Abstract: We describe a versatile infrared camera/spectrograph, IRIS, designed and constructed at the Anglo-Australian Observatory for use on the Anglo-Australian Telescope. A variety of optical configurations can be selected under remote control to provide several direct image scales and a few low-resolution spectroscopic formats. Two cross-dispersed transmission echelles are of novel design, as is the use of a modified Bowen-Burch system to provide a fast f/ratio in the widest-field option. The drive electronics includes a choice of readout schemes for versatility, and continuous display when the array is not taking data, to facilitate field acquisition and focusing. The linearity of the detector has been studied in detail. Although outwardly good, slight nonlinearities prevent removal of fixed-pattern noise from the data without application of a cubic linearising function. Specific control and data-reduction software has been written. We describe also a scanning mode developed for spectroscopic imaging.

1. Introduction

Astronomically useful infrared arrays have been available for several years, and are growing in both variety and quality. Using this new technology we have developed an infrared camera/spectrograph, IRIS, for the 3.9 metre Anglo-Australian Telescope (AAT). A brief description of the mechanics and optics of IRIS was given by Gillingham and Lankshear (1990); the optics were described more fully by Gillingham (1993); and the control electronics were summarised by Barton, Allen and Gillingham (1992). Preliminary scientific results were presented by Allen et al. (1992). Here we provide a more detailed description of the entire instrument.

2. Detector

As detector for IRIS we chose a HgCdTe NICMOS2 array manufactured by the Rockwell Science Center, California. The format is 128 x 128 pixels each 60 μm square. A long-wavelength cutoff of 2.5 μm is generated by a suitable alloy ratio between the mercury and cadmium, as discussed by Rode et al. (1987). The NICMOS2 device is described by Blessinger et al. (1989).

Technology transfer restrictions delayed acquisition of the array, which was the first of its kind to be imported into Australia. We acknowledge the outstanding support by His Excellency L. W. Lane, then U. S. Ambassador to Australia, and his staff to expedite the importation.

HgCdTe detectors similar to that in IRIS have been in use at several institutions over the past few years, and experience with another detector material, InSb, dates from even earlier (e.g. McLean, 1987). A detailed description of a camera using the same detector material as IRIS has been given by Persson et al. (1992; hereinafter PWCSM), while Hodapp, Rayner and Irwin (1992; hereinafter HRI) describe a camera that uses a NICMOS3 detector of format 256 x 256. In this description we do not describe aspects of the instrument or its performance that are adequately described by PWCSM or HRI, unless they merit emphasis or we find important differences.

3. Detector Control

For compatibility with other AAO equipment we drive the detector with standard AAO CCD controllers which have been modified in hardware and firmware, and we use modified controller software which we describe in section 5. The controller modifications included generation of the IRIS clocks, implementation of the sequencing circuits and signal processing facilities to operate the array in several readout modes, and incorporation of an IDLE mode of operation.

In IDLE mode the array repeatedly integrates and reads out. The data are displayed in real time, but not retained. We have found this attribute extremely valuable for image acquisition, focusing, etc.

We also retained in the controllers the ability to window onto small parts of the array. The resulting faster readout allows brighter scenes to be observed without saturation. Windowing finds its major application when observing photometric standard stars. We use a 31 x 31 window in a particularly clean part of the array, and thereby gain a factor of seven in readout time, or more than two magnitudes on the bright limit. Even so, on the AAT the bright limit is fainter than magnitude 7 in the broad-band filters. A set of 8th magnitude photometric standards has been established in collaboration with the South African Astronomical Observatory (Carter and Meadows, in preparation).

(a) Readout schemes

Three readout modes are used in the IRIS signal processing. They are described and fully illustrated in Barton et al. (1992).

The simplest is a “double correlated sampling” option, which we call mode 1, where the output provides at the end of each integration the difference between the signal amplitude and the subsequent reset level of each pixel. This procedure does not eliminate the thermal (kT) noise present on the detector node after it has been reset; the readout noise is...
about 130 $e^{-}$. However, mode 1 is efficient since the detector is continually collecting photons and is quickly reset at the end of each exposure cycle. We have found this to be the preferred mode for broad-band photometry, since photon shot noise from the sky exceeds the readout noise after only a few seconds.

Figure 1 displays the output waveform from a single pixel of the array during the reset-read cycle used in mode 1 observing, and shows the data level (lower right end of integration ramp) and reset level. Note the pedestal when the reset is unclamped, so that the integration ramp starts from a different level. We find the pedestal to be highly structured across the array, as Figure 2 shows, but to remain stable provided that the detector temperature does not vary. Because the pedestal opposes the signal, it would produce a negative output at low light levels. Consequently we add an electronic offset, identical for all pixels, to the double-correlated sample before it is digitised. The sum of the two is normally referred to as the bias, and its image as a bias frame. Here to avoid confusion with voltage biases applied to the detector we use only the term bias frame. It is secured by a dark exposure of minimum duration.

The second readout type is a “double double correlated sampling” option, called mode 2, identical to the triple correlated sampling discussed by Blessinger et al. 1989). The signal processor produces two differences, both of which contain the $kTC$ noise. The first is formed and saved in memory at the start of each integration and comprises a measure of the difference between the signal amplitude at the start of the exposure and the reset level. The second difference is generated at the end of the exposure in the same way as for the mode 1 sample. The two difference samples are subtracted to yield the signal amplitude with the $kTC$ noise eliminated; the electronic offset is removed in the same operation. The resultant readout noise is about 80 $e^{-}$.

The efficiency of mode 2 sampling is lowered by the need for two complete array readouts per exposure. Photocharge accumulated by each detector element between the readout at the end of an exposure and the readout at the start of the next integration is lost during the second readout. This is a direct result of using an unmodified CCD-based double-correlated sampling system for signal processing.

In mode 2 the pedestal component would be expected to subtract off, to leave only signal. We find, however, that a small, negative pedestal remains. Presumably there is a leakage of charge following the reset at the start of the inte-

![Figure 1](https://www.cambridge.org/core/core/10a40.11, on 15 Mar 2019 at 00:29:17, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1323358000025911)
optimise other performance parameters. The regression eliminates the kTC noise components. We have shown that the resulting noise of complete exposures up to 1000 s reduces with the square root of the number of samples as predicted by Chapman et al. (1990); this confirms that our system has the required stability.

Further advantages of this readout scheme include an updating display while the exposure proceeds, and accommodation of sources which saturate before the end of the exposure. In this regard it is superior to yet another scheme described by Fowler and Gatley (1990, 1991) and favoured by both PWCSM and (with reservations) HRI, whereby a burst of NDRs is taken at the start and end, and the gradient determined from the difference of the averages. Both schemes are capable of reducing the readout noise below the shot noise created by dark current.

Mode 4 is well suited to extremely low light levels, but not to the idle display.

While only the linear regression fit is normally output to disk, we can dump all intermediate frames. This facility proved essential when characterising the array, and in particular to explore its linearity. We found an additive decaying component superimposed on the linear response, whose intensity depends on the incident signal. We attribute this component to the same injection that affects the pedestal level in mode 2 sampling. On this account we reject the first NDR from a regression. If this same situation pertains in other detectors it might compromise the PWCSM sampling scheme.

(b) Array optimisation

Adjustable bias supplies, powering the shift registers, row and column buffers, and detector elements, enabled the drive conditions to be varied in a controlled manner to determine the cause of the dark current and to locate the sources of radiated light emissions within the array. These adjustments were used to optimise array operation for minimum dark current and readout noise.

Since not all parameters can be optimised simultaneously, the final configuration must be a compromise driven by the astronomical requirements. The temperature of the chip is an example of this type of optimisation. At 62° K the dark current (which is of concern in spectroscopy) falls to below 0.1 e− s−1 in virtually all pixels. At higher temperatures increasing numbers of pixels appear with higher dark currents. At 82° K some pixels deliver > 10 e− s−1 whereas most still produce < 1 e− s−1. Discrete pixels with high dark current are not reported by HRI or PWCSM, but both groups find the expected rapid increase in dark current with temperature. On the other hand, trapping sites lead to remanence and other effects. The time constant associated with the trapping sites falls dramatically with increasing temperature. Another benefit of the higher temperature is increased uniformity in sensitivity. For cosmetic reasons, therefore, the higher dark current is accepted and the chip is operated at 82° K; HRI adopted a similar value.

(c) Nonlinearities

Leakage current is not the only contributor to the dark current. Radiation is emitted by the serial registers and output amplifier around the chip periphery. In minimising this component we drive the output amplifier with low current and voltage supplies. We suspect that in the higher pixel values fall below the lower figure, if the photon shot noise from the sky is to exceed readout noise in mode 1. Thus a linearity correction is not normally essential to attain photometric accuracy.

We examined the linearity characteristics in some detail, using the intermediate values of NDR samples on exposures driven to the saturation level. In addition to that rollover, we found that the response is well described by a gentle parabola of positive curvature. We are surprised to find that this has the opposite curvature to the nonlinearity found by PWCSM. We find a cubic correction to the observed counts adequate to linearise the data. The quadratic term accounts for the curvature and the cubic term handles the initial rollover of the output amplifier.

The input to the cubic, \( I_o \), is the absolute output from the array and comprises four components—the data, the pedestal, the electronic offset, and a fourth representing the level to which pixels are lowered on reset (Figure 1). This last component has an arbitrary zero level, but additionally shows structure across the array. In effect this is an A.C. component rejected by double-correlated sampling but retained in NDR reads. It is reproduced in Figure 3. Believing this to originate in the multiplexer we refer to it as the silicon swirl. The amplitude of this pattern, from brightest to darkest, is about 60 000 e−.

The form of the linearing cubic \( Z \) is:

\[
I_i = 
-35372 + 1.25 I_o (1 - 4.414 \times 10^{-7} I_o (1 - 7.028 \times 10^{-7} I_o))
\]

where \( I_i \) is the observed intensity and \( I_o \) is the linearised intensity, both in electrons. \( I_o \) ranges from a little above zero to nearly 600 000 e−.

The constant term and factor of 1.25 together take out the initial decay from the preceding reset. From 260 000 to 550 000 e− \( I_i \) never differs from \( I_o \) by more than 0.4%, and in the presence of the various additive components relatively few pixel values fall below the lower figure, if the photon shot noise from the sky is to exceed readout noise in mode 1. Thus a linearity correction is not normally essential to attain photometric accuracy.

However, linearisation must be applied to remove the pedestal stripes and silicon swirl from the data, especially at low light levels. To appreciate this, consider two pixels \( P \) and \( Q \) for which the sum of swirl, pedestal and offset (i.e. the NDR bias frame) have values 10 000 and 210 000 e−.
respectively. These are close to the most extreme delivered by the detector. If 100 000 electrons of signal were registered at each pixel we would expect \( I_s \) to be 110 000 and 310 000 respectively. Solving equation (1) we find the the observed counts to be 122 336 and 299 570 in the two pixels, which after subtraction of the bias and swirl frames would become 112 336 and 89 570 respectively, values differing by 25%. Nor would flat fielding remove this effect (unless the flat field exposure had very closely the same number of counts as the relevant data frame). Suppose a flat field exposure received 200 000 counts, pixels \( P \) and \( Q \) would still differ by 22% after bias and swirl subtraction and flat fielding. This, then, would be the amplitude of the residual pedestal and swirl patterns (Figures 2a and 3) in the absence of linearisation. The figures should be compared to the contrast between objects and sky: it is not uncommon to observe point sources below 0.1% and extended sources considerably below 1% of the sky intensity.

In mode 4, using non-destructive reads, the ADU output to software includes all three components, but in mode 1, using double-correlated samples, the silicon swirl has been rejected. In order to flat field data taken in mode 1 we must add a swirl frame before applying the linearity correction. Failure to do so introduces relic swirl patterns into data whose mean ADU count differs from that of the calibration flat field frame. Mathematically, mode 1 data are flat fielded and bias (+ dark) subtracted by the operation:

\[
\Delta (\text{data} + \text{bias frame} + \text{swirl frame}) - \Delta (\text{bias frame} + \text{swirl frame}).
\]

Similarly mode 2 data are linearised by:

\[
\Delta (\text{data} + \text{bias frame} + \text{swirl frame}) - \Delta (\text{bias frame} + \text{swirl frame}).
\]

However, flat fielding mode 2 data remains unsatisfactory at the few percent level.

4. Optical and Mechanical Aspects

(a) Overview

We sought a versatile instrument, offering several image scales and low-resolution spectroscopic capabilities. We were keen to avoid opening the dewar to change optical configurations (as for instance in the cameras described by HRI and McLean [1987]) and so did not constrain the optics and mechanical components to fit within a commercial cryostat. Instead we constructed a vessel large enough to hold transmission optics without folding the light path, except for the special case of the widest-field configuration described below. Figure 4 shows IRIS mounted at the Cassegrain focus of the AAT. Figure 5 is a schematic diagram of the various components, and Figure 6 shows the optical configurations.

IRIS mounts at the Cassegrain focus and can be used at either f/15 or f/36. Radiation enters at the top. Table 1 details the popular configurations available at each, together with observed image scales and resolutions. A detailed description of the major optical components was given by Gillingham (1993). The narrow field option listed therein has not yet been introduced.

PWCSM lamented the lack of data on refractive indices of potentially useful materials at all wavelengths of interest and at their expected operating temperatures. We trusted that a design adopting readily-available room-temperature refractive indices would result in a system requiring only focus adjustments at operating temperature; this has worked out well in practice. For mechanical simplicity no provision was made for motorised focus adjustment. In the spectroscopic modes this has necessitated some iteration, and additional care in adjusting the optics.

All achromatic doublets are of fused silica and CaF\(_2\); of the combinations modelled this gave the best control of aberrations, though not the least residual chromatism. Because of the difficulty of turning non-spherical surfaces in CaF\(_2\) we retained spherical optics in all cases. The design was undertaken using a ray tracing program originally developed by Roderick Willstrop of Cambridge University. All the small optical parts were figured by Francis Lord Optics in Sydney, and we were able to adjust our design marginally to take advantage of spherical masters available in their optical shop.

For all but the wide-field mode we create a collimated beam which is refocused onto the detector. Within the collimated beam we insert dispersing optics for low-resolution spectroscopy. We resisted the temptation to improve resolution by adding optical surfaces, seeking designs that used the minimum number of elements. Not only is light lost at each surface, but the possibility of ghost reflections is a concern. This was exacerbated by our reticence to cement dou-

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**Table 1. Major optical configurations within IRIS**

<table>
<thead>
<tr>
<th>Telescope f/ratio</th>
<th>Field</th>
<th>Components</th>
<th>Image scale arcsec/pixel</th>
<th>Wavelength coverage (μm)</th>
<th>Spectral resolution λ/Δλ</th>
<th>Slit length arcsec</th>
</tr>
</thead>
<tbody>
<tr>
<td>f/15</td>
<td>Wide</td>
<td>Two mirrors Field flattener</td>
<td>1.94</td>
<td>1.4-1.8</td>
<td>300</td>
<td>70</td>
</tr>
<tr>
<td>f/15</td>
<td>Intermediate</td>
<td>Singlet collimator Doublet camera</td>
<td>0.61</td>
<td>2.0-2.4</td>
<td>300</td>
<td>70</td>
</tr>
<tr>
<td>f/15</td>
<td>Intermediate</td>
<td>H grism</td>
<td>0.61</td>
<td>0.85-1.5</td>
<td>400</td>
<td>12</td>
</tr>
<tr>
<td>f/15</td>
<td>Intermediate</td>
<td>K grism</td>
<td>0.79</td>
<td>1.4-2.5</td>
<td>400</td>
<td>12</td>
</tr>
<tr>
<td>f/36</td>
<td>Wide</td>
<td>U echelle</td>
<td>0.79</td>
<td>1.8-2.5</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>f/36</td>
<td>Wide</td>
<td>HK echelle</td>
<td>0.79</td>
<td>1.2-2.1</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>f/36</td>
<td>Wide</td>
<td>H grism</td>
<td>0.79</td>
<td>0.85-1.5</td>
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<td>f/36</td>
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<td>0.79</td>
<td>1.4-2.5</td>
<td>400</td>
<td>12</td>
</tr>
<tr>
<td>f/36</td>
<td>Intermediate</td>
<td>Singlet collimator Doublet camera</td>
<td>0.26</td>
<td>1.2-2.1</td>
<td>100</td>
<td>60</td>
</tr>
</tbody>
</table>
blets together, fearing a limited lifetime for available optical cements under thermal cycling.

To cool we use a closed-cycle compressed helium refrigeration unit manufactured by CTI Cryogenics (Waltham, Massachusetts). The outer vessel of IRIS is cylindrical and all components, including the cooling unit, are attached to the flat base. The outer vessel and radiation shield can be removed completely, allowing ready access to all working parts. The only items attached to the upper face of the vacuum vessel are the entrance window/Fabry lens and the drive for one internal wheel. Figure 4 shows IRIS in use. The motors and cooling mechanism are visible on the flat lower face.

The detector, associated electronics, and all optical components are mounted in a rigid aluminium box referred to as the tower. It contacts the base through three steel balls resting on vee grooves (to allow differential shrinkage while transmitting little heat) and is held down by spring-tensioned wires. The tower supports seven motorised wheels which rotate within IRIS to provide different image scales and spectroscopic options. Each is detented within the tower, while their drive shafts are connected to the external motors through dog clutches that have considerable backlash. To avoid heat conduction, once a new detent position has been set the stepping motor drives are moved under computer control to the midpoint of the backlash. The drive for the topmost wheel is carried on the upper face of the cylindrical vessel. The dewar window is a weak doublet field lens that forms an intermediate image of the telescope pupil to allow baffling of stray thermal radiation. The focus of the telescope lies inside the vessel at the plane of a 12-position wheel, mounted on top of the tower. This wheel carries a selection of slits for spectroscopy, masks for direct imaging, and occulting squares for coronographic work near bright point sources. All slits are inclined so that the reflection from their jaws can be viewed by an integrating optical television in the AAT's acquisition and guiding unit. The coronographic mask comprises a set of square mirrors mounted on a slender arm and inclined so that the star can be seen reflected in the mirror with the same television.

Below the slit wheel, radiation next encounters a collimating lens and a cold baffle, the order of these two being...
determined by the configuration. They are brought into position by a pair of concentric wheels, one of which detents inside the other and is carried round by it. Together these provide more than a dozen potentially useful optical configurations, not all of which have yet been exploited. The same wheels carry the camera lenses that refocus the collimated beam onto the detector. Two filter wheels lie within the converging beam below the camera lenses.

(b) Motor control
Four of the seven drives are direct. To increase available torque, the three remaining drives incorporate a 4:1 toothed belt reduction between the motor and the rotary vacuum feed-through located in the dewar's base. In all cases the feed-through has been modified to serve as the driving half of the dog clutch. Because thermal contraction of the tower changes the location of the drives as it cools, the two sections of the drives are set to align when the dewar is cold.

The control of all seven stepper motors is identical: a 6809 microprocessor determines the step size and direction. Position encoding is by precision servo potentiometers mounted on the back of the stepper motors, or on the drive shaft of the belt-driven mechanisms. Motors are moved in up to three stages, first rapidly, then slowly into the required wheel position, to avoid overshoot due to inertia of the wheels, and then in reverse by about 7 degrees to break the thermal connection, leaving the wheel held by the chosen detent. The shorter route is chosen whenever mechanical constraints permit. Motor (and thus wheel) positions are table driven, but since those positions differ between room and operating temperatures, two tables are maintained and selected by a software command.

(c) Configurations
The optics for the intermediate field are shared by both telescope foci, but different optics are needed for the two wide-field configurations. In the widest-field (f/15) case we use a reflecting system based on the Burch-Bowen design (Burch, 1947; Bowen, 1967). A small convex spherical primary mirror, mounted on one of the motorised wheels, serves also as the cold stop, and feeds a large spherical concave mirror which is permanently in place. Ray tracing predicts very small images (see Gillingham, 1993), but the focal plane is curved. A field flattener, very close above the detector, is thus also required, and introduces coma. The final image quality represents a compromise between coma and extrafocal effects. Nowhere in the field is an image more than 1.3 pixels in extent, and the mean FWHM is much smaller than one pixel. This camera works at f/1.6. The vignetting ranges from about 9% on axis to 15% at the extreme corners of the field. Because the filters lie in a strongly converging beam and have a range of optical thicknesses, a different telescope focus is required for each. For this reason we also see very slight differences in image scale, comparable to those experienced by HRI. These peccadillos are absent for the other optical configurations.

No field flattener is necessary for other configurations. One position in the field-flattener mechanism contains a brass block which, being cold, provides a suitably dark environment when moved in front of the detector for dark exposures (to determine the bias frame and dark current). Other than this, and the ability to place a similar blank in the slit wheel, no shutter is provided in IRIS.

In the f/36 wide-field mode the collimator is a single fused silica lens and the camera a doublet. With the separation between the collimator and camera needed to accommodate an echelle, the beam expands considerably in the direct imaging case and would have given very poor images in the corners of the field had all the rays been passed. With this in mind, the camera aperture was made large enough to pass all rays only in the spectroscopic case, in which the rays diverge over a shorter path. The resulting vignetting in the corner of the direct imaging field is 18%. In good seeing the images are still perceptibly inferior towards the corners of the field; the f/15 intermediate field offers better imaging performance. It too uses a collimator-camera arrangement.

(d) Spectroscopic configurations
The grisms employed at f/15 were introduced subsequent to the description by Gillingham (1993). At present they cover only the H and K atmospheric windows; a grism for the J window is being designed. The slit length with the grisms is 76 arcsec, but the spectral resolution is degraded towards the ends, and the useful slit length is about 50 arcsec.

A novel feature of IRIS is the use of cross-dispersed transmission echelles for spectroscopy in the f/36 wide-field configuration. They were described by Gillingham and Lankshear (1991) and Gillingham (1993), and have been used for a variety of studies. Their efficient usage of the square array can be seen from Figure 5 of Allen (1992), and for the HK echelle from Figure 7 of this paper. Gratings for both the grisms and echelles were manufactured by Milton Roy (Rochester, New York); where possible we used standard rulings.

The measured transmission of the echelles approaches 50% at most wavelengths, but is appreciably lower than that of the grisms. Image quality varies across the field, but never exceeds two pixels in total spread. Spot diagrams are given in Gillingham (1993). Four or five orders are arrayed on the detector. To avoid order overlap the slit is restricted in length to 12 arcsec.

When first commissioned the echelles suffered from stray radiation. For example, when the 1J echelle (0.85–1.5 μm)
was in use defocused 2-micron orders were seen crossing the array at an angle. These had been reflected off the side walls of the echelle substrate block. In addition, the detector proved unexpectedly sensitive to radiation at optical wavelengths, down to at least H/\(\lambda\) (0.49 microns), which appeared in second or higher order of the cross-disperser, contaminating the data. All these problems were solved by installing in front of each echelle a bandpass filter transmitting only the wavelength ranges of interest.

All spectroscopic slit widths required to attain the stated resolutions are of order 1 arcsec. The grisms can also be used with the f/36 intermediate field but the slit is then 0.4 arcsec wide.

5. Software

(a) Instrument control and data taking

We opted to control IRIS as closely as possible to the way optical CCDs are handled. There are several advantages to this route, including familiarity for frequent AAT users and reduced programming load. The CCDs run under the ADAM environment (Kelly, 1992), and the strength of this facility was demonstrated by the relative ease with which a fundamentally different instrument could be integrated with existing hardware and software.

Nonetheless, there are differences between IRIS and CCDs. First, control was required for the many motorised components. For simplicity, all drives used the same type of stepper motor. Control and status information had also to be provided for the user, and it was found possible to include all important data on a single terminal screen which has proved easy to use. The intermediate level CCD control program that mediates between the user interface program (OBSERVER) and the software running on the M6809 in the CCD controller also required substantial additions to cope with the real-time aspects of IRIS.

The non-destructive read mode has no counterpart in CCDs. In addition, the intense background emission at the longer operating wavelengths, or when observing bright stars, enforces frequent reads which generate too many data to archive. Consequently, operating modes were required in which many successive frames were coadded before being saved. Indeed, IRIS is never used to produce a single readout image: for configurations in which the background radiation is high all observations comprise many coadded frames, and when the background is low the reduced readout noise of mode 4 requires the use of NDRs.

For both these purposes data are temporarily stored in an external memory that was built in house as an intelligent interface between instruments and mainframe computers.

(b) The external memory

When the AAO’s CCD control and data acquisition system was migrated to a VAX/VMS computer, it became obvious that high-speed detector readouts or large (1024 x 1024 or greater) format could no longer be handled. The VAX virtual memory system could not accept a data transfer rate and size which was essentially dictated by an external device. Our solution was to buffer the CCD data in semiconductor memory. At the same time a display of the data could be provided as they were acquired. The Large External Memory (XMEM) originated as that intelligent memory buffer and quasi-realtime display system. Following the CCD readout the data could be transferred at relatively high speed to the VAX and stored on disk, at a rate determined by the VAX itself.

The XMEM system has been implemented using commercially available VMEbus components, which includes a CPU board (25 MHz 68030), a VMEbus system controller, static RAM and EPROM boards, a display controller, a high-speed parallel DMA interface (which emulates a Unibus DR11-W), and several fast Dynamic RAM boards (currently 48 Mbytes). To interface the VMEbus system to the AAO CCD controller data output port we used a board designed in house, and originally the two were interconnected using a 16-bit serial data link also designed in house. The software running on the system is based on a real-time kernel called pSOS (and has recently been ported to VxWorks), and provides basic image handling and readout facilities. The XMEM is controlled by software running on the VAX over an RS232 link. Data are transferred to the VAX using back-to-back connected DR11W interfaces. The VxWorks version, which is still under development, uses Ethernet for control and data transfer.

Six different data types can be generated by the controller. To simplify the processing software which would now be running on the XMEM, and to keep acquisition overheads to a minimum, we opted to tag each data pixel from the controller with its type, and to design a new interface for the XMEM which could recognise the data types and store the IRIS frames in separate buffers with minimal software intervention. Since the 16-bit pixel data had to be tagged, a 32-bit serial data link was developed to connect the CCD controller to the XMEM. The interface also had to be able to cope with changes in window sizes and keep synchronised with an almost continuous data flow from the controller. The system easily handles the fastest data rates from all window sizes used on the detector.

A section of memory within the XMEM is set aside to hold the current data stream. Up to 500 consecutive images may be stored. At the end of the observation the images are processed according to the mode of data taking. In mode 1 they are merely averaged, with an option to reject cosmic rays and other glitches through \(\sigma\)-clipping. In mode 4 the frames are first linearised (as described above) and then a linear regression is applied through all points. The necessary processing time is a further small overhead when observing in mode 4.

Once compressed to a single image, the data are transferred to a VAX-4000 as a Figaro-format file. An additional command allows the entire stack of images to be dumped to the VAX, and this has proved particularly valuable during the commissioning phase.

Code in the XMEM also provides display of the incoming data. Display is handled in a background task and is performed when the XMEM is not otherwise occupied transferring or processing data. When the instrument is idling the image is continuously updated. When data taking is underway the display shows both the last individual observation and the accumulated data to date.

Because of the structure in the bias frame (Figure 2), raw data displays are not always helpful, especially now that mode 2 is no longer used for data taking. However, the XMEM additionally stores an image which is subtracted from the current or accumulated data, and the resultant frame is also displayed. The image to be subtracted may be any frame, even one processed from a different night. However, the two most useful are a dark exposure and a recent observation of a relatively uncluttered field taken
with the same filter combination. The array has quite strong flat-field patterns (Figure 8) which modulate the sky to dominate over weak sources. Subtraction of a recent sky frame removes the pedestal and virtually all the sky emission, rendering celestial sources clearly visible.

(c) Telescope control

Sky removal remains one of the most demanding tasks in infrared data taking. It is most satisfactorily achieved by observing at a number of positions and then forming a mean of the frames, rejecting stars to derive a representative sky frame, as described in section 7a. If the object being observed is smaller than the frame, it may be “jittered” a small amount so as to land in different portions of the array; if it is extended then the frames will need to be stepped so as to give small overlap. For such observations the user generates a file, to be read line by line, that specifies a telescope offset from base and initiates an IRIS observation when the telescope has settled. Once that observation ends the next line of the file is read and executed. A popular pattern for this type of observing is nine positions in a square grid.

Telescope motion during spectroscopy has also been installed. In this case the telescope travels perpendicular to the slit, and a sequence of observations is combined into a data cuboid. Each frame is a plane in a spatial/wavelength domain, and as time passes the orthogonal spatial dimension is grown. From such a data cuboid one may extract monochromatic image planes at any wavelength. Images in continuum-subtracted line emission or broad wavebands can easily be constructed.

This spectral imaging technique has proved particularly powerful in cases where a strong continuum underlies an emission line. Narrow-band filters are available for the major lines of interest, but their spectral resolution is only of order 1%, often insufficient to separate the lines from the continuum. Moreover, separate images in filters centred on and off the line are rarely matched in point spread function due to changes in the seeing, and even if autoguided may not match in location. Continuum subtraction then proves extremely difficult. The spectral mapping technique samples continuum points at exactly the same time as the lines, so the continuum may be removed to high precision. The technique works as well for absorption lines, and is not constrained to redshift ranges covered by existing filters.

The technique suffers from two disadvantages. First, the AAT must drift unguided, so that small tracking inaccuracies distort the images. These distortions can be removed by comparing continuum images derived from the spectral cubes with standard broad-band data taken in imaging mode. But of course the data reduction task is a discouragement. A better alternative would be to move the AAT under autoguider control.

The second disadvantage is variation of the sky during the scan. Since the sky is not subtracted from the cuboids, any change in its intensity is manifested by banding of the image parallel to the slit. The removal of this component is straightforward if one or more strips of the image, corresponding to specific locations on the slit, can be identified free from celestial sources. This is usually the case for continuum-subtracted line images. These strips contain a record of the sky variation, which may then be subtracted strip by strip from all slit positions. In FIGARO the commands YSTRACT and YSUB (or EXTRACT and XSUB if the slit is aligned perpendicularly) perform this operation.

Examples of spectral imaging data have been published by Burton and Allen (1992) and Allen, Crisp and Meadows (1992). Visiting observers have recently taken successful data using this technique.

6. Experience in Use

(a) Imaging and photometry

The Rockwell array has good cosmetic characteristics. Initially only about 70 pixels (0.4%) were unusable for normal imaging either because they lacked response to radiation or because of extreme nonlinearities. Two years after first use the array had developed more defective pixels, now totalling about 100. This is still not sufficient to cause anything but mild annoyance for most observing. Because charge is not shifted through the array, as in a CCD, there are no cosmetic problems due to poor charge transfer efficiency or trapping sites.

At 2 μm the uniformity is quite good (rms 8.1%), but nonuniformities become more pronounced at shorter wave-
Because of time constants within the chip architecture and the reduced bandwidth available in the modified CCD signal processors, the readout time for the entire chip is 1.5 sec. The well capacity under its operating conditions ranges from about 300 000 to 550 000 e\(^{-}\), and in the widest field options this can be filled in under 1 sec by thermal radiation through the broad-band K filter. Observations with this filter in summer are possible only with narrow field options. We have acquired alternative filters to compensate for this difficulty and generally to improve sensitivity. The K′ filter, described by Wainscoat and Cowie (1992), has nearly 90% of the throughput of the K filter but one third of the background intensity, and therefore offers 0.5 mag better sensitivity. For moist sites such as Siding Spring, however, the 1.9 μm short-wavelength cut-off is not very satisfactory, and deters reliable photometry due to water vapour absorption. We have recently taken delivery of a newly-specified filter (manufactured by Barr Associates, Westford, Massachusetts) with half-power points at 1.95 and 2.30 μm. This filter, which we have dubbed Kn (for narrow K) has excellent throughput and retains most of the 0.5 magnitude extra sensitivity over the older K filter. It may become the filter of choice for 2-micron photometry.

In broad-band imaging IRIS is limited by photon statistics from the sky radiation. The performance thus differs little from that of other infrared cameras, particularly for point sources, except in the cosmetic quality and quantum efficiency of the detector. Area photometry of extended objects provides a more stringent test and has yielded satisfactory results down to K = 21 mag arcsec\(^{-2}\) even for galaxies that overfilled the detector and had to be covered by mosaics.

As noted above, we took care to image the telescope pupil onto a cold stop, and to ensure that the stop underfilled the primary and overfilled the central obstruction. Despite these precautions, some residual radiation from the telescope metalwork does reach the detector. Reasons for this include internal flexure, scattering within the instrument, and Fresnel diffraction. Early observations used reflective baffles on the AAT secondary, so that the detector viewed sky via the primary and secondary mirrors. To attain photometric accuracy, the vignetting and chip response must be subtracted from that of other infrared cameras, particularly for point sources, except in the cosmetic quality and quantum efficiency of the detector. Area photometry of extended objects provides a more stringent test and has yielded satisfactory results down to K = 21 mag arcsec\(^{-2}\) even for galaxies that overfilled the detector and had to be covered by mosaics.

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Table 2. Typical sky brightness and performance figures

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (μm)</th>
<th>Bandpass (μm)</th>
<th>Sky brightness (mag arcsec(^{-2}))</th>
<th>Throughput ( magnitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>1.26</td>
<td>0.25</td>
<td>15.2</td>
<td>0.05</td>
</tr>
<tr>
<td>H</td>
<td>1.66</td>
<td>0.27</td>
<td>13.7</td>
<td>0.16</td>
</tr>
<tr>
<td>Kn</td>
<td>2.16</td>
<td>0.32</td>
<td>13.6</td>
<td>0.32</td>
</tr>
<tr>
<td>K</td>
<td>2.22</td>
<td>0.39</td>
<td>12.5</td>
<td>0.29</td>
</tr>
</tbody>
</table>

The quantum efficiency of our array falls rapidly shortward of 1.5 μm. Table 2 gives performance figures for IRIS, including total throughput measured by the photons detected as a fraction of those entering the atmosphere above the telescope. These figures are for the f/15 wide-field configuration, which offers the highest throughput. PWCSM found for their camera a lower throughput at K (0.24) but significantly higher at J (0.09), while HRI quote figures even more extreme in the same sense (J: 0.11; K: 0.18). These comparisons tend to confirm that our detector is unusually unresponsive at short wavelengths. The steep wavelength dependence in the J window limits the accuracy of flat fielding, and ultimately of photometry across the entire array, because it is impossible to feed the array with light having sufficiently similar spectral content to starlight. Attempts to use a defocused image of the moon to flat field have not met with success. The moon is about 1000 times too bright, and no effective neutral density filter has been found that does not suffer from scattered light.

Photometric accuracy is also affected by an apparent loss of light between pixels. Although the architecture of the HgCdTe material is not pixellated, electrons generated near the corners of multiplexer pixels have further to travel through the HgCdTe before they reach the indium bond that drains them into the silicon multiplexer; they may recombine with a hole before getting there. When using the f/15 wide-field option in very good seeing the losses can be significant. We have found a star whose centroid lies exactly at a corner to be as much as 0.1 magnitude fainter than the same star central on a pixel. The effect is greatly reduced for the larger image scales, and can be neglected. We have not demon-
strated better than 1% rms photometric accuracy in the K-band, rising to 2% at H and 4% at J. These figures are rms values for images of the same star observed sequentially at positions scattered across the entire array, and thus include the flat-field correction. For stars observed in the same part of the array we have demonstrated an rms photometric accuracy close to 0.5% in the K band, similar to the values claimed by HRI and PWCSM. It thus seems that infrared arrays are capable of attaining 1% photometry with careful use.

(b) Spectroscopy

One of the great strengths of the integrated design of IRIS is the ease of interchange between modes. An object of interest observed on a wide-field image may immediately be studied at higher spatial resolution, or its spectrum can be taken. In the latter case the field of view may be imaged directly through the slit before the dispersing component is inserted. This facility makes spectroscopy of infrared sources lacking optical counterparts easy and reliable.

The dark current limits sensitivity, for a few pixels, only when using the IJ echelle, where the background radiation is low. We always use mode 4 (non-destructive reads) for such work, attaining readout noise figures below ~20 e− from the multiple reads. Then in exposures of 1000 s or so the data are mostly sky limited. The increasingly poor fixed-pattern noise at shorter wavelengths becomes more extreme at wavelengths around 1 μm, where broad-band imaging has not been attempted. However, for most purposes spectroscopic observations are more tolerant of cosmetic defects, seeking at best 10% accuracy. For such purposes the detector poses no problems.

There is a need of a well-defined set of spectrophotometric standard stars, selected to have few or no absorption lines, and properly calibrated over the entire wavelength range 0.8–2.5 μm. We still use the G dwarfs listed by Allen and Cragg (1983), but many are too bright for the grisms, and none has acceptable flux calibration over the range 0.8–1.2 μm.

7. Data Reduction

(a) Imaging and Photometry

Although software has been written to reduce the data from other infrared cameras, no package is comprehensively suited to IRIS data. Moreover, following AAO practice, the data are written to disk in Figaro format so that extra translation steps are needed for use on systems such as IRAF. We have therefore written several reduction routines within Figaro. The flexibility built into the Figaro suite has assisted this development, particularly the multi-dimensional facilities, which allow quality and variance arrays to accompany data, and access to instrument parameters written into the FITS-format file headers.

The most instrument-specific task, IRISLIN, linearises mode 1 data (mode 4 data have been corrected before leaving the XMEM), converts to electrons using the system gain determined in the laboratory, and appends a variance array derived from a combination of the photon statistics and the expected readout noise. Subsequent routines maintain the variance array correctly, so that uncertainties can be assigned to data at any stage. Bulk processing through IRISLIN is made possible by some supporting programs that search the file headers to match observations with dark or bias frames, and generate listing files.

Division of frames by a flat field exposure, generated as described in section 6a, does not produce constant sky counts across a frame. We expect three components to the background. Two of these, the sky itself and the thermal emission of the mirrors, should at this stage be uniform across the image, while the third, stray thermal radiation from metalwork, should be negligible at short wavelengths. We also expect the latter to vary more slowly than the former. In practice neither of these expectations is fully met. Even in the J band we see structured thermal radiation, probably leaking past the filter by multiple reflections within the dewar. And in the K band it seems that both components vary with comparable time constants.

We remove the sky from our images using median filtering of a group of frames. The skies are first scaled so that each frame has the same median. HRI prefer additive rather than multiplicative matching of skies, possibly because their telescope produces less thermal background on the chip so that a flat-fielded sky is already quite uniform across the array. Then for each pixel an estimate of the sky free from stars is derived from the samples. Conventionally the value is the median, but we prefer to form a mean after n-a clipping to remove stars (or extended objects). There are two advantages to the clipping algorithm. First, if any frame contains extra radiation from a celestial source, the median will normally be higher than that of the same frames without that source. We have indeed seen faint images of stars on sky frames formed using the median. Clipping can be made to reject stars completely by adjustment of the value of n. In crowded star fields we have sometimes had to reduce n to 1.2 to eradicate stars, but in those same frames median filtering has never succeeded. Second, a median sky frame comprises pixels whose individual values are identical to those in the (scaled) data. When it is subtracted from the data, many pixels will be identically zero. This non-Gaussian sky can negate statistical analyses. To overcome this difficulty it is common practice to subtract from each image a median sky formed from all the other images in the set, excluding itself. There is no such need if means are formed, so the computational load is greatly reduced.

Once a mean sky frame exists it can be scaled to match the data, and subtracted. Again, a median of the data frame is not an appropriate measure of the sky intensity, especially if many pixels contain flux from an extended object. A preferred technique is histogram matching, and we have developed software to derive the mode of a smoothed histogram in order to scale the sky accurately. However, all these techniques fail if the stray radiation has varied, and in the 2-micron window this is often the case for f/36 wide field data. We commonly find on our sky-subtracted images residual structure matching the pattern of stray thermal radiation. Though unsightly, this is at a sufficiently low level to have no influence on point-source photometry. Moreover, since the pattern is stable, we have had success in its subsequent removal.

An alternative method that has also proved quite satisfactory is to divide all frames by a median sky frame, numerically subtract the sky as a constant across the frame, then multiply again by the sky and divide by the dome. With this scheme the sky frame is generated using different weighting of the raw data. We continue to seek optimal sky-subtraction procedures.

In Table 2 we list typical sky brightness and sensitivity figures. The latter assume that stellar photometry requires summation over 9 (0.6 arcsec) pixels in the f/15 intermedi-
ate field option. We give two sensitivity estimates, 5-σ after a 1 minute integration and 3-σ after 30 minutes. The latter can be compared directly with PWCSM, and is encouragingly similar when allowance is made for sky brightness and telescope collecting area. We are surprised to find that they measure a significantly brighter sky than us in the K band. By comparison, HRI find Mauna Kea skies darker at all wavelengths, which is also somewhat surprising since J and H are dominated by airglow features that arise at high altitude.

Mosaicing together of images is commonly required. If an object has been observed in several positions of a jitter pattern the frames must be aligned and coadded, whilst very extended objects may be covered by overlapping frames. A routine IRISMOS, running under Figaro, was written to combine frames, and has been used extensively. A composite of 100 images has been successfully mosaiced.

IRISMOS subdivides raw pixels into 3 x 3 subpixels within memory, aligns the images at the subpixel level, and then rebins back to the original pixel size. Flagged defective pixels are not used. Several means of aligning images are available, including cross correlation of regions of overlap collapsed separately onto the two coordinates. The most satisfactory uses the centroids of stars common to more than one component image. A similar algorithm has recently been described for dealing with HST images (Hook and Lucy 1993).

Mosaics are unsatisfactory if the sky levels have not been precisely set to zero, as is often the case for very extended objects. In this case a constant is added to each frame so that the median in each overlap region is the same. An iterative routine to perform this function was kindly provided by Mark Walker.

Figure 9 shows an example of mosaicing on an extended object. Extended objects provide a critical test because the joins between overlapping frames are prominent if not well matched. In this case the edges of eight frames lie on the disk of the planet. The inset gives an indication of the improved signal/noise from mosaicing overlapped images, but also shows a perceptible loss of resolution, because the data are undersampled.

(b) Spectroscopy

Spectroscopic data require a number of specific programs. The echelles generate spectra that are slightly curved and on which the projected slit rotates with position along each order. The orders are straightened and set parallel to the detector rows by a linear shift along each column. Within each order the slit is then set vertical by a linear stretch and shift specific to every row. A similar interpolation is required for the grism data, since the slit projects into a weakly curved line. A slight loss of spectral resolution accompanies all such manipulations, and IRIS would benefit from a larger array with smaller pixels, to oversample the images.

Whenever possible, observations are made in pairs, with the object at two non-overlapping positions on the slit. The images are directly differential, which has the effect of cancelling pixels with high dark current and removing most of the sky emission. An illustration of this technique is given in Figures 4 and 5 of Allen (1992). Both positive and negative versions of the object spectrum are created; when these are extracted from the image and differenced, any residual sky radiation cancels to high precision. Infrared spectroscopy is less tolerant than optical of sky emission because of its greater intensity relative to celestial sources. This procedure is superior to any other means of sky subtraction, including the standard optical technique of forming a mean sky spectrum from a long-slit observation.

Figure 10 reproduces a spectrum taken using the full range of the IJ and HK echelles.

8. Potential Enhancements

A number of enhancements can be forseen, and IRIS offers a sufficiently versatile base that others might be possible. The following are currently (May 1993) under discussion. Most could be fitted with relatively little difficulty.

- A grism for the 1.0-1.25 μm (J) atmospheric window.
- A narrower image scale to deliver about 0.25 arcsec pixels at f/15 and 0.1 arcsec at f/36 (Gillingham, 1993).
- A larger format array with smaller pixels. Over most of the field an improvement in spatial or spectral resolution
by a factor of 1.5–2 could be achieved on an array having smaller pixels. A narrower entrance slit would be required to attain the higher spectral resolution.

- A module to allow area polarimetry. Such a module has been constructed by J.H. Hough and collaborators at the University of Hertfordshire, and was successfully commissioned in May 1993. It covers half of the field of view of the detector, in two parallel rectangles, and uses a MgF$_2$ Wollaston prism to image the o- and e-rays side by side. A rotating half-wave retarder provides linear polarimetry. The instrumental polarization is less than 0.1%. Only the intermediate field optics are available. Use of a quarter-wave retarder would allow circular polarimetry. Direct imaging and spectropolarimetry are also possible using a wire grid analyser. The possibility of using the existing system directly with the grisms is also being explored.

- A tunable Fabry-Perot etalon placed in front of IRIS would allow imaging, particularly of emission lines, at higher spectral resolution. An initial target resolution would be 300 km s$^{-1}$.

- A fibre-optic coupling at the top of the dewar to feed optical radiation to the existing low-resolution optical spectrograph FORS. A suitable dichroic would probably allow simultaneous optical and infrared spectroscopy of point sources down to the 0.5 μm wavelength cutoff of FORS.

- An optical CCD inside IRIS and fed by a dichroic mirror could be used for guiding and optical photometry.

In addition to these mechanical upgrades, the control software is a continuously evolving code. Major changes are unlikely, but significant improvements are anticipated through the introduction of a mouse control to select options on the external memory, and the use of X-windows.

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