PIRATE: A Remotely Operable Telescope Facility for Research and Education

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ABSTRACT. We introduce PIRATE, a new remotely operable telescope facility for use in research and education, constructed from off-the-shelf hardware, operated by The Open University. We focus on the PIRATE Mark 1 operational phase, in which PIRATE was equipped with a widely used 0.35 m Schmidt-Cassegrain system (now replaced with a 0.425 m corrected Dall-Kirkham astrograph). Situated at the Observatori Astronòmic de Mallorca, PIRATE is currently used to follow up potential transiting extrasolar planet candidates produced by the SuperWASP North experiment, as well as to hunt for novae in M31 and other nearby galaxies. It is operated by a mixture of commercially available software and proprietary software developed at the Open University. We discuss problems associated with performing precision time-series photometry when using a German Equatorial Mount, investigating the overall performance of such off-the-shelf solutions in both research and teaching applications. We conclude that PIRATE is a cost-effective research facility, and it also provides exciting prospects for undergraduate astronomy. PIRATE has broken new ground in offering practical astronomy education to distance-learning students in their own homes.

1. INTRODUCTION

PIRATE (Physics Innovations Robotic Astronomical Telescope Explorer) is a remote telescope facility situated on the Balearic island of Mallorca (2°57′03.34″E, 39°38′34.31″N), at the Observatori Astronòmic de Mallorca (OAM), ~162 m above sea level. It is a remotely operable facility used for research and undergraduate teaching, allowing for a practical astrophysics component to be implemented within The Open University’s (OU, Milton Keynes, UK) distance-learning modules. PIRATE is constructed entirely from off-the-shelf hardware and is operated primarily with commercial observatory control software, with some additional proprietary software developed to support simultaneous use by groups of students. The total cost of the facility, combining all purchased hardware and software, is of the order of $150,000.

The funding for PIRATE was primarily made available by a teaching innovation initiative (piCETL6) to explore the integration of a remotely controlled observatory into university-level distance-teaching modules. The aim of the project was to reproduce the hands-on experience of a traditional laboratory course with real-time access to a telescope from any computer linked to the Internet.

In this article we refer to the PIRATE Mark 1 facility (unless mentioned otherwise), which featured a Celestron7 C14 0.35 m Schmidt-Cassegrain optical tube assembly (OTA). This OTA is currently no longer in use within the PIRATE facility, having been superseded in 2010 August by a 0.425 m PlaneWave Systems8 CDK17 f/6.8 corrected Dall-Kirkham astrograph telescope, which makes use of a new custom microfocuser (provided by PlaneWave), which we designate as PIRATE Mark 2. The Mark 1 hardware remains an obvious choice for cost-effective astronomy, so we report in detail on its capabilities, features, and drawbacks.

1.1. Use in Education

PIRATE needs to cater to a relatively large student body with little or no prior experience in observational astronomy and with a very limited amount of remote supervision by a tutor. Granting a sufficiently high level of access to the facility, such as the ability to initiate the opening and closing of the dome, is considered essential for the student learning experience. The adopted software solution, a combination of the commercial product ACP9 and the proprietary software described in Lucas & Kolb (2010), achieves

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7 See http://www.celestron.com.
8 See http://www.planewave.com.
9 See http://www.dc3.com.
the desired student access privileges without compromising the safe operation of PIRATE. After one tutor-led induction evening conducted via audio communication and World Wide Web interfaces, the student groups could operate PIRATE successfully on their own. A (remote) night-duty astronomer was on call, but was only occasionally contacted.

PIRATE was deployed for OU undergraduate students for the first time in spring 2010 in a 10-week project that is part of the third-level (third year) OU module S382 astrophysics. A total of about 30 students formed three groups with alternating access to PIRATE, for a total of 40 observing nights. Each group selected a suitable target source from the catalog by Norton et al. (2007) of periodic variables found by SuperWASP (Wide Angle Search for Planets) and coincident with a ROSAT (Röntgensatellit) source. The groups then built up a long-term light curve of their target, such as the example shown in Figure 1. Individual observing sessions were staffed by small observer teams of two–four students, who kept in audio and text contact throughout the night. The collaboration of different observer teams in the larger groups on the same target source ensured the emergence of a usable database to which all group members could develop a sense of ownership, even when occasional nights were clouded out and the observer teams on duty may not have succeeded in obtaining data themselves. A fuller account of the challenges and solutions for the PIRATE teaching project can be found in Kolb et al. (2010).

1.2. Use in Research

In its research role, PIRATE performs follow-up photometry of SuperWASP Transiting Extrasolar Planet (TEP) candidates from the SuperWASP (Pollacco et al. 2006) survey, and it discovers extragalactic novae.

Wide-field transit surveys produce light curves of millions of objects. Transit search algorithms (Collier Cameron et al. 2006) are applied to trend-filtered (e.g., Tamuz et al. 2005) light curves to select TEP candidates from the millions of surveyed objects. Most of these candidates will not be TEPs, but will be “astrophysical false positives”, which are estimated to outnumber TEPs in a transit search survey by at least an order of magnitude (O’Donovan et al. 2006). High-priority candidates are followed up with radial velocity measurements to confirm the mass, and therefore the planetary nature, of the transiting object, but this requires scarce large-telescope spectroscopy.

To winnow TEP candidates from wide-field surveys like SuperWASP, small-to-medium-sized telescopes provide higher-precision, higher spacial resolution follow-up photometry (Haswell 2010). In this role, PIRATE can act as a link in the planet-finding chain, reducing the amount of large-telescope time spent on false positives.

PIRATE has also detected novae in M31 (e.g., M31N 2010-01; Burwitz et al. 2010) as part of an XMM-Newton large program for studying the source population in the Andromeda Galaxy, M31, in which a large number of supersoft X-ray sources were identified as counterparts of optical novae (Pietsch 2008). This requires the long-term monitoring of M31 in X-rays with XMM-Newton, Chandra, and occasionally SWIFT. PIRATE forms part of a wider network of optical telescopes that routinely monitor M31 to discover optical novae and track their light curves. Optical spectra of the freshly discovered novae are also obtained with larger telescopes, such as the Hobby–Eberly Telescope (United States) and the BTA (Russia) to classify the novae. With the help of the information extracted from these X-ray and optical data, we are beginning to obtain a better picture of the physical processes that take place in nova outbursts. This optical observing campaign grew out of the XMM-Newton/Chandra M31 nova monitoring collaboration (Pietsch 2010).

In the following sections we describe the hardware and software used in the PIRATE facility, as well as detailing commissioning issues, data reduction techniques, and future improvements.

2. HARDWARE AND SOFTWARE

PIRATE Mark 1 is a remote telescope facility consisting of a 14″ Schmidt-Cassegrain reflector mounted on a Paramount ME10 German equatorial mount (GEM) (Fig. 2). Its main imager is an SBIG STL-1001E, which houses the Kodak KAF-1001E CCD,

See http://www.bisque.com.
a 1024 × 1024 pixel front-illuminated detector with a pixel size of 24 μm and a quantum efficiency of 0.4, 0.55, and 0.65 for wavelengths of 450, 550, and 650 nm, respectively. In combination with the 3.91 m focal length of the Celestron C14, this produces a plate scale of 1.21" pixel⁻¹ and a field of view of 22' × 22'. An Optec TCF microfocuser is located between the photometer enclosure and optical assembly, along with an eight-position filter wheel, containing Johnson-Cousins standard BVRI broadband filters and three narrowband filters (Hα, SII, and OII). PIRATE has a Celestron 80 mm refractor with SBIG ST402 ME camera for autoguiding. The telescope is housed within a Baader Planetarium 3.5 m diameter all-sky clamshell dome (Fig. 3) with built-in weather systems for automatic shutdown in adverse conditions. On-site weather is monitored by a weather station and Boltwood cloud sensor (to the side of the dome) and by both internal and external dome-mounted weather systems (rain, internal humidity, and internal temperature). The dome has its own firmware, which interfaces with the proprietary dome driver, as well as with the Boltwood cloud sensor, allowing for shutdown conditions to be communicated directly to the dome, bypassing the control PCs. Four D-Link Webcams (three internal, one external) provide live video and audio feeds, as well as IR beams for night viewing.

2.1. Camera Characteristics

To characterize the CCD we determined the gain, linearity, read noise, and the dark current (which was measured at a range of temperatures). The gain and the linearity measurements were made using the same set of dome flats for each. A set of dome flats of increasing exposure time was taken in order to measure the median counts of a 100 × 100 pixel subframe in the middle of each image. For the short exposure times (of the order of a few seconds), we attempted to generate a shutter correction map using the methodology of Zissell (2000), anticipating that we might see position-dependent corrections to the exposure time (due to the shutter travel) of the order of 10⁻³ s. However, this produced a null result, and further investigation into the shutter mechanism of the STL-1001E confirms a rotating shutter wheel that should be devoid of shutter travel effects. We therefore do not apply any shutter correction to the short-exposure flat fields. We measured the bias level from contemporaneous bias frames and subsequently subtracted the mean pedestal level of 107 ADU from each flat. The subframe was chosen to be the center of the vignetting function, where the image is at its flattest. To assess the linearity of the CCD, we plotted median subframe counts against exposure time (Fig. 4a) and fit a linear trend to the same ADU range. The residuals of this fit can be seen in Figure 4b. We note a deviation from linearity of less than 1% at the top end of the dynamic range and less than 2% at the bottom end. We measured the gain using the following relationship: \( \sigma_{\text{ADU}}^2 = \langle 1/g \rangle \langle N_{\text{ADU}} \rangle \) (Howell 2000), where \( \sigma_{\text{ADU}} \) is the standard deviation of the subframe counts, and \( \langle N_{\text{ADU}} \rangle \) are the mean recorded counts in the subframe. To derive this expression, one assumes that the statistical relationship \( \sigma_e^2 = \sqrt{N_e} \) holds, where \( \sigma_e \) and \( N_e \) are the uncertainty in and the number of recorded photoelectrons, respectively, which only holds when the process is governed by Poisson statistics. To determine \( g \), we therefore plot \( \sigma_{\text{ADU}}^2 \) against \( \langle N_{\text{ADU}} \rangle \) (see Fig. 4c). We needed sufficient photoelectrons for photon-counting (Poisson) noise to be dominant, and so we fitted to the range of 20,000 ADU < \( \langle N_{\text{ADU}} \rangle \) < 40,000 ADU. We chose an upper limit of 40,000 ADU to be well clear of the digital counting limit of 65,535 ADU (16 bit). We measured a value for the gain of

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11 KAF-1001E specification sheet: http://www.kodak.com/ek/US/en/KAF-1001ELongSpec.htm.
12 See http://www.baader-planetarium.com/.
where $b \sim d$ in each pair, so that for consistency, we also split the bias frames into pairs, subtracting the expected linear region $20,000 - 40,000$ of the preceding fit.

To measure the readout noise, we took 30 bias frames at a temperature of $15 \, ^\circ C$ to $-20 \, ^\circ C$ in increments of $5 \, ^\circ C$. The measured values are listed in Table 1. We measure a dark current of $0.02 \pm 0.02 \, e^- \, s^{-1}$ and $0.08 \pm 0.02 \, e^- \, s^{-1}$ at $-20 \, ^\circ C$ and $-10 \, ^\circ C$, the typical operating temperatures for winter and summer, respectively. We also find a value of $0.51 \pm 0.03 \, e^- \, s^{-1}$ at $0 \, ^\circ C$ (compare the manufacturer’s specification of $1 \, e^- \, s^{-1}$ at $0 \, ^\circ C$).

2.2. The Mount

The Paramount ME GEM is able to deliver an all-sky pointing accuracy of around $2'$. We employ the software TPPoint$^{13}$ to model system flexure to achieve this value, in which we use 30 model points that capture the discrepancy between intended and actual pointing for a variety of telescope positions. We had previously employed an $\sim 150$-point model, which was abandoned due to the addition of new hardware. We noted that the subsequent 30-point model replacement provides sufficient pointing accuracy to enable the control program to plate-solve and correct for pointing inaccuracy with only a small contribution to interframe overhead, and so we have settled at 30 points for convenience. We also have the ability to identify and remove periodic error in the sidereal tracking from within the mount control software, by measuring the correcting impulses provided by the autoguider. The periodic error is caused by irregularities in the rotation rate of the worm gear through one cycle, and so it presents itself entirely in right ascension. We fitted a fifth-order polynomial with a peak-to-peak amplitude of $4.8'$ and subsequently saw improvements in the circularity of each star’s point-spread function. As this is a German equatorial mount, the OTA must flip from one side of the pier to the other when the tracked target crosses the meridian. This results in the observed field being rotated $180^\circ$ with respect to the optics and camera.

2.3. Software

The hardware is controlled by a collection of Windows-based software (MaxIm DL$^{14}$ for imaging, TheSky6$^{15}$ for mount control, and FocusMax$^{16}$ [Weber & Brady 2001] for control of the microfocuser), which are each controlled by ACP$^{17}$, an observatory control suite that automates the command of each of the component software packages through the ASCOM-standard driver layer. These programs are run on a 2.13 GHz CPU Windows XP PC with 2 Gbyte of RAM. The site receives its Internet connection via satellite; connection speeds are good, with typical upload speeds from the OAM to the UK of $\sim 250$ kbyte s$^{-1}$ and operating latencies of around 60–100 ms. We use Dimension 4 from Thinking Man Software$^{18}$ to synchronize the control PC’s clock to UTC via a Network Time Protocol server every 10 s.

$^{13}$ See http://www.tpsoft.demon.co.uk/.
$^{14}$ See http://www.cyanogen.com.
$^{15}$ See http://www.bisque.com.
$^{16}$ See http://users.bsdwebsolutions.com/~larryweber/.
$^{17}$ See http://ACP.dc3.com.
$^{18}$ See http://www.thinkman.com/dimension4.
For a given observation or group of observations in a night, ACP will first typically initiate an autofocus via FocusMax, which searches for magnitude 4–7 stars within a $2^\circ \times 2^\circ$ region to focus with. Once focused, ACP starts a 4 s pointing exposure, which it subsequently plate-solves via PinPoint\textsuperscript{19} using the Guide Star Catalog\textsuperscript{20} to determine the pointing error. A corrective slew is applied, and the image sequence commences. Each full exposure, once read out, is plate-solved once more to check the pointing. We apply a maximum pointing error of 3 $''$, forcing a pointing update if a given image is determined to be misaligned by more than 3 $''$. The benefits of doing so can be seen in Figure 5, where the centroid deviation is significantly reduced. This reduces the contribution to photometric noise from flat-fielding errors (more on this in § 3.3).

The software tasks performed between exposures in a time-series run are as follows:

1. The previous image is read out and plate-solved, from which the astrometric residual, pointing error (magnitude and direction), mean FWHM, true focal length, true image center, and camera sky position angle are calculated.

2. The centering is tested: if within the maximum pointing tolerance, no slew update is performed; if outside the maximum error tolerance, the autoguiding is temporarily stopped, and a corrective slew is performed.

3. A guide star is selected from the guider image, with the star providing a signal-to-noise ratio $\geq 3$ for the shortest exposure interval chosen. The exposure is started.

We typically see astrometric residuals from the plate-solve of $\sim 0.2''$. The total interframe overhead between exposure end and exposure start is $\sim 15$ s. Each frame takes $\sim 2.5$ s to read out and download, meaning that the overhead is dominated by the time taken to find the plate solution. The 15 s quoted refers to the case where no subsequent pointing update is required after the plate-solve. When a pointing update is required (pointing error $>3''$), 1–2 s is added to the overhead time.

ACP also provides a Web control interface, which made it an obvious choice for implementation in a distance-learning, group-based education scenario. When used by researchers, direct access to the PIRATE control PC is achieved by remote access of the control PC’s desktop. Students, however, are not given direct access to the main control PC and instead interact with the hardware through a proprietary server/client setup that limits their control. The server-side application (switch server) provides access to relay switches that are used to turn components on individually, and it also has a suite of extra capabilities. These include preventing the dome from being opened in daylight hours; closing the dome in case of excessively high humidity or strong winds; automatically cooling the two cameras in a monitored, staggered sequence; and checking the availability of the local Internet connection, forcing a dome shutdown in case of lost Internet connection. Further information on the operation of PIRATE’s switch server can be found in Lucas & Kolb (2010).

3. DATA ACQUISITION, REDUCTION, AND COMMISSIONING ISSUES

3.1. Observing Strategy

On a given night, the user cools the main imaging camera down automatically using the switch server to a target temperature of $\sim 40^\circ$C below the current ambient temperature. Consequently, the operating temperature of the CCD varies seasonally, usually between $-10^\circ$C in the summer and $-20^\circ$C in the winter. This ensures that the camera is always operating at

\begin{table}[h]
\caption{Measured dark current for range of chip temperatures}
\centering
\begin{tabular}{cccc}
\hline
$T$ (°C) & D.C. $\epsilon$ (e$^{-}\text{s}^{-1}$) & $\sigma_{\text{D.C.}}$ (e$^{-}\text{ADU}^{-1}$) \\
\hline
$-25$ & 0.01 & 0.02 \\
$-20$ & 0.02 & 0.02 \\
$-15$ & 0.05 & 0.02 \\
$-10$ & 0.08 & 0.02 \\
$-5$ & 0.27 & 0.03 \\
$0$ & 0.51 & 0.03 \\
$5$ & 1.13 & 0.03 \\
$10$ & 2.25 & 0.03 \\
$15$ & 5.20 & 0.04 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{*}D.C. indicates dark current.

\textsuperscript{19} See http://pinpoint.dc3.com/.

\textsuperscript{20} Vizier Online Data Catalog, II/143A (Lasker et al. 1996).
the lowest available temperature. Once the target temperature is achieved, ACP is started and the dome is opened at around sunset. ACP’s automatic sky-flat procedure is then initiated. This procedure automatically scales exposure times to achieve a target peak count of ~33,000 ADU in each filter’s flat fields. During the flat procedure, sidereal tracking of the mount does not occur. The flat fields are dithered so that any stellar sources present in the sky flats can be removed upon combination of each flat into the master flat field. Once the flat fields are obtained, the dome is then shut while waiting for the end of nautical twilight (ACP allows observations through astronomical twilight). During this time, the user takes calibration frames. Fifty bias frames are taken first, to assist in completely flushing the chip of any residual charge from the flat fields. Then dark frames are taken in batches of 10 for each anticipated exposure time to be used for the science frames throughout the night. Typically, these exposure times are 30, 45, 60, 90, and 120 s. The dome is then reopened in time for the end of nautical twilight, and the observing schedule for the night commences.

3.2. Photometric Reduction, Performance, and Light-Curve Generation

The data are available in real time via direct FTP to the control PC, and users with direct access to the control PC may also inspect each image live after being read out from the camera. Each morning the previous night’s science and calibration frames are then transferred from the OAM to a local archive at the OU; the user may obtain the frames the following day. Reduction (in the research case) is performed by a custom IRAF scripts that make use of the IRAF task (Stetson 1987). The DAOPHOT output is then fed back into an IDL script that performs differential photometry and generates the final light curves for each object in the frame. When used for teaching, the students do not make use of such scripts and must process their frames manually using MaxIm DL.

The initial IDL script first compiles a list of available light frames from the previous night and then iteratively displays each one in turn, asking the user to reject or accept each frame. This allows for the rejection of frames with defects, such as a lack of usable point sources in the frame, trails, or excessive pointing error. The user then accepts or rejects a final list of rejected frames, producing a master file list on acceptance. Lists are generated for each calibration frame type, discriminating flat fields by filter. If flat fields matching the chosen filter of the light frames do not exist, no flat-fielding is performed. An IRAF script is generated for the task CCDCOR, which performs standard CCD calibrations and then executes the requisite post-calibration rotation commands for preflip light frames.

The IDL routine first proposes a master frame according to a simple statistical test performed on all frames. The master frame proposed will be the frame that exhibits the highest standard deviation from the quartile of frames that have the lowest mean values. The mean test ensures a low sky background (high sky backgrounds are often indicative of Cirrus scattering), while selecting a frame with high standard deviation ensures many strong point source fluxes well above the background. The user can override the proposed frame selection and select their own frame as the master frame. An alternative method would be to determine the frame with the minimum average FWHM and to designate this the master frame, due to the superior seeing. This is not currently implemented.

Once defined, we use DAOFIND on the master frame (making use of a user-given average frame FWHM) to find all sources above a $6\sigma$ threshold. An initial PHOT task run on the master frame determines the master coordinate list, with only sources that do not suffer a PHOT task failure flag going into the master coordinate list. A linear transformation is then deduced between the master frame coordinates and those of all other frames, and this is used to generate the final coordinate lists for each frame. Final photometry is standardly performed with an aperture 3 times the input (master frame) FWHM, though the aperture size can be changed if the data warrant (e.g., in the case of close companions to the target that lie within or partially contaminate the measuring aperture).

Once the instrumental photometry is obtained, it is fed into another IDL script that places the whole night’s photometry in memory as a data cube. Mid exposure time in UTC then is converted to HJD for all frames. We note the preference of using BJD over HJD, which can differ by as much as 4 s (Eastman et al. 2010), as well as calculating BJD from terrestrial time instead of UTC, which currently differ by 66.184 s as of 2011 July. We will be incorporating these changes into IDL scripts in the near future. The night’s data are then investigated for PHOT task failures. Light curves that suffer a photometry failure in one or more frames are rejected from the cube. In case of bad frames still present in the data (which would lead to an excessive number of light curves being cut), we introduce a parameter (to be set by the user) defined as $N_{\text{star}}/\alpha$, where a frame is removed if it contains a fraction of photometry failures $>N_{\text{star}}/\alpha$. Here, $N_{\text{star}}$ is the number of stars in the frame, and $\alpha$ is a free parameter. We find a value of $\alpha = 10$ to usually be sufficient. The cube is then sorted by magnitude, and an iterative ensemble compilation procedure begins. We employ a similar methodology to that of Burke et al. (2006), where for each star, all the corresponding comparison light curves are sorted according to a light-curve figure of merit. Each comparison light curve is normalized to unity, and these light curves’ rms values (i.e., the standard deviation about the mean) are used as the figure of

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21 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
merit. Starting with the best-rated light curve (i.e., lowest rms) for a given star, each subsequent light curve in the list is iteratively included in the ensemble, using inverse variance weights, where the weights derive from the IRAF photometric uncertainties. Note that the ensemble never contains the flux from the target star, as the target star is excluded from the list of light curves. The following refers to the production of the final light curve for one star only. The ensemble flux, $E_j$, for a given frame $j$, containing comparison stars $i = 1, \ldots, N$ is compiled as follows:

$$E_j = \frac{\sum_{i=1}^{N} \omega_{ij} F_{ij}}{\sum_{i=1}^{N} \omega_{ij}},$$

where $F_{ij}$ are the stars’ individual fluxes, and the individual weights are given by

$$\omega_{ij} = \frac{1}{\sigma_{ij}^2}.$$

The uncertainty in the ensemble is given by the standard deviation of the weighted average:

$$\sigma_{E_j} = \left[ \frac{\sum_{i=1}^{N} \omega_{ij}^2}{\sum_{i=1}^{N} \omega_{ij}} \right]^{-1/2}.$$

With each new star added to the ensemble, the differential target star light curve $d_s = (d_1, \ldots, d_N)$, where $d_{s,j} = F_{s,j}/E_j$ ($j = 1, \ldots, N$) is calculated from the recorded flux of the target star, $F_{s,j}$, and calculated ensemble flux, $E_j$. The light curve $d_s$ is then normalized by dividing through by its median value, and the rms is computed. The final light curve, $d_s;_{fin}$, makes use of the ensemble that produces the lowest rms. Each star therefore has its own unique comparison ensemble. In Figure 6, we display the results of this method for the stars in the WASP-12 field on two consecutive nights with approximately 30% and 39% Moon illumination, at a separation of $\sim 142^\circ$ and $\sim 132^\circ$ from the Moon, respectively, comparing USNO-B1.0 magnitudes with the rms precision of PIRATE $R$-band light curves from 60 s exposures. The observation runs of 2009 November 22 and 2009 November 23 contain light curves of 759 and 730 objects, each consisting of 359 and 321 exposures, respectively. We see from this plot that sub-percent precision is available for magnitudes $\sim 13.5$ and less with an operating cadence of 76 s (including the aforementioned overheads). For comparison, we include the contribution to the uncertainty from photon noise alone.

As an example, this particular method of light-curve compilation was used in the production of light curves of the transit of WASP-12b, for which six nights of data were captured during the months of 2009 October–November, the details of which can be found in Haswell et al. (2011, in preparation). We show the light curve from the night of 2009 November 23 in Figure 7, which has a postfit residual rms of $\sim 2.6$ m mag. These data were used to confirm the published ephemeris for a Hubble Space Telescope visit investigating the exosphere of WASP-12b (Fossati et al. 2010). The displayed model light curve is the published model light curve (fit to the data from the discovery article) using the parameters of Hebb et al. (2009) and analytic light-curve solutions of Mandel & Agol (2002), using the limb-darkening coefficients of Claret (2000).

We find that the entire light curve’s rms is an unsuitable figure of merit for determining how accurately a light curve has captured an object’s inherent variability in certain cases. Substantial out-of-transit coverage of WASP-12 (out to phase

![Figure 6](image1.png)

**Fig. 6.**—Light-curve rms deviation as a function of USNO-B1.0 $R$ magnitude for the nights of 2009 November 22 and 2009 November 23, 60 s exposures, WASP-12 field.

![Figure 7](image2.png)

**Fig. 7.**—WASP-12b transit observation ($R$ band) from 2009 November 23. Residuals from the model fit are shown offset by 0.05.
1.4 [not shown]) meant that the rms is an acceptable figure of merit for the observations shown in Figure 7. Obviously, if one has prior knowledge of the transit ephemeris, as with these WASP-12 observations, solely the out-of-transit light curve should be used to calculate the figure of merit. In the case of the follow-up of candidate planets, or for other purposes (e.g., cluster surveys), the ephemeris might not be well constrained. The method’s success is therefore subject to the amplitude, timing, and character of the star’s intrinsic variability.

When tackling variable stars with amplitudes over and above ∼10%, the procedure will often select very faint, nonvarying stars for inclusion within the ensemble, as long as their light-curve rms is less than the intrinsic variability of the target star. In Figure 1 we showed the light curve of a larger-amplitude (∼20%) variable, 1SWASPJ163420.90+424433.4 (Norton et al. 2007), taken on 2010 June 7 by OU undergraduate students as part of their practical module. The data were reduced separately for inclusion here, with four comparison stars chosen manually for combination through inverse-variance weighting into a comparison ensemble, as the rms-minimization method does not work for this target. We also find the procedure to be inadequate in some smaller-amplitude situations, such as a typical hot Jupiter transit with insufficient out-of-transit coverage. For example, a light curve that captures 1 hr in-transit, egress, and 1 hr out-of-transit approximates a step function and is bimodal in $d_a$—a scenario for which the rms is a poor figure of merit.

To combat this, we are developing an extension of the technique that breaks each comparison light curve into multiple segments and performs a linear regression in each segment, producing a selection of relevant statistics: segment rms, residual segment rms (after subtracting the fit), and segment median value. By careful analysis of each light curve’s segment statistics, as well the statistics of the segments as a whole (e.g., range or standard deviation of the segment medians), it will be possible to identify variable stars for exclusion from a comparison ensemble, while simultaneously allowing for any variable star to have an optimal comparison ensemble automatically determined. This technique will facilitate serendipitous PIRATE discoveries of previously unknown variable stars.

### 3.3. Flat-Field Inaccuracy and Optical Response Calibration

The systematic errors of flat fields as optical response calibrators are often overlooked in the application of differential photometry, as modern autoguiding systems are sufficiently good at locking the stellar point-spread functions to fixed positions on the chip for the duration of a time series. As the observer is only interested in time variability, systematic offsets in the magnitude zero points of any two stars in the field can be ignored. PIRATE’s GEM executes a pier flip as the tracked target crosses the meridian. This moves the OTA to the other side of the pier and inverts the image of the stellar field with respect to preflip frames. This operation effectively moves each stellar point-spread function to an entirely different part of the focal plane. To maintain continuity in the flux ratio between two stars across the pier flip, the vignetting must be determined perfectly. In reality, most flat fields suffer from inaccuracies at the $10^{-2}$ level (Manfroid 1995). We therefore expect, and indeed see, varying flux ratios between two objects in the field across the pier flip. We term this effect a “light-curve discontinuity” (LCD). Several mechanisms contribute to the flat-field systematic errors:

1. Uneven illumination from the source can occur in sky flats, even when they image the sky null point (Chromey & Hasselbacher 1996) as PIRATE’s automatic procedure does. It will also occur in dome flats.

2. Physical changes in the hardware between taking flat fields and science images modify the response function of the system. In the case of PIRATE Mark 1, it is suspected that primary mirror flop, which occurs despite the presence of mirror locks, and/or flexure in the microfocuser assembly changes the vignetting function. It may also lead to the misalignment of the focal plane with the CCD surface, meaning that consistent focus across the field of view is not achievable. In this scenario, the FWHM of the stellar profiles will be a function of chip position, and the measuring apertures used for photometry would see different levels of flux leakage, due to the changed stellar profile after a pier flip.

3. Scattered light in the optical tube assembly is additive and not representative of the optical response of the system. Off-axis, unfocused stray light due to insufficient baffling can contribute to the flat-field exposure. Scattered light is additive. If included in the flat field, this additive light is incorrectly used in the multiplicative flat-field calibration.

We have been unable to develop a wholly effective procedure for self-consistently calibrating the LCD effect without investing much of the night in taking calibration observations. We thoroughly explored these possible approaches:

We used data from the night of 2009 July 23, during which the Moon had 3.2% illumination, so we might expect sky background gradients to be limited. The data were processed in the usual manner and investigated separately as two groups of preflip and postflip frames. The frames in each group were median-combined, and a sixth-order Legendre polynomial was fit to the sky background in each of the two (preflip and postflip) resultant frames using the IRAF task IMSURFIT. Note that the preflip frames were rotated 180°. We denote the background fits by $A_{\text{pre}}(x, y)$ and $A_{\text{post}}(x, y)$, where $x$ and $y$ are image coordinates corresponding to positions on the sky (not pixel coordinates, due to the aforementioned rotation of the preflip frames).

A simple ratio of the pre- and postflip background fits reveals any discrepancy in the sky background for a given star position. We denote this ratio as $A_{\text{map}}(x, y) = A_{\text{pre}}(x, y)/A_{\text{post}}(x, y)$. We show $A_{\text{map}}$ in Figure 8. We note that it has structure predominantly in the $x$ direction and displays a peak-to-peak
variation of \( \sim 7\% \). The (nondifferential) light curves of each of the \( N \) stars (here, \( N = 517 \)), which we denote by \( F_i(t) \), where \( i = 1, \ldots, N \), were median-combined to create an approximation (to first order) of the sky transparency, \( \tilde{F} \). We assume that each star remains at a fixed position in the image \((x_i, y_i)\) for the duration of the observing run. For all of the light curves (including the transparency function), the fluxes were averaged over time for preflip frames and also for postflip frames, producing a single preflip and postflip flux value for each light curve. We therefore use \( F_{\text{pre},i} \) and \( F_{\text{post},i} \) to refer to these time-averaged values. We define the LCD of a star to be

\[
\Delta F_i = \frac{F_{\text{pre},i}}{F_{\text{post},i}}.
\]

We now have the ability to assess the applicability of the background map; if the shape of the sky background (after flat-fielding) provides an estimation of any residual error in the flat-fielding process, then it should correlate well with the observed LCDs. To compare the map with the LCDs, we fit a second-order polynomial through least-squares regression to the irregularly gridded \( \Delta F_i \) values. The result of this fit can be seen in Figure 9. Far from correlating well, the pattern of the LCDs also exhibits greatest deviation in the \( x \) direction, but with opposing orientation. The structure of the map in Figure 8 suggests a fixed and constant light source comoving with the optical tube assembly, inducing the same background structure in both pre- and postflip frames, which is then amplified when the preflip frames are rotated. One would expect any transformation of the vignetting function to be recorded in the sky background, as this gives a continuous indication of the vignetting function. However, the presence of any scattered light in either the science frames or flat fields renders the true vignetting function for each side the pier flip unrecoverable.

The scattered light structure present in the science frames could also have been present in the flat field, and thus the LCDs introduced to the data through the flat-fielding process alone, but the non-flat-fielded data show the same LCD structure seen in Figure 9. Given the dark night (one night after a new Moon) for this data set, it is apparent that scattered (additive) light is likely always present and greatly reduces the accuracy of standard flat-fielding and sky-flat procedures; the GEM simply highlights this inaccuracy.

The data of 2009 July 23 exhibit strong structure in the LCD map and are hence a good demonstration of the problem. A more typical structure can be seen in Figures 10 and 11, from the WASP-12 field on the night of 2009 November 23. The polynomial fit to the LCDs exhibits a smaller peak-to-peak amplitude of \( \sim 2\% \), and there is significant scatter in the residuals of this fit to \( \Delta F_i \).

We conclude that background fitting, sky flats, and even flat-fielding are all ineffective at negating the percent-level LCD effect seen in PIRATE Mark 1. Instead, there are two routes to achieving correct photometric calibration across the pier flip.

The first of these involves creating a photometric superflat. This is discussed in detail in Boyle (2007), Grauer et al. (2008), Manfroid (1995), Regnault et al. (2009), and Selman (2004). At its simplest, this involves observing a set of standard stars at different positions in the field of view and determining the
position-dependent response to the standards in order to build the large-scale, low-frequency optical response of the system into the final flat field. Sky flats or dome flats are observed in tandem, with polynomial fits to their large-scale variation made in order to flatten them. This retains the small-scale, high-frequency intrapixel response, which can then be combined with the standard star-determined low-frequency response function to create a photometric superflat. In constructing the large-scale component, it is preferable to make multiple dithered observations of a cluster containing many standards that span the field of view in order to reduce the number of frames needed. As we expect the response to be different from one side of the pier to another, this involves observing the same cluster twice: once in the eastern sky and again later in the western sky.

The second method involves lending a degree of freedom to the normalization of each light-curve section (preflip and postflip), shifting the flux levels up and down to minimize the $\chi^2$ of a model fit. This method has its limitations in the extent of foreknowledge required to work successfully. In the case of SuperWASP follow-up, the Markov chain Monte Carlo (MCMC) fitting routine of Collier Cameron et al. (2007) can take the light curves from each side of the pier as separate input light curves and include the normalization factor as a free parameter in the fitting procedure. However, this algorithm works with prior knowledge of the light curve, in that its initial parameters from which the MCMC routine iterates are taken from the SuperWASP light curves. This prior expectation of the light curve’s model parameters (including, crucially, the transit ephemeris) assists with the cross-flip normalization. If there is no prior knowledge of the light curve, adjusting flux levels is almost certainly perilous. For example, take the worst-case scenario of a pier flip occurring midway through ingress or egress. In such a scenario it would prove difficult to determine if the flux deficit across the pier flip is instrumental or astrophysical. Great caution is called for in interpreting such light curves.

4. SUMMARY AND DISCUSSION

PIRATE is a remotely operable telescope facility built primarily from readily available off-the-shelf components, used in both education and research. In its educational role, it has successfully supported small groups of simultaneous student users in their efforts to observe and classify variable stars in the SuperWASP archive. We showed that relatively inexpensive equipment can play a useful role in modern astrophysical research, including high-precision time-series photometry required for transiting Jupiter-size exoplanets. The PIRATE system employs a GEM, which provides exceptional stability and all-sky pointing accuracy for its cost. The pier flip introduces LCDs, which are difficult to correct for by calibration procedures alone; the best strategy is to treat pre- and postflip light curves as separate observing runs.

The OTA and camera combination described here awaits reassembly in a neighboring dome at the OAM. We note that the combination of a Paramount ME and the affordable Celestron C14 can be found in many installations worldwide.

The use of a remotely operable telescope in the OU module proved the feasibility of deploying such complex hardware in real time to create an inspirational teaching tool for distance education. The great enthusiasm of the students involved and the quality of the acquired data and of the scientific

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22 See http://www3.open.ac.uk/study/undergraduate/course/s382.htm.
reports generated at the end of the project demonstrate the success of the PIRATE teaching project. Use by level-2 (year-2) students is being implemented, and use by level-1 (year-1) OU students is currently under consideration.

PIRATE has very recently undergone an OTA change to a PlaneWave Systems CDK17 f/6.8 corrected Dall-Kirkham astrograph, which provides a bigger field of view and larger aperture (0.425 m). Future work will involve linking ACP to the dome control via the ASCOM driver layer, allowing for full scripting of a night’s events, adding a level of autonomy to the observing process. Use of ACP Scheduler23 with the current weather station hardware and switch-server intelligence would effectively allow PIRATE to run in a fully autonomous, robotic mode, which will be explored as an operation mode for research purposes. The real-time remote operation will remain the only mode of operation for teaching applications, however, in order to make the learning process as interactive as possible.

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23 See http://scheduler.dc3.com/.

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