstrated the potential of this technique. Most AO instruments to date have been imaging systems. However, scientific returns are multiplied many-fold by access to spectroscopic data. The light gather power of an 8 m telescope is essential to perform high spatial resolution observations at even moderate spectral resolution, and an IFU is needed to efficiently sample complex spatial structures. Within current limitations on the availability of suitable guide stars, NIFS promises to realize the potential for high spatial resolution imaging spectroscopy at near-infrared wavelengths on an 8 m telescope.

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