

Engineering performance of IRIS2 infrared imaging camera and spectrograph

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ABSTRACT

IRIS2, the infrared imager and spectrograph for the Cassegrain focus of the Anglo Australian Telescope, has been in service since October 2001.

IRIS2 incorporated many novel features, including multiple cryogenic multislit masks, a dual chambered vacuum vessel (the smaller chamber used to reduce thermal cycle time required to change sets of multislit masks), encoded cryogenic wheel drives with controlled backlash, a deflection compensating structure, and use of teflon impregnated hard anodizing for gear lubrication at low temperatures. Other noteworthy features were: swaged foil thermal link terminations, the pupil imager, the detector focus mechanism, phased getter cycling to prevent detector contamination, and a flow-through LN₂ precooling system. The instrument control electronics was designed to allow accurate positioning of the internal mechanisms with minimal generation of heat. The detector controller was based on the AAO2 CCD controller, adapted for use on the HAWAII1 detector (1024 x 1024 pixels) and is achieving low noise and high performance.

We describe features of the instrument design, the problems encountered and the development work required to bring them into operation, and their performance in service.

Keywords: vacuum cryogenic mechanisms, balanced structural deflections, infrared detector, dewing, multislit, mask

1. INTRODUCTION

The IRIS2 instrument is a near infrared ($\lambda = 0.9$ to $2.5 \mu\text{m}$) imager and spectrograph for use on the Anglo Australian Telescope (AAT). Primarily it is used at the Cassegrain focus as shown in Figure 1, with the telescope in the F/8 wide field configuration (8 x 8 arcminutes). It may also be used in the F/15 and F/36 Cassegrain configurations providing different image scales and field sizes. At F8 it has both single 1arcseconds slits (one of these is offset relative to the other in order to provide better centering of the J- and H-band spectra), and multislit spectrograph capability offering multiple 1arcseconds slits on specially produced masks.

The instrument utilises a structure based on a matched pair of trusses, rather than the more usual optical bench (see Section 2 for more detail). One truss is located in the fore vessel and the other in the main. The main structural plate, which serves as the common structural reference also acts as the wall between the two vacuum vessels.

The dual vacuum vessel design comprises a fore vessel, enclosing the slit wheel, and the main vessel enclosing all the other components. Adopting this approach it is possible to open only the much smaller fore vessel while exchanging multislit masks, to avoid thermally cycling the detector and to reduce the turn around time between observations.

The optical design, which is described in Gillingham and Jones¹, is a straight-through all refractive configuration containing, in order, slit (or open aperture in imaging configuration), field lens, collimator assembly, filter (spectroscopic order sorting or imaging band pass), cold stop, grism (not used for imaging), camera assembly (including

field flattener), and detector. Further detail on the mechanical design and layout of IRIS2 can be found in Smith and Churilov².

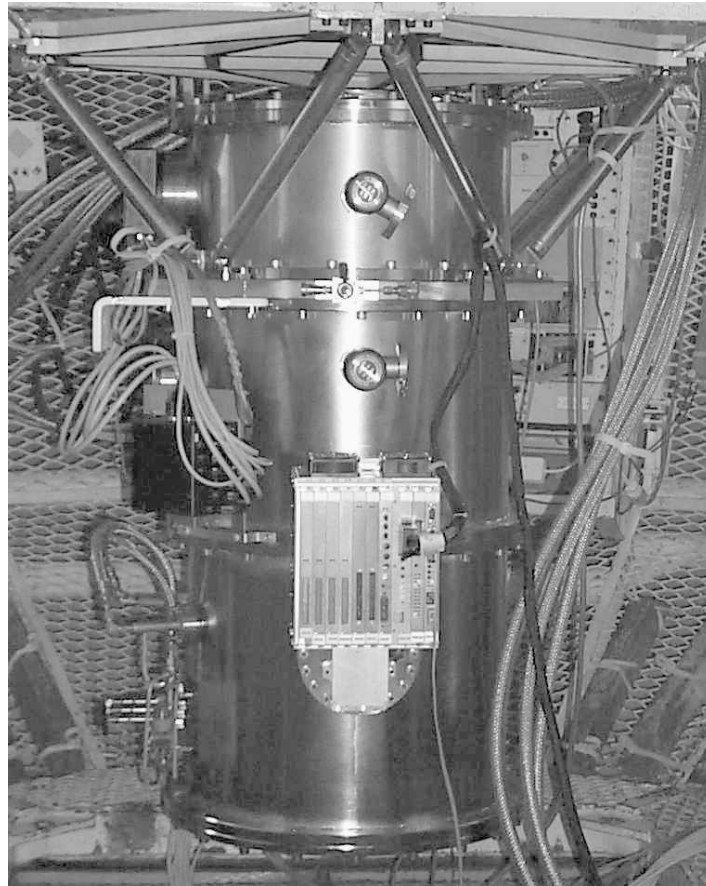


Figure 1 IRIS2 mounted at the Cassegrain focus of the AAT

The instrument optical specification is summarised (for the F/8 configuration) in Table 1. The overall arrangement is shown in Figure 2.

Telescope aperture	3.9 m
Telescope focal scale	6.7 arcseconds/mm
Slit length	69 mm (long slit)
Collimator speed	F/8
Cold stop diameter	50 mm
Camera speed	F/2.2
Detector	HgCdTe Rockwell Hawaii 1024 × 1024
Pixel size	18.5 μm × 18.5 μm
Detector scale	0.45 arcseconds/pixel

Table 1 IRIS2 optical specification F/8 configuration

2. STRUCTURAL DESIGN

2.1. Internal Structure

Consideration of the potential misalignment caused by structural deflections led us to a scheme for the internal structure where the plate (known as the main structural plate or MSP) between the main and fore vessels was the common foundation for a pair of hexapod trusses (Stewart platforms). The truss within the main vessel carries the wheels housing, to which the collimator and camera assemblies and the detector are attached. This wheels housing contains the filter, cold stop and grism wheels. The truss in the fore vessel carries the slit wheel housing.

The internal structure can be seen in the cut away view Figure 2. The lengths and angles of the truss members are determined by the locations of the wheel housings relative to the main structural plate. However, inspired by Serrurier, the cross sections of these truss members have been proportioned so the transverse deflections of the fore and main vessel wheel housings are identical and there will be no relative motion, and thus minimal drift of the slit image on the detector. The housings also remain parallel to one another and to the main structural plate. To ensure zero backlash in the structure the legs are pinned at each end to the feet. The pins were cooled in LN₂ before fitting to achieve interference fits in both the legs and the feet. As the legs, feet and pins are of the same material, the interference fit is maintained throughout the full temperature range, from room to operational (~300K to 100K).

The success of this design has been ratified by deflection tests carried out during commissioning where the flexure of components in the slit wheel have been examined with respect to the detector. A matrix mask, comprised of a grid of 75µm holes (equivalent to 0.5arcseconds images on the AAT, or 1.114 pixels) on a 3mm pitch, was placed in the slit wheel. This showed that the slit wheel moved relative to the detector by approximately by 0.5 pixels (~9µm) when the telescope is moved from Zenith to 60° in an East-West (E-W) direction. No perceptible flexure can be seen when the telescope is slewed in the North-South (N-S) direction. As the internal truss structure is symmetrical in the two directions (E-W & N-S) it is believed that the relative movements are not due to the structure. The relative movements are thought to come via the slit wheel positioning system and or detector mounting itself (see further comments in Section 3).

2.2. External Structure

An eight legged truss (octopod) structure joins the mounting points of the Cassegrain rotator and four locations at the periphery of the main structural plate (the structure is clearly visible top of Figure 1). In most other respects this external truss is similar to the main vessel internal truss. A spreader plate is fitted between the legs at the telescope interface end to prevent splaying of the feet. Although not quantified it is believed that this structure is very stiff and no noticeable deflections are attributable to it when compared with those being imposed by other parts of the system.

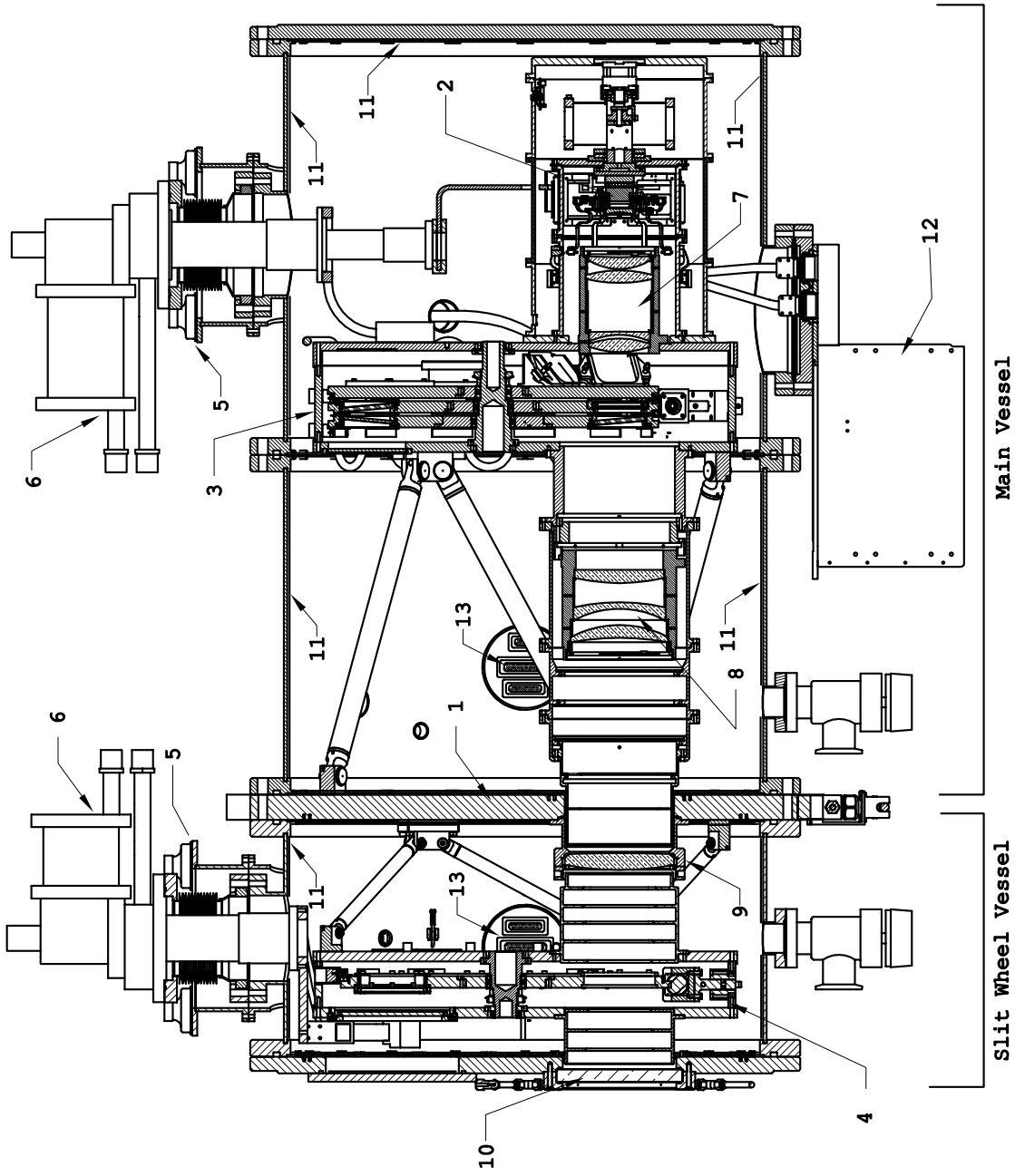
At commissioning shims were placed between the feet of the external structure and the Cassegrain rotator. These shims were determined using the pupil imager optics that are housed in the grism wheel for this purpose. The pupil imager allows the alignment of the pupil image with the cold stop to be observed and hence verify alignment of the instrument relative to the telescope. The alignment has proved to be highly repeatable with the shims determined on the first commissioning night have been in use since that time.

3. MECHANISMS

IRIS2 contains wheel mechanisms and a detector translator, all of which are designed to operate at operational (~100K) and room temperatures (to facilitate testing and commissioning). To minimise the number of mechanical penetrations of the vessel walls, and to locate the motors close to the mechanisms they drive, they were placed within the vessel and operated at low temperature. The stepper motors used (AML 17.1) although supplied with a cryogenic and vacuum rating had to be modified to operate at low temperature by replacing the bearings with MoS₂ lubricated ball bearings and replacing the aluminium end-caps, which contained the bearings, with martensitic stainless steel, to more closely match the thermal contraction of the bearings.

The slit wheel, filter wheel, cold stop wheel, and the grism wheel are driven by identical worm drive mechanisms. On the rim of each wheel is cut a 168 tooth helical gear, which meshes with a two thread worm directly driven by the

Figure 2 IRIS2 General Arrangement



- 1. Main structural plate
- 2. Detector assembly
- 3. Wheels assembly (filter, cold stop and grism wheel)
- 4. Slit wheel assembly
- 5. Anti-vibration mount
- 6. Cryocooler
- 7. Camera assembly
- 8. Collimator assembly
- 9. Field lens assembly
- 10. Window
- 11. Multi-layer insulation MLI (on inside of vessel wall)
- 12. Detector controller box
- 13. Through-wall electrical connectors

motor. The mesh clearance is varied by pivoting the worm and motor assembly about an axis parallel to the wheel axis. The worm is pivoted to cope with the effects of differential expansion during all facets of operation i.e. room temperature maintenance, during cooling or at operational temperature. The pivot mechanism is assembled using flexure leaves to obtain a virtual pivot and eliminate any errors from bearing clearances. The rotation of each wheel is encoded. Commercial infrared gap sensors read position encoding flags around the perimeter of each wheel, together with a reference flag on the worm shaft. These sensors are operated at 100K. The wheel mechanism and encoding system is described in detail in Churilov et al³. The worm drive assemblies are shown in Figure 3. Each wheel is carried by a pair of bearings mounted in a hub of martensitic stainless steel that matches the thermal expansion of the bearings. The wheel shafts are also of stainless steel. The aluminum gear wheel has clearance on the hub at room temperature and shrinks to an interference fit at the operating temperature.

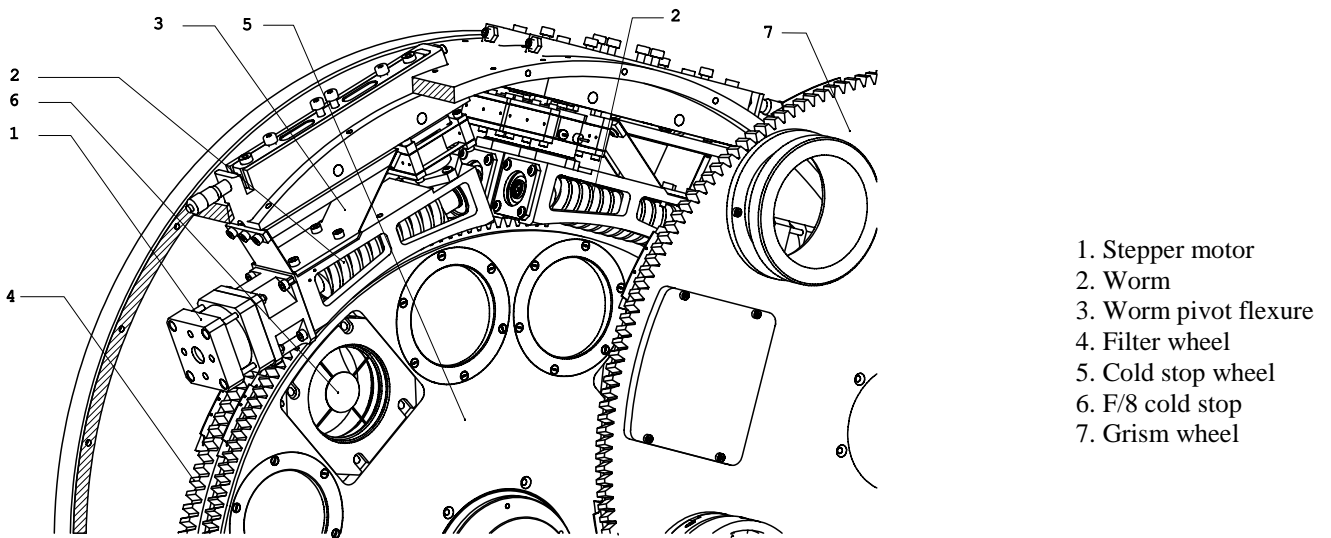


Figure 3 Worms and wheels - main vessel housing shown sectioned

To trim focus of the instrument a detector translator is provided (see Figure 4), which compensates for drifts due to thermal effects and small errors in manufacture or assembly. This mechanism, implemented using flexures, translates the detector assembly $\pm 0.4\text{mm}$ along the optical axis from the nominal focus position. A Teflon coated screw mounted on the shaft of the stepper motor directly drives the motion. No encoding is required, limit switches are implemented using infrared gap sensors and a rotation stop limits travel. The assembly is biased to one side of the flexures neutral point to load the screw and nut to eliminate backlash.

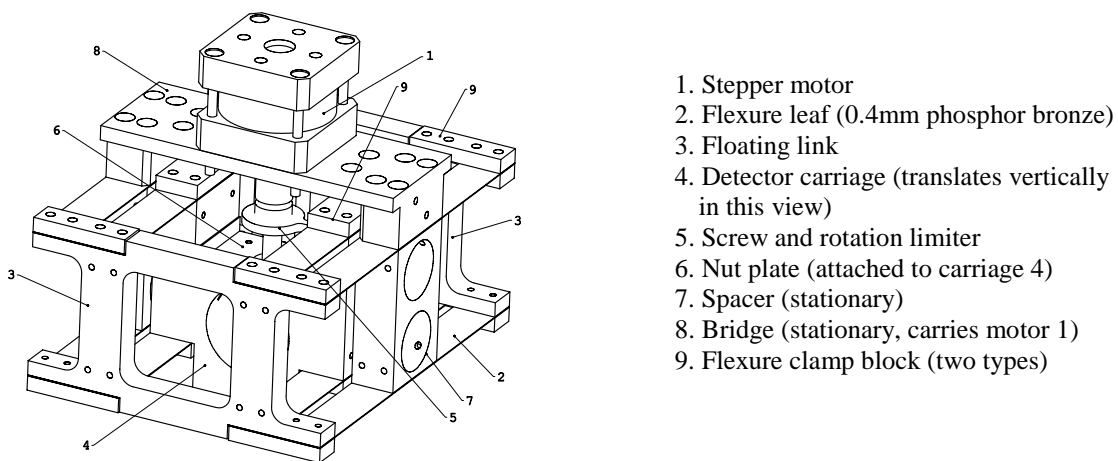


Figure 4 Detector focus translator

All mechanisms have proven extremely reliable in service with no instrument downtimes being attributable to the drive mechanisms. In service the wheels do very occasionally fail to position correctly, this is detected when the stepper motor encoder reaches its reference position but the encoding flag on the perimeter of the wheel does not confirm that the position has been obtained. In this case the software automatically implements a routine to reestablish its reference position and then sends the wheel back to the required position in a process almost invisible to the user.

The repeatability of the wheel repositioning, as proven with tests on the slit wheel, has been demonstrated to be within 0.1 arcseconds (7 μ m) of the previous position. This repositioning repeatability is not obtained if the wheel is repositioned from a different direction. However, normal observing sequences always return the wheel to the required position in one direction only.

Focus sequences performed with the matrix mask (described in Section 2.1) in the slit wheel at a variety of telescope orientations indicate that best camera focus seems to decrease by ~35 motor micro-steps when the telescope is moved off the vertical (in any direction) by a Zenith Distance (ZD) of 41°. That is best camera focus decreases by (0.834 micro-steps / degree ZD). 35 micro-steps are equivalent to a translation along the optical axis of 22 μ m of the detector. The factors affecting this movement have not been studied in detail, as examination of the sensitivity of camera focus, using the matrix mask, have determined that errors in camera focus of less than 50 micro-steps have no noticeable effect on image quality, while errors of 75 micro-steps have only a marginal effect in all but the very best seeing conditions. Thus the impact of loss of focus related to movement/flexure of the instrument during observing is very small, and can be neglected.

The camera focus has been determined to be very stable and repeatable and only needs to be rechecked if the camera has been removed during a maintenance operation. This has had to be done on a few occasions to install filters that were not available at the time of commissioning. A base focus value is then obtained for the various filter and spectrographic configurations and is applied automatically by the software and remains unchanged unless camera removal is required.

In section 2.1 the movement of the slit image on the detector (0.5 pixels) when the telescope is moved Zenith Distances of 60° is briefly discussed. It is felt that some of the source for these movements may come via the drive mechanisms although this has not been proven. The slit movements may be attributable to slippage between the slit wheel gear and its worm (ref. Figure 3), this being sensitive to the gravity vector; and also the detector translator (ref. Figure 4) that has a different stiffness in the spatial and spectral directions. This deflection, although small, is managed by the observers who first image the slit after slewing to each new field. Together with the slit wheel positioning repeatability discussed above, this ensures that the target can be precisely centered on the actual slit at any zenith distance.

4. THERMAL

Refrigeration for the two vessels is provided by Gifford-McMahon cryocoolers, mounted on vibration isolators designed for 10:1 attenuation at the excitation frequency. A CTI 1050CP two-stage helium cryorefrigerator cools the contents of the main vessel. The detector and a getter (cryo-absorber) are cooled by the second stage, and the first stage cools the wheels housings and optical assemblies and another getter. The contents of the fore vessel are cooled by a CTI 350CP single stage helium cryorefrigerator. Flexible, layered aluminium foil 'cold straps' swaged into solid aluminium end blocks⁴ couple both cold heads to their thermal loads. Indium foil interleaves were used to ensure reliable thermal contact at bolted joints.

The external walls of the vacuum vessel, including the front, rear and main structural plate (MSP) are not cooled. The internal surfaces are covered with multi-layer insulation to minimise the radiation load. However, as the wheel assemblies are connected to the MSP via the truss legs there is some parasitic cooling of this plate, although it is limited via the use of 304 stainless steel for the legs and connecting feet, as it has a relatively low conductivity as well as adequate structural stiffness.

To reduce the cool down time for the contents of the main vessel (particularly desirable during the testing and commissioning period, and after maintenance), a flow-through liquid nitrogen (LN2) precooling system was devised. A copper tube heat exchanger was fabricated around the wheel housing, coupled to flexible bellows style stainless steel

tubes leading from the feedthroughs in the shell wall. After the cool down phase the system is evacuated to prevent ice formation in the tubes. This system has also proved useful in maintenance where warm gas has been put through the system in order to speed up the warming process.

In service two problems arose the first of which was dewing of the front window (ref. Item 10. Figure 2). To minimise stray light, and self-radiation from the vessel, the optical path throughout the instrument is surrounded by housings or baffles, which are a cooled (with the exception of the Field Lens Holder Item 9. Figure 2, which is attached to the MSP). The baffle ahead of the slit wheel housing is positioned very close to the front window and radiative cooling has been sufficient to lower the temperature of this window to below the local dew point at the telescope. This problem was not encountered during pre delivery testing as dew point temperatures were never encountered at the AAO laboratories in Sydney. The problem was resolved by placing a further enclosure ahead of the window; the enclosure is fed with dry air to ensure that no moist air is in contact with the window of the fore vessel. The enclosure is fitted with a further window situated 29mm ahead of the fore vessel window. This window as well as being protected by the dry air being fed into the enclosure still requires dry air to be fed across it's front surface to ensure no dewing occurs. The distance between these two windows was limited by the space available between the instrument and the Cassegrain rotator. The additional throughput losses imposed by this window are thought to be in the order of 5% and were accepted in the interests of improving the instrument availability.

As mentioned above the field lens holder assembly forms part of the MSP and is not directly cooled. To try to counter the effects of radiation from the field lens holder (Item 9 Figure 2) the front baffle of the collimator (Item 8 Figure 2) protrudes through the MSP to the field lens. Also the baffle on the back of the slit housing (Item 4 Figure 2) terminates as close as possible to this lens. No problems were encountered with this configuration using the instrument in imaging mode. However, in the spectrographic mode radiation emitted by the field lens holder was found to reflect off the slit holder and hence enter the optical train to the detector. This significantly increased the spectrographic background in the K Band. To counter this effect an additional baffle was placed on the very tip of the slit baffle as close as possible to the lens, and cooling straps were run from the slit wheel housing to the field lens holder (see Figure 5). These straps were made from copper braid soldered into copper end blocks. The straps differ from those described earlier, but were chosen, as they were quick to manufacture and offer more flexibility for fitting in the confined space.

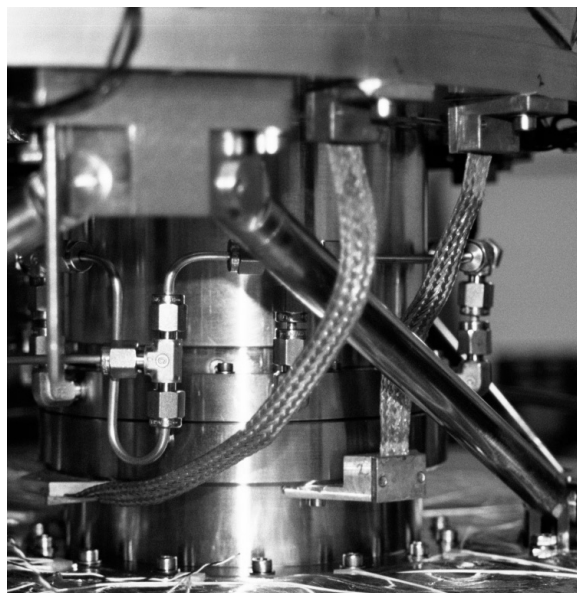


Figure 5 Field Lens Holder with cooling straps

These straps took the temperature of the field lens holder to 239K; this reduced the background radiation in the K band by a factor of two, with the downside that the fore vessel takes slightly longer to cool after a mask change due to the additional thermal load.

The multislit masks, which are unique for each observed field, are laser cut from 100 μ m thick sheet brass, as aluminum sheet of this thickness was far too flimsy. However, they are still prone to out-of-plane buckling, so that support frames with similar thermal expansion characteristics were essential. The mask housing was designed with integral mounting flexures, which compensate for the aluminium slit wheel's differing shrinkage.

The detector operates at 66K and is controlled by over cooling and then using a strain gauge heater to maintain the stabilized temperature. The performance of the detector (see Section 7) has been excellent and so by inference the cooling system has been deemed successful. The main vessel wheels and housing, collimator and camera, and various baffles operate between 75K and 100K. The slit wheel and its housing operates at around 110K and can be controlled via a similar heating system as employed on the detector.

5. VACUUM

To prevent contamination of the signal from the IR radiation generated by the instrument itself, the instrument is cooled, which necessitates enclosing it within a vacuum vessel. In fact a dual or split vessel was used, enclosing the slit wheel in one chamber and the rest of the instrument in the other. This was done to allow replacing multislit masks on the slit wheel without the need to go through the slow process of warming, then pumping and re-cooling the entire instrument. In this way the detector is subjected to a minimum number of temperature cycles. The general construction is two cylindrical shells with a flat plate (the main structural plate, or MSP) separating the chambers and flat plates at each end. Flat plates, rather than domed ends, were utilised because of the space constraints within the telescope's Cassegrain focus cage.

The MSP carries the field lens of the collimator, which acts as the window between the vessels, and may be subject to pressure differentials when the fore vessel is opened while the main vessel remains evacuated. The field lens holder assembly is not designed to operate with the main vessel open to atmosphere and the fore vessel evacuated. For this reason a vacuum safety system was incorporated between the two vessels to vent the main vessel into the fore vessel if the fore vessel were pumped prior to evacuating the main vessel. The fore vessel also has an over pressure valve that opens to atmosphere, so if an over pressure situation occurred (liquid nitrogen pre cooling leak) in either of the two vessels it would be vented to atmosphere.

For long-term maintenance of vacuum the vessels are furnished with charcoal getters. Charcoal was chosen over zeolite for its lower regeneration temperature, to prevent damage to the cryorefrigerator heads. To prevent leakage of powder into the vessels, porous sintered bronze screens contain the charcoal. Sintered bronze also shields the charcoal from radiation. Printed circuit style heaters (Minco foil heaters) mounted on the getter's outer surfaces are used for regeneration (boil off absorbed gasses).

Two getters are used in the main vessel to allow for the temperature profiles developed during the cool down period. To prevent condensation of contaminants on the detector, it is essential that a getter is colder than it at all times. This has been accomplished by directly cooling one getter from the LN₂ pre cooling system, and one from the second stage of the cryorefrigerator. During the cool down phase the housing is 'precooled' by the flow of LN₂, at which time the getter mounted on the housing is colder than the detector. As cooling progresses, eventually the second stage of the cryorefrigerator becomes even colder and the getter mounted on it becomes the coldest point within the vessel, and dominates the cryopumping. At all times one of the getters is colder than the detector. A getter is also mounted on the slit wheel housing in the fore vessel.

All materials used within the vessels were chosen for their low outgassing properties. The overall design has proven highly successful with hold times (pressure below 10⁻⁶ torr) between main vessel pump-downs of greater than 6 months.

6. IMAGE QUALITY

The matrix mask (described in Section 2.1) installed in the slit wheel was used to test the intrinsic image quality of the IRIS2 optical train. Although manufacturing tolerances meant that there is some variation in the diameters of these mask holes, the mask permits precise evaluation of IRIS2's image quality as a function of camera focus across the whole

field. While there is some curvature of the IRIS2 focal plane at the detector, this is sufficiently small that a best focus can be achieved delivering images of <1.2 pixels Full Width Half Maximum (FWHM) over the whole field. Given the mask itself delivers 1-1.1 pixel (FWHM) images, the image quality of the IRIS2 optical train is clearly excellent - better than 0.3 arcseconds over the whole field.

7. DETECTOR PERFORMANCE

The IRIS2 HAWAII1 detector is read out by the “AAO2 Optical Detector Controller (ODC)” – a system developed in-house at the AAO and implemented both with IRIS2 (with a dedicated infrared video board) and with the AAO’s optical CCDs (with an optical video board). When in use with IRIS2, the AAO2 ODC is configured for use in two read modes.

Double Read Mode (DRM): The array is reset; a read is done, followed by a second read at the end of the exposure. The image delivered is the difference between the two reads. There is an overhead of one array read time per exposure. This is the mode used for all imaging applications. (Also known as Double Correlated Sampling)

Multiple Read Mode (MRM): The array is reset and then non-destructively read repeatedly throughout the specified exposure time. The image delivered is a least-squares fit through the non-destructive reads. There is an overhead of one array read per exposure (usually a tiny fraction of the total exposure length) and several seconds to complete the least-squares fit. This is the mode used for all spectroscopic applications. (Also known as 'Up-the-Ramp' sampling).

The performance on each of the Normal operating modes is given in Table 2

Mode	Read Time (s)	Gain (e/adu)	Read Noise/NDR (e)	Typical Read Noise (e)	Full Well (ke-)	Linearity (at Full Well)
DRM	0.5982	5.3	10.0	14.1 (for DRM)	180	~1%
MRM	0.7866	4.3	8.6	4.8 (for 61reads)	75	~0.3%

Table 2 IRIS2 Detector Performance in Normal Modes of Operation

Measured dark current performance is typically 0.1 to 0.2 e- per second. Finally, the cosmetic quality of the array as delivered by the AAO2 ODC is excellent. In both DRM and MRM modes, there are no significant structures in the images IRIS2 produces (apart from two defect regions in the array, and the usual read-out register glow at the array edges). These combined parameters give IRIS2 one of the best read-noise/dark current performance currently available for observing in low-background applications – like R=2400 spectroscopy.

8. CONCLUSION

IRIS2 has now been observing for just over two years. The structural concept, and wheel driving and detector translation mechanisms have been proven on the telescope. Installation on the telescope has been straight forward, and the pupil imager has been shown to be useful and easy to use to verify alignment. Spectra from up to 50 objects have been observed in a single observation using the multislit masks, thus validating the concept the mask design and the manufacturing process. Presently a run is planned where limited object spectra will be studied with the observing team hoping to study upwards of 500 objects using three installed multislit masks.

Post first light only two problems have had to be addressed, a front window dewing problem and a slit reflection problem related to the field lens holder. The instrument is delivering very good performance and has been highly reliable in service.

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