INGRID: A near-infrared camera for the William Herschel Telescope

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ABSTRACT

Rapid developments in near-infrared (NIR) arrays and adaptive optics systems have driven the development of wide-field and high-spatial-resolution, high-optical-quality NIR imagers and spectrographs, providing an unparalleled boost to NIR observations. Based around a 1024 × 1024 pixel² Hawaii-1 array, the Isaac Newton Group Red Imaging Device (INGRID) imager provides a field of view >16 arcmin² (at the Cassegrain focus) whilst Nyquist sampling the median summer seeing disc. When used in conjunction with the Nasmyth Adaptive Optics for Multi-Purpose Instrumentation (NAOMI) system and a second set of collimation optics, a high spatial resolution mode (0.04 arcsec pixel⁻¹) is offered, providing near-diffraction-limited imaging. INGRID uses an all-refractive design and employs a cold stop to reduce thermal background emission, critical to the performance as it is used on the non-infrared optimized 4.2-m William Herschel Telescope (WHT). We discuss the design and operation of INGRID and illustrate its performance by discussing commissioning observations of the cluster Abell 2218 and the spiral galaxies NGC 3351 and 1530.

Key words: instrumentation: adaptive optics – instrumentation: detectors – instrumentation: high angular resolution – instrumentation: miscellaneous – instrumentation: photometers.

1 INTRODUCTION

We describe a common-user near-infrared (NIR) camera, INGRID (Isaac Newton Group Red Imaging Device), built for use at the Cassegrain and adaptive optics (AO) foci of the 4.2-m William Herschel Telescope (WHT). The Isaac Newton Group of Telescopes (ING) identified the need for a NIR imager for the WHT for (a) wide-field NIR imaging, exploiting the relatively large field of view of the WHT as compared to 8-m class telescopes, and (b) for near-diffraction-limited NIR imaging when used with the common-user AO system, NAOMI (Nasmyth Adaptive Optics for Multi-Purpose Instrumentation) (Longmore et al. 1997; Zadrozy et al. 1999). Imaging at NIR wavelengths allows investigations of dusty regions often obscured at optical wavelengths, such as star-forming regions and active galactic nuclei, as well as facilitating studies of galaxies and high-redshift objects. The range of activities that INGRID was envisioned for had the contradictory requirements of a wide field of view and very high (diffraction-limited) spatial resolution. INGRID meets these requirements through the use of exchangeable external collimation optics, enabling use at the Cassegrain and NAOMI foci of the WHT. INGRID was initially developed by the former

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Royal Greenwich Observatory but was transferred to the INGRID for completion.

INGRID is based around a Rockwell Hawaii-1 1024 × 1024 pixel\(^2\) HgCdTe array sensitive to radiation at wavelengths from 0.8–2.5 \(\mu\)m (Hodapp et al. 1996). At the time of detector selection, this array was the largest format high quantum efficiency NIR array available. The Hawaii devices can be operated at liquid nitrogen temperatures, adding to their ease of operation when compared to other NIR arrays. Several similar NIR cameras based around the Hawaii array are in operation at other observatories (see e.g. Hodapp et al. 1996; McCarthy et al. 2001) and there are several papers describing their optimal operating parameters (see e.g. Kozlowski et al. 1996; McCarthy et al. 2001) and there are several papers describing their optimal operating parameters.

In the three observing semesters following commissioning (2000 March), INGRID was allocated >100 nights of observing, immediately becoming the second most used instrument on the WHT. INGRID at the Cassegrain focus is used optimally to observe fields of large angular diameter; in this paper, we present two such examples observed during commissioning. The first is the gravitationally lensed cluster Abell 2218 showing numerous arc-like features around the brightest galaxies at the cluster center. These represent the gravitationally distorted magnified images of distant galaxies behind the cluster. The second example is the pair of galaxies NGC 1530 and 3351, both showing prominent bars and a number of rings outlined by relatively young stars. The design of INGRID is detailed in Section 2, the control/acquisition hardware and software are presented in Section 3, and the performance of the instrument and the first observations are presented in Section 4. Finally, a discussion and future upgrades are presented in Section 5.

### 2 INSTRUMENT DESIGN

The optical design of INGRID was optimized (a) to Nyquist sample the point spread function (PSF) of the image across the array, (b) to provide a \(<10\%\) degradation of the median summer PSF when used at the Cassegrain focus, and (c) to maximize throughput. Wilson et al. (1999) found the median summer seeing at 500 nm is 0.69 arcsec full width half maximum (FWHM), which, when using the standard seeing/wavelength relationship of \(\lambda^{-0.4}\) (Ricort et al. 1981), yields a 2.2-\(\mu\)m seeing of 0.51 arcsec. Thus, the pixel scale was set at 0.25 arcsec and the worst degradation of the PSF was estimated at \(<4\%\), clearly meeting the optical requirements. The large field of view provided by INGRID is illustrated by a comparison of selected NIR instruments available either as common user or on a collaborative basis to UK astronomers, as shown in Table 1. As shown below, the combination of a 4-m telescope and a relatively large field of view make INGRID an excellent NIR survey instrument.

NAOMI was expected to deliver diffraction-limited images in the H band and at all longer wavelengths. At shorter wavelengths, seeing was expected to limit the FWHM to a similar value. Assuming the ratio of the obscuration of the secondary to primary, \(e\), to be 0.24, the diffraction limit of the WHT at 1.6 \(\mu\)m is \(<0.09\) arcsec. Hence, when used in conjunction with NAOMI, the optical design was set to provide a plate scale of 0.04 arcsec in order to Nyquist sample the expected delivered FWHM.

INGRID makes use of a dual cooling system based around a liquid nitrogen tank and a CTI closed-cycle cooler (CCC) supported on an antivibration mount. In the usual Cassegrain imaging mode and during storage, INGRID utilizes the CCC. However, when used in

### Table 1. Survey power of selected near-IR imagers available to UK astronomers.

<table>
<thead>
<tr>
<th>Telescope/Focus</th>
<th>Instrument</th>
<th>Diameter (m)</th>
<th>Plate scale (arcsec pixel(^{-1}))</th>
<th>F.o.V (arcmin(^2))</th>
<th>Survey power (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHT/Prime</td>
<td>CIRSI(^b)</td>
<td>4.2</td>
<td>0.32</td>
<td>119.30(^c)</td>
<td>526.13</td>
</tr>
<tr>
<td>INT/Prime</td>
<td>CIRSI(^b)</td>
<td>2.5</td>
<td>0.46</td>
<td>243.33(^c)</td>
<td>380.20</td>
</tr>
<tr>
<td>AAT/Cass</td>
<td>IRIS2</td>
<td>3.9</td>
<td>0.45</td>
<td>57.94</td>
<td>220.31</td>
</tr>
<tr>
<td>VLT/Nasmyth</td>
<td>ISAAC</td>
<td>8.2</td>
<td>0.15</td>
<td>6.38</td>
<td>107.25</td>
</tr>
<tr>
<td>NTT/Nasmyth</td>
<td>SOFI</td>
<td>3.6</td>
<td>0.07</td>
<td>1.46</td>
<td>24.61</td>
</tr>
<tr>
<td>WHT/Cass</td>
<td>INGRID</td>
<td>4.2</td>
<td>0.24</td>
<td>16.50</td>
<td>72.76</td>
</tr>
<tr>
<td>Gemini/Cass</td>
<td>NRI</td>
<td>8.1</td>
<td>0.12</td>
<td>3.99</td>
<td>65.40</td>
</tr>
<tr>
<td>VLT/Nasmyth</td>
<td>CONICA</td>
<td>8.2</td>
<td>0.11</td>
<td>3.46</td>
<td>58.17</td>
</tr>
<tr>
<td>Gemini/Cass</td>
<td>Flamingos-1</td>
<td>8.1</td>
<td>0.08</td>
<td>2.65</td>
<td>42.65</td>
</tr>
<tr>
<td>UKIRT/Cass</td>
<td>UIST</td>
<td>3.8</td>
<td>0.12</td>
<td>4.19</td>
<td>15.14</td>
</tr>
<tr>
<td>UKIRT/Cass</td>
<td>UFTI</td>
<td>3.8</td>
<td>0.09</td>
<td>2.41</td>
<td>8.71</td>
</tr>
<tr>
<td>HST/Cass</td>
<td>NICMOS (3)</td>
<td>2.4</td>
<td>0.20</td>
<td>0.73</td>
<td>1.05</td>
</tr>
</tbody>
</table>

\(^a\)Survey power defined as (\([\text{diameter}/2]^2\] \times \text{field of view}\), where ‘\(\text{diameter}\)’ refers to the diameter of the collecting aperture, ignoring effects from undersized secondary mirrors, pupil masks, obscurations, etc.

\(^b\)Private instrument.

\(^c\)Non-contiguous fields.
conjunction with NAOMI, a low-amplitude image motion driven by
the CCC is detected, so liquid nitrogen cooling only is used during
AO operation. The hold time of the nitrogen tank is $\sim 12$ h, but this
is extended to $>20$ h when operating the CCC in conjunction with
nitrogen cooling.

The camera is housed in a side-looking aluminum cryostat and
uses four trusses mounted to a removable lid to secure and to de-
fine the position of the optical table. The camera is an all-refractive
design with all optical components antireflection coated and me-
chanical components located close to the optical beam coated in
Nextel paint to reduce ghosts and to decrease scattered radiation.

Fig. 1 shows the optical layout when used at the Cassegrain focus
and Fig. 2 shows a schematic diagram of INGRID. When used at
the folded Cassegrain focus ($f/11$, collimated to a 25-mm beam), a
flat silver mirror is used to redirect the light to the exchangeable warm
collimation optics of INGRID. The collimator uses a singlet field
lens made from CaF$_2$ with a singlet aspheric lens of BaF$_2$ providing
most of the optical power. When used with NAOMI, a second collin-
mator ($f/16$ collimated to a 4-mm beam) is used. The optical beam
is re-projected through the tilted CaF$_2$ cryostat window and forms a
pupil image where seven remotely selectable cold stops are located.

The beam passes through two filter wheels before entering the cam-
era optics. The beam is incident on the first pair of spherical lens
doublets (BaF$_2$ and Corning 9754 glass, 43- and 41-mm diameter,
respectively) and is focused on the array by the second spherical lens
doublet (MgO and 9754 glass, 45- and 34-mm diameter, re-
spectively) – see Appendix 1 for further information regarding the
optics. The camera is of Petzval design and provides excellent over-
all image quality across the full field of view, as demonstrated in
Figs 3 and 4, which show the predicted enclosed energy diagrams
for both operational modes. With careful selection of lens materials,
full correction of field curvature was achieved over the 0.8–2.5 $\mu$m
operating range, as well as providing a compact camera design.

The elements of the first camera doublet were located to a rela-
tive positional tolerance of 10 $\mu$m in order to meet the image quality
requirements outlined above, with the result that any residual mis-
alignment had a negligible effect on the image quality. In order to
achieve such alignment, an athermal mount was developed using
a compliant ‘v-block’ arrangement (see Fig. 5) that was used for
all lenses. When warm, the preload is provided from the Delrin
spring to permit room-temperature alignment. During cooling, the
PTFE pads and Delrin spring contract towards their centres, which,

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image1.png}
\caption{INGRID optical design (Cassegrain focus): optical layout of INGRID when used at the folded Cassegrain focus. Two fields are shown: on axis (0.0 arcsec) and at the array corner (181.0-arcsec radius). The path length from the f/11 focus to the array is 567.8 mm. This figure is available in colour in the online version of the journal on Synergy.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image2.png}
\caption{Schematic diagram of INGRID at the orientation when used at the Cassegrain focus.}
\end{figure}
combined with the lens contraction, ensures that no overstressing of the lens occurs. Instead, a residual load of \( \sim 2 \) g holds the lens in position. Alignment of the lenses was performed using double-pass interferometry with a HeNe laser to determine each lens centre and their centres relative to each other accurately. Alignment of each doublet pair was performed separately, warm and then combined in one optical mount, before installation in the cryostat and subsequent cooling. During cooling, the alignment was monitored, revealing no significant misalignment owing to thermal effects.

Owing to a production problem of the aspheric field lens, a temporary doublet was used for one year after commissioning, providing slightly inferior optical performance and increasing the level of thermal emission. The aspheric was fitted and commissioned in 2001 March.

As the WHT is not an infrared optimized telescope (i.e. it has an oversized secondary mirror, extended optical light baffles, and numerous warm components near the science beam), the cold stops are crucial in minimizing the thermal background. Seven laser-cut aluminum cold stops are available, three for the Cassegrain focus and four for the Nasmyth focus. The cold stop includes a central obscuration to mask the warm central Cassegrain hole and a masking outer ring that are required to vignette \( \leq 2 \) per cent of the science beam. The cold stops are located at different locations in the pupil wheel to optimize the pupil focal location for each wavelength of observation. The Nasmyth cold stops are designed for the particular configuration of the NAOMI AO system. By using the correct optimized pupil stop, the thermal background is minimized whilst the overall throughput is maximized, thereby increasing overall observing efficiency. A remotely deployable set of lenses is located within the camera to provide an image of the entrance pupil of the telescope at the detector focus. Alignment of INGRID is usually achieved by centroiding the reflection off the INGRID collimation optics by a
laser located at the opposite folded Cassegrain port of the WHT, although the pupil-imaging mode is used to perfect alignment and to minimize the thermal background. By using the combination of the laser and pupil imaging alignment, the pupil alignment is achieved in a repeatable fashion, as evidenced by a consistent longest time to background saturation, consistent with the sky dominating the background rather than a pupil misalignment.

The filter set consists of five broad-band and eleven narrow-band filters that are or will be available for use with INGRID (see Table 2). These have been purchased as part of the Mauna Kea Observatories Near-Infrared filter set (Tokunaga, Simons & Vacca 2002) and are of high optical quality and hence are suitable for use with AO systems. This filter set also serves to set the current standard photometric pass bands at NIR wavelengths. Two filter wheels, each with 11 filter positions, are available to provide flexibility in the filter selection, key to minimizing the frequency of thermal cycling, which is both time consuming and potentially damaging to the detector (see Section 3). When using narrow-band filters, the other filter wheel can be used to provide additional out-of-waveband blocking, which has proven to be necessary for the [Fe II] and H-continuum filters.

**Table 2. Filter list.**

<table>
<thead>
<tr>
<th>Filter name</th>
<th>50 per cent cut-on/ off Bandpass (μm)</th>
<th>Peak measured transmission (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>0.996–1.069</td>
<td>88</td>
</tr>
<tr>
<td>J</td>
<td>1.170–1.330</td>
<td>90</td>
</tr>
<tr>
<td>H</td>
<td>1.490–1.780</td>
<td>87</td>
</tr>
<tr>
<td>K</td>
<td>2.028–2.364</td>
<td>95</td>
</tr>
<tr>
<td>Ks</td>
<td>1.990–2.300</td>
<td>95</td>
</tr>
<tr>
<td>He I/A</td>
<td>1.075–1.091</td>
<td>–</td>
</tr>
<tr>
<td>Pa-gamma</td>
<td>1.086–1.102</td>
<td>–</td>
</tr>
<tr>
<td>J-continuum</td>
<td>1.198–1.217</td>
<td>63</td>
</tr>
<tr>
<td>J</td>
<td>1.278–1.296</td>
<td>68</td>
</tr>
<tr>
<td>H-continuum</td>
<td>1.560–1.583</td>
<td>74</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1.629–1.654</td>
<td>74</td>
</tr>
<tr>
<td>H2 v = 1 − 0</td>
<td>2.105–2.135</td>
<td>72</td>
</tr>
<tr>
<td>Br-gamma</td>
<td>2.153–2.186</td>
<td>69</td>
</tr>
<tr>
<td>H2 v = 2 − 1</td>
<td>2.251–2.285</td>
<td>59</td>
</tr>
<tr>
<td>K-continuum</td>
<td>2.253–2.287</td>
<td>70</td>
</tr>
</tbody>
</table>

*Filters currently unavailable.

*Projected or measured at 77 K.*

**3 COMPONENT CONTROL AND DATA ACQUISITION**

INGRID uses a Hawaii-1 array that possesses high quantum efficiency (>50 per cent from 1–2.5 μm), low read noise (<10 e− pixel−1) and a large number of detector elements (>1 × 106 pixel) of HgCdTe. These features make the Hawaii-1 detectors common in astronomical observatories. The NIR-sensitive HgCdTe pixels use a sapphire substrate which is bonded to a silicon multiplexer. Bonding of different materials can lead to thermal delamination of the detector bonds when cycling the array thermally, but we find the loss of pixels per cycle is small (<10 pixel).

The detector is subdivided into four quadrants, permitting each quadrant to be read out simultaneously to provide faster array reads. The signal is passed through one of four pre-amplifiers (one for each quadrant) and then passed in parallel to separate external filter/amplifiers located outside the cryostat. The array is controlled and read by a San Diego State University (SDSU) controller with four analogue-to-digital conversion boards (Leach & Low 2000). Finally, the signal is fed via the PCI bus to a dedicated Sparc station for archiving and quick-look data reduction. As INGRID has no shutter, the readout electronics set the limit of 0.865 seconds per frame read, dominated by the time required for the analogue-to-digital conversion. A typical readout of the array makes use of the correlated double sample (CDS) technique (Hodapp et al. 1996). Thus, each exposure consists of two array reads, one pre-exposure read (pre-) and one post-exposure read (post-), where the requested exposure time sets the time difference between the pre- and post-reads. The output electronics are reset to a reference value before transferring the charge in each pixel to the output electronics and the final readout value assigned to each pixel is given by the difference between the reference value and the transferred charge for each array read. Thus the CDS technique samples the bias level for each pixel and each readout, yielding the best representation of the true charge associated with each pixel. The read noise is reduced significantly as the bias level is sampled directly before making the exposure, yielding typically a read noise lower than the background photon noise of the image. In CDS operation, the minimum possible exposure time with INGRID is 0.865 s, but double that time is required to take such an image.

Further to the CDS technique, two other modes of readout are available, with the exact readout method usually dependent on the bandwidth of the selected filter. Typically, INGRID is photon-noise limited when using broad-band filters but is read-noise limited for most of the narrow band observations. However, the Hawaii-1 arrays allow reading the array multiple times in non-destructive mode, termed multiple non-destructive read (MNDR). By reading the array n times before and after an exposure, the read noise is reduced by approximately a factor of \( n^{1/2} \) (Hodapp et al. 1996). The performance of the array read noise is discussed in Section 4 below.

For observations where numerous short exposures are required (such as high background observations or bright sources), co-averaging of m frames is available. Co-averaging frames saves overhead time associated with post-exposure processing and data archiving, as well as reducing the required disk space. Thus an array read consists of seven key steps to obtain a given exposure: (a) reset of array; (b) read array n times (pre-); (c) exposure of array for set time; (d) read array n times (post-); (e) subtraction of pre- from post-; (f) repeat steps (a) to (e) m times; and (g) co-average m frames. Then the frame is stored as a 32-bit real frame of 1024 × 1024 × 2 in FITS (Flexible Image Transport System) format for display and
400  C. Packham et al.

![Figure 6. Idealized INGRID exposure schematic. The array temperature is regulated using a custom-built temperature controller with a temperature sensor attached to the array mount. The standard operational temperature of the array is 74 K at the Cassegrain focus – slightly colder than liquid nitrogen temperatures, to reduce read noise. When used with NAOMI, a standard operating temperature of ~78 K is used. Internal to the cryostat are live motors, customized for cryogenic operation. Each motor is linked to a mechanism, providing independent selection for each of the two filter wheels, the cold stop wheel, the array-focus control and the pupil imager mechanism. All motors are controlled from a VME electronics rack with a Motorola CPU card running VxWorks. The control software and the engineering displays were developed using the EPICS (Experimental Physics and Industrial Control Systems) tools.](image)

![Figure 7. Model versus measured encircled energies: WHT theoretical diffraction limit (solid line), theoretical central field point source (dashed line) and a measured J band source (dotted line) encircled energies.](image)

manipulation. Fig. 6 shows an idealized schematic of an INGRID exposure where the array is read in MNDR mode three times.

Typically, observing at NIR wavelengths requires the field of view of the detector to be stepped by subarray amounts to sample the sky background accurately, to remove bad pixels and, sometimes, to remove effects of undersampling the image, a process commonly termed dithering. This is achieved for INGRID by linking the observing system directly to the telescope control system, also allowing telescope pointing, focus, etc. to be copied to the FITS header of each INGRID frame. When observing with INGRID, the user controls the instrument through a combination of command line inputs, automated scripts and graphical user interfaces. An automatic display tool offers limited image arithmetic and rapid image display to confirm telescope pointing and that the array is not saturated. The display tool can be used to subtract the post- from the pre-reads or any other archived image which can be used to provide a first-order sky subtraction to reveal faint structure in the current image. The automatic display checks each pixel in both the pre- and post-exposures for saturation and colours any saturated pixels on the display to warn the observer of the onset of saturation. This feature samples the level of saturation continuously across the image, particularly important when observing at NIR wavelengths, owing to the often rapid fluctuations in sky background. Finally, a suite of automated quick-look data reduction scripts is provided in IRAF format to enable the data to be processed using simple data reduction techniques.

4 SYSTEM VERIFICATIONS

INGRID has been commissioned successfully at both the Cassegrain and Nasmyth foci of the WHT. Performance at each focus is described at the time of commissioning unless otherwise noted, but it should be noted the commissioning at the Nasmyth focus with NAOMI is ongoing.

4.1 System performance at Cassegrain focus

INGRID was successfully commissioned on the WHT in 2000 March. Six nights of observing time were allocated for commissioning, of which four were used for tests and optimization and two for science verification. Observing conditions were good throughout the run, and the science optimization observations were made in near-photometric conditions. Seeing was good throughout the commissioning (≤0.8 arcsec at V), as measured at other ING telescopes. A second set of commissioning tests was made in 2001 March when the aspheric field lens was fitted to the foreoptics and new filters were installed. In the second set of commissioning observations, seeing was poor but conditions were otherwise good.

With the temporary doublet field lens, the plate scale was found to be wavelength-independent at 0.242 ± 0.001 arcsec pixel−1; with the aspheric field lens, this changes to 0.238 ± 0.001 arcsec pixel−1 (the latter pixel scale to be used for all observations made after 2001 March). Thus, the field of view of INGRID with the doublet or aspheric field lens is 4.13 × 4.13 or 4.06 × 4.06 arcmin2, respectively. The FWHM of field stars was measured at <2 pixel in numerous K and K_s images and was seeing-limited in all other frames and other wavelengths. The encircled energy diagram is shown below in Fig. 7, as measured with the aspheric lens. The deviation in the FWHM across the array was found to vary by an average of ~16 per cent from the best FWHM, but by ~50 per cent in the north-west corner of the array, well modelled by a tilt of the array with respect to the optical axis, which will be corrected at the earliest opportunity. The encircled energy diagram is made in the J band and is the average of three stellar profiles positioned around the center of the array. The WHT diffraction limit and predicted central field encircled energy is also shown on the graph, but these curves are exclusive of seeing affects and hence are shown as guides only. Additionally, the images can suffer from a number of aberrations (image drift, telescope defocus, telescope aberrations, etc.) that act to increase the INGRID FWHM.

Exposure times at J, H, K_s and K are limited typically by the onset of array non-linearity (see below) owing to the sky background, as listed in Table 3 below (measured in 2001 April, air temperature ~7°C). Also included in Table 3 is the time to be dominated by

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1 Available from Wind River, Corporate Headquarters, 500 Wind River Way, Almeda, CA 94501, USA.
Table 3. Background limit and background noise dominated regime.

<table>
<thead>
<tr>
<th>Photometric band</th>
<th>Background limited exposure time (s)</th>
<th>Exposure time to reach background noise limit (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>500</td>
<td>145</td>
</tr>
<tr>
<td>H</td>
<td>120</td>
<td>34</td>
</tr>
<tr>
<td>K, J</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td>K</td>
<td>21</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 8. INGRID limiting magnitudes for an on-source integration time to obtain a signal-to-noise ratio of 3.0 in 0.7-arcsec seeing and background limited conditions. This figure is available in colour in the online version of the journal on Synergy.

2

Photometric zero-point (for 1 ADU s$^{-1}$) and background with aspheric.

<table>
<thead>
<tr>
<th>Photometric band</th>
<th>INGRID zero-point (mag)</th>
<th>INGRID background (mag arcsec$^2$)</th>
<th>WHIRCAM background$^a$ (mag arcsec$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>23.4</td>
<td>15.4–16.4$^a$</td>
<td>16.0</td>
</tr>
<tr>
<td>H</td>
<td>23.4</td>
<td>13.5–14.7$^a$</td>
<td>14.3</td>
</tr>
<tr>
<td>K, J</td>
<td>22.9</td>
<td>11.9–12.5$^a$</td>
<td>–</td>
</tr>
<tr>
<td>K</td>
<td>23.0</td>
<td>11.7–12.1$^a$</td>
<td>11.3</td>
</tr>
</tbody>
</table>

$^a$Several photometric standard stars observed.

$^b$Standard values.

respectively. Table 4 lists the sky background of the WHT Infrared Camera (WHIRCAM) (Hughes, Roche & Dhillon 1996). WHIRCAM was deployed on the WHT from 1995–1999 and used similar filters to those of the IRCAM NIR camera on UKIRT. The measured background values were changed to the new NIR filter system using standard photometric transformation, as described on the UKIRT photometric standards web page.$^2$ It may be seen from Table 4 that the background level of INGRID is similar to that of WHIRCAM at $J$ and $H$, but lower by at least 0.4 mag at $K$, presumably because of the improved baffling and cold stops interior to INGRID providing improved rejection of thermal radiation. The parameters remain under vigilance; please see the INGRID web pages for current details.$^3$

The array shows a large number of hot pixels, which increase in both number and intensity with increasing exposure time (>100 hot pixels in 2 s). However, these are entirely repeatable and act as a ‘pedestal’ added to the signal frame and, thus, can be subtracted as part of the standard reduction routine (i.e. with dithered observations). The non-linearity of the array was found to be <4 per cent over the range 0–18 000 ADU, worsening rapidly at higher counts until the full well capacity was reached at 28 000 ADU. The gain of the array was found to be 5.3 e$^{-}$ ADU$^{-1}$, the read noise was measured to be 26–45 e$^{-}$ rms (CDS) and the average dark current is <1 e$^{-}$ pixel$^{-1}$ s$^{-1}$. The read noise has now been reduced to 16–24 e$^{-}$ rms, which has a negligible effect on the sensitivity as most INGRID observations are photon-noise limited (see Table 3 above). The higher than expected read noise is currently under investigation. The post-exposure processing and archiving takes ~2.5 s (CPU dependent) and telescope overheads associated with standard dither patterns (~5-arcsec positional offset) add ~5 s to the overhead.

4.2 System performance at Nasmyth focus with NAOMI

INGRID was commissioned with NAOMI, the adaptive optics system of the WHT, during 2000 and 2001. Replacement of the warm external collimator set the pixel scale at 0.04 arcsec, which Nyquist samples the delivered FWHM. In 0.7-arcsec seeing, NAOMI yields images with FWHM 0.2 arcsec in $K$ band and 0.3 arcsec in $J$ band (Strehl ratios of a few tenths for bright guide stars). There is still significant correction in seeing as poor as 1.2 arcsec, with FWHM being reduced to 0.6 arcsec. At the $K$ band, the Strehl ratio is predicted to fall to about half its on-axis value at radius 20 arcsec from the guide star, matching well the 40-arcsec diameter of the INGRID field. The fall-off is faster at shorter wavelengths. Currently, there are few measurements of Strehl ratio delivered off-axis, but they are consistent

$^2$ http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/phot_trans.html

$^3$ http://www.ing.iac.es/Astronomy/instruments/ingrid/index.html
Figure 9. \(B, J\) and \(K\) composite image of A2218. The true-colour image is constructed from the INGRID \(J\) and \(K\) frames (coded as green and red), along with a deep \(B\)-band image of the cluster taken with the 5.1-m Hale telescope at Palomar Observatory (shown as blue). The field is 190 arcsec on a side and covers the central portions of the INGRID images. In addition to the population of luminous, early-type cluster galaxies visible in the image, several highly elongated gravitationally-lensed arcs are identifiable around the brightest cluster galaxies. The wide range in the optical-infrared colours of these high redshift galaxies is illustrated graphically by this true-colour image.

The throughput of NAOMI is \(\sim 0.85\), and that of the Nasmyth derotator preceding NAOMI is currently \(\sim 0.75\), so the NAOMI/INGRID zero-points are about 0.5 mag lower than for INGRID at Cassegrain. The sky brightness measured in \(J\) and \(H\) bands is similar to that at Cassegrain, but at the time of commissioning, that in \(K_s\) was somewhat higher owing to unexpectedly high emission from surfaces upstream of the NAOMI/INGRID optics, e.g. those in the Nasmyth derotator. Redesign of the derotator and other components is expected to improve both throughput and emissivity. The suspected detector tilt has a negligible effect on the image quality of the NAOMI/INGRID combination as a result of the slower focal ratio providing a greater depth of focus.

Two software modifications were needed to allow INGRID to operate effectively with an AO system. First, dithering was synchronized with corresponding movements of the guide-star pick-off mirror of NAOMI, to avoid the wavefront sensor losing lock on the guide star. Secondly, fast-readout of a small section of the INGRID chip was implemented to allow rapid (\(\sim 2\) Hz) iteration on the shape of the deformable mirror to converge on an initially ‘flat’ configuration yielding diffraction-limited images.

4.3 Observations of galaxy cluster A2218

During commissioning in 2000 March, images of A2218 were obtained under photometric conditions in \(\sim 0.6–0.8\) arcsec seeing (measured at \(K_s\) band). The exposures consist of a total of 8.3 ks integration at \(K_s\) and 9.1 ks at \(J\). The \(K_s\) frames comprise multiple sets of three individual 20-s exposures which were co-added in hardware, and the \(J\)-band images represent single 60-s exposures. Each of the 60-s exposures are spatially offset on a non-repeating rectangular grid with 90-arcsec spacing. They were reduced in a standard manner, using a smoothed illumination correction derived from all the \(J\) or \(K_s\) frames obtained during the night and then a local sky correction constructed from a running median of nine frames around a particular science frame. Then the frames were aligned using integer pixel shifts and combined using a cosmic-ray rejection algorithm to produce a final frame.

INGRID images (see Fig. 9) have been analysed in combination with deep optical photometry from the Hubble Space Telescope to

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4 Further updated information on the performance of NAOMI may be found at the following web page: http://www.ing.iac.es/Astronomy/instruments/naomi/index.html
investigate the colours of morphologically classified galaxies in the core of A2218 (Smail et al. 2001). These authors analysed the high-precision optical and optical–infrared colours of galaxies spanning a factor of 100 in K-band luminosity and compared these with grids of stellar population models to estimate the ages and metallicities of these systems. The INGRID photometry was crucial for breaking the degeneracy between age and metallicity in this analysis. They concluded that the locus of the colours of the stellar populations in the luminous (>0.5 $L^*_K$) early-type galaxies, both ellipticals and S0s, traces a sequence of varying metallicity at a single age. At fainter luminosities (<0.1 $L^*_K$), this sequence is extended to lower metallicities by the morphologically classified ellipticals. However, the faintest S0s exhibit very different behaviour, showing a wide range in colours, including a large fraction (30 per cent) with relatively blue colours that appear to have younger luminosity-weighted ages for their stellar populations, 2–5 Gyr. Smail et al. (2001) show that the proportion of these young S0s in the cluster population is consistent with the claimed decline in the S0 population seen in distant clusters and that these observations provide additional support for the recent evolution in the morphological mix within clusters.

The INGRID images are also being used to study the properties of a variety of high-redshift galaxies that are gravitationally magnified by the massive cluster core. These populations include the optically-selected galaxies seen as arcs and arclets (e.g. Kneib et al. 1996), extremely red objects (EROs, Smith et al. 2002) and submillimetre-selected galaxies (van der Werf et al., in preparation).

### 4.4 Observations of barred galaxies NGC 1530 and 3351

During its 2000 March commissioning, INGRID was also used to image two barred spiral galaxies with nuclear rings of enhanced star formation: NGC 1530 and 3351 (Messier 95). Bars in galaxies are best studied using NIR imaging; in fact, the fraction of disc galaxies showing bars increases significantly – by ~75 per cent – when using NIR rather than optical imaging (e.g. Knapen, Shlosman & Peletier 2000). NIR imaging is more sensitive to the bar structures than optical imaging is as it is much less sensitive to attenuation by dust in a galaxy (a factor of 10 less than at V band), and because bars are mainly populated by older, redder stars.

The presence of a bar has important implications for the dynamics and evolution of the galaxy as a whole. For instance, bars may lead to an inflow of gaseous material from the disc towards the central regions, as the gas can lose angular momentum due to dissipation in shocks in the bar (see, for example, reviews by Shlosman 1992; Sellwood & Wilkinson 1993). In the two galaxies considered here, this gas inflow stagnates, presumably under the influence of a pair of inner Lindblad resonances, in a ring-like region a few kpc in radius around the nucleus. The much increased gas density leads to enhanced star formation in the so-called nuclear ring. As relatively young stars (mostly K and M supergiants) also emit in the NIR, a pattern of individual star-forming knots in the nuclear ring is clearly observed, especially in NGC 3351 (Fig. 10). In NGC 1530, the star formation in the nuclear ring region follows the morphology of spiral arm fragments, as discussed in more detail by Pérez-Ramírez et al. (2000).

NGC 3351 hosts another ring: a so-called inner ring, located at the radius where the bar ends, which is apparent in the $K_s$ image (Fig. 10). Although this inner ring is much more prominent when imaged at Hα wavelengths, due to the enhanced star formation within it, it is still well outlined in the NIR. Such inner rings are thought to be directly related to the location of dynamical resonances in galactic discs. That such resonances do not always lead to the formation of multiple rings can be seen in the case of NGC 1530, a galaxy which hosts a prominent bar, very well seen in the NIR (Fig. 11), and a nuclear ring-like region with much enhanced star formation, but no inner ring near the end of the bar. Even in $K_s$, with an order of magnitude less dust extinction than in V, well defined dust lanes are clearly seen coming into the nuclear region. On the leading side of these dust lanes, star-forming ‘knots’ are visible in $K_s$, indicating young stellar populations with ages of less than about 10 Myr. Similar star-forming regions are also seen in the bar and in the spiral arms near the end of the bar.

![Figure 10](image-url) J- and $K_s$-band observations of NGC 3351. J (left-hand panel) and $K_s$ (right-hand panel) observations of NGC 3351. The J-band image (scale in arcmin) shows the large-scale structure, whereas the $K_s$ image (scale in arcsec) shows the inner regions of the same galaxy (indicated by the box on the left-hand panel), including the nuclear ring.
K$_{s}$ images such as the ones shown here have been used by Block et al. (2001) to determine the gravitational torque due to the bar, which can be interpreted as a measure of the strength of the bar. This is a difficult task, only possible with the use of NIR imaging of complete galaxy discs. Here lies the power of INGRID, an imager on a 4-m class telescope with small enough pixels to sample good seeing conditions (see Fig. 10), but which has a field of view of $>$4 arcmin, and which with careful mosaicking can routinely image galaxy discs of $>$8 arcmin across (see Fig. 10). Block et al. conclude from the study of INGRID images of tens of galaxies, including the image of NGC 3351 shown in Fig. 10, that the relative bar torque, or strength, correlates only weakly with traditional bar classifications – as listed, for example, in the main catalogues – and that the Hubble classification scheme poorly recognizes the gravitational influence of bars.

5 DISCUSSION AND FUTURE WORK
INGRID has been demonstrated to be a highly effective NIR imager for the 4.2-m WHT. For the UK astronomical community, the large field of view that INGRID offers when used as the Cassegrain focus complements the higher-resolution UKIRT Fast-Track Imager (UFTI). INGRID meets the optical quality requirements for both Cassegrain and AO imaging, although a slight tilt of the array to the optical axis degrades the optical quality when used at the Cassegrain focus slightly. Future improvements to the readout chain and computing infrastructure will reduce the computing time and hence increase observing efficiency. Also, a modification to the MNDR readout is envisaged where the array is read whilst exposing (the so-called ‘read-up-the-ramp’), providing a further reduction in read noise. Additionally, the data will have a linearity correction applied prior to archiving using a look-up table. The array will be relocated in the optical beam to correct the slight tilt. Finally, a pipeline data reduction package will produce bad-pixel-corrected, flat-fielded, sky-subtracted, astrometrically calibrated images.

ACKNOWLEDGMENTS
The design and construction of INGRID included several other members of the RGO and the ING, to which the authors wish to express their deep gratitude. Thanks also go to Richard McMahon of the IoA, UK, for providing assistance with the table of survey power. The authors wish to thank the anonymous referee for numerous useful comments. This paper is based on observations made with the WHT operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. CP acknowledges support from the NSF. DFMF acknowledges financial support from the ‘Subprograma Ciencia e Tecnologia do 2 Quadro Comunitário de Apoio’. IRS acknowledges support from the Royal Society and Leverhulme Trust. AH acknowledges support from the Isaac Newton Group and the University of Hertfordshire.

REFERENCES
Hodapp K.-W. et al., 1996, New Astron., 1, 177

### Table A1. The parameters of the powered INGRID optics.

<table>
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<th>Description</th>
<th>Glass</th>
<th>Leading edge radius of curvature (mm)</th>
<th>Following edge radius of curvature (mm)</th>
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<td>4th camera lens</td>
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### APPENDIX 1

The path length from the f/11 focus to the array is 567.8 mm and the path length from the front of the Cassgrain field lens to the array is 522.75 mm. Table A1 lists the parameters of the powered INGRID optics.

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