EXOPLANETS FROM THE ARCTIC: THE FIRST WIDE-FIELD SURVEY AT 80°N

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ABSTRACT

Located within 10° of the North Pole, northern Ellesmere Island offers continuous darkness in the winter months. This capability can greatly enhance the detection efficiency of planetary transit surveys and other time domain astronomy programs. We deployed two wide-field cameras at 80°N, near Eureka, Nunavut, for a 152 hr observing campaign in 2012 February. The 16 megapixel camera systems were based on commercial f/1.2 lenses with 70 mm and 42 mm apertures, and they continuously imaged 504 and 1295 deg², respectively. In total, the cameras took over 44,000 images and produced better than 1% precision light curves for approximately 10,000 stars. We describe a new high-speed astrometric and photometric data reduction pipeline designed for the systems, test several methods for the precision flat fielding of images from very-wide-angle cameras, and evaluate the cameras’ image qualities. We achieved a scintillation-limited photometric precision of 1%–2% in each 10 s exposure. Binning the short exposures into 10 minute chunks provided a photometric stability of 2–3 mmag, sufficient for the detection of transiting exoplanets around the bright stars targeted by our survey. We estimate that the cameras, when operated over the full Arctic winter, will be capable of discovering several transiting exoplanets around bright (mV < 9.5) stars.

Key words: binaries: eclipsing – instrumentation: miscellaneous – planets and satellites: detection – site testing – techniques: photometric – telescopes

Online-only material: color figures

1. INTRODUCTION

The diurnal cycle is a significant impediment to ground-based transit surveys, limiting their detection efficiency for planets with orbital periods of tens of days or more (Brown 2003). Consequently, exoplanet transit surveys rely on long-term observing campaigns and/or the use of multiple observing sites to reach an acceptable probability of detecting multiple transits. In contrast, circumpolar locations provide continuous darkness in the winter months, potentially allowing single-instrument ground-based surveys to reach longer period planets with high detection efficiencies. The detections of transiting planets around very bright stars (e.g., Charbonneau et al. 2000; Henry et al. 2000; Sato et al. 2005; Bouchy et al. 2005; Christian et al. 2006; Bakos et al. 2007; Pál et al. 2010; Winn et al. 2011; Howell et al. 2012), and the relative ease of characterization of those planets (e.g., Agol et al. 2010; Collier Cameron et al. 2010; Demory et al. 2011; von Braun et al. 2011; Stevenson et al. 2012; Majewski et al. 2012), have demonstrated that very-small-aperture telescopes can discover exciting exoplanets. Here, we describe two circumpolar very-wide-field, small-aperture cameras designed to search for transiting exoplanets around 5000 stars brighter than mV = 9.5.

The advantages of circumpolar astronomy have already motivated several site characterization and observational projects based on the high Antarctic glacial plateau. The Gattini cameras have measured the optical sky brightness, cloud cover, and auroral emission at both Dome A and Dome C (Moore et al. 2006, 2008, 2010), while small, robotically controlled, optical and infrared telescopes are in the testing and operation phases (di Rico et al. 2010; Daban et al. 2010). The CSTAR project (Wang et al. 2011) demonstrated long-term photometry on 10,000 stars in a 23 deg² region centered on the south celestial pole.

In this paper, we present the first astronomical survey conducted from Ellesmere Island, located in the High Canadian Arctic at 80°N in the territory of Nunavut (Figure 1). Robotic site-testing systems deployed at nearby coastal mountain sites found a high clear-sky fraction, low median wind speed, and the possibility of excellent seeing (Steinbring et al. 2010). More intensive site testing at a lower-elevation manned station, the Polar Environment Atmospheric Research Laboratory (PEARL), showed photometric conditions for approximately half of the continuously dark polar night, and continuous periods of hundreds of hours of clear, dark skies. Furthermore, sufficiently clear conditions for spectroscopy or differential photometry occur for up to 86% of the winter (Steinbring et al. 2012). Seeing measurements at the same location show the presence of a weak turbulence layer near the ground (Hickson et al. 2010), potentially providing excellent observing conditions.

The excellent conditions at the Ridge Lab site and their implications for exoplanet detection efficiencies, along with the existing infrastructure and relative ease of accessibility, encouraged us to design astronomical survey instruments for the site. In this paper, we describe the design, operation, and first results from two very-wide-field exoplanet-search cameras, the AWCam (Arctic Wide-Field Camera) prototypes, which we deployed to the Ridge Lab in 2012 February. Although lasting only a week, and so within the regime for which a mid-latitude observatory could achieve similar efficiencies, this initial campaign was intended as a test of the survey capabilities achievable under real observing conditions at the site, as a prelude to longer operations in later years.

The AWCam cameras continuously observed a several-hundred-square-degree field around the north celestial pole,
using short exposures to avoid the need for a tracking mount. Like several lower-latitude transiting exoplanet surveys such as SuperWASP (Pollacco et al. 2006), HAT (Bakos et al. 2004), and KELT (Pepper et al. 2007, 2012), the systems are based on commercial camera lenses. The cameras are primarily designed to search for transiting planets around bright \((m_V < 10)\) stars, but the wide fields also provide continuous photometric coverage of tens of thousands of fainter stars, along with atmospheric transmission, cloud structure, and auroral measurements. The initial survey demonstrated multi-color photometry on \(\approx 70,000\) stars, showed that the images can be precisely astrometrically and photometrically calibrated, and demonstrated that the systems can achieve millimagnitude-level photometry.

The paper is divided as follows. In Section 2, we evaluate the expected transit detection efficiency at the Ellesmere Island site. In Section 3, we describe the system design and construction, including details on the thermal protection systems used to keep the optical elements clear of snow and ice, allowing continuous unattended operation in the Arctic conditions. In Section 4, we describe the data collected during our test campaign, along with the data-reduction pipeline we developed for the systems. Section 5 details the image quality and photometric performance of the cameras, and Section 6 describes some initial astrophysical results from the data set. Section 7 concludes with a discussion of concepts for much larger arctic surveys based on these camera prototypes.

2. TRANSIT DETECTION EFFICIENCY AT ELLESMERE ISLAND

Located on a 610 m ridge at the tip of the of the Fosheim Peninsula, the PEARL facility—often referred to as the “Ridge Lab”—is accessed by a 15 km long road from Eureka, a research base operated by the meteorological division of Environment Canada, the weather service of the Canadian government. The Eureka base is open to air traffic year round, allowing astronomers to visit the site for observing runs throughout the winter.

Each year, the Sun is continuously below the horizon at the Ridge Lab site for 3096 hr (129 days) and is continuously lower than \(-12^\circ\) 1224 hr (51 days). Fall and spring “shoulder seasons,” when the Sun is up for short periods, contribute a further 1441 hr of dark time, for a total of 2665 hr during which the Sun is below \(-12^\circ\) each year. The continuous darkness during the winter months allows continuous monitoring of a field, eliminates day aliases in the measurement of variable objects, and improves the detection probability of a repeating event such as a planetary transit (Pont & Bouchy 2005; Daban et al. 2010; Crouzet et al. 2010).

To quantify this improvement, we performed Monte Carlo simulations of the detection efficiency of a transiting planet survey as a function of orbital period for both a mid-latitude site and the Ridge Lab site (Figure 2). In the simulation, we assume that the telescopes only observe when the Sun is below an altitude of \(-12^\circ\) and when the target is above an airmass of 2.0. We remove nights in which the available observation length is less than three hours, as it is difficult to establish a useful photometric baseline for transit detection in that time. We include weather-time-loss in each simulation, with 24 hr periods of bad weather starting at randomly chosen times (with overlapping bad-weather periods being allowed). We simulated correlated weather outages by assigning a 25% probability for a bad-weather period being immediately followed by another period of bad weather (and so on for subsequent days). The weather simulation parameters were chosen to approximately reproduce typical weather outage patterns at mid-latitude sites (with a total of 35% of observing hours affected by weather), but provide a conservative estimation for the Arctic site, which often sees periods of hundreds of hours of clear skies in the
winter (Steinbring et al. 2012). For the secure detection of an exoplanet candidate we require the detection of three transits. As shown in Figure 2, Polar sites offer much improved detection efficiency for longer period planets, although we note that a mid-latitude site can improve the number of detected shorter-period planets by observing several fields throughout the year. Circumpolar surveys relying upon precision photometry or astrometry can also benefit from the near-zenith location of the celestial poles. At the Ridge Lab site an object at 80° declination can be continuously tracked throughout the winter months at an airmass range of 1.00–1.06, a small range of motion that can reduce atmosphere-induced systematic errors for many astronomical programs.

3. INSTRUMENT DESIGN

The AWCam prototype systems were required to operate autonomously in temperatures as low as −45°C, to avoid or remove ice and snow deposition on their optical surfaces, and to survive storm events including blowing snow with wind speeds as high as 40 m s$^{-1}$. For these reasons, we designed the systems to be both simple and extremely robust.

The cameras are based on a fast Digital Single Lens Reflex (DSLR) camera lens mounted to a 16 MPix CCD camera. The wide-field-imaging system is aligned on the north celestial pole, and we take short 10 s exposures to avoid the need for sky-rotation tracking. Continuous photometry of a circular area of several hundred square degrees around the pole can be obtained. In the 2012 campaign we tested two systems, identical except in their lens and filter choices. The hardware and survey characteristics are summarized in Table 1, and an overview of the hardware is shown in Figure 3.

The two camera systems were mounted on the observing platform of the Ridge Lab building, with ethernet and AC-power connections to a warm control room within the building. The control room also contained a network power switch for remote rebooting of the systems, a network switch, and a server for data storage.

![Block diagram of the camera and data recording hardware. The cameras were placed in convenient locations on the Ridge Lab roof, with an approximately 100′ cable run to the networking and data storage hardware in the PEARL control room.](image)

(A color version of this figure is available in the online journal.)

### Table 1

| Survey characteristics | north celestial pole |
|------------------------|----------------------|
| Survey dates           | 2012 February 14–2012 February 21 |
| Survey length (total)  | 152 hr               |
| Survey length (dark and clear) | 98 hr         |
| Data collected         | 44583 images (1.36 TB) |

#### CCD hardware

| Peak CCD Quantum Efficiency | 59% |
| Pixel size                 | 9 μm |
| Readout time               | 4 s  |

#### 85 mm camera

| Camera lens               | Canon EF 85 mm f/1.2L II USM |
| Field dimensions          | 25.4 × 25.4 |
| Continuous-coverage field | 504 deg$^2$ |
| Pixel scale               | 22′3 pixel$^{-1}$ |
| Image quality             | 2–5 pixel FWHM over entire field |
| Filters                   | Clear, g, r, i, z |

#### 50 mm camera

| Camera lens               | Canon EC 50 mm f/1.2L USM |
| Field dimensions          | 40.8 × 40.8 |
| Continuous-coverage field | 1295 deg$^2$ |
| Pixel scale               | 35′9 pixel$^{-1}$ |
| Image quality             | 2–5 pixel FWHM over entire field |
| Filters                   | Clear, g, r, i, z |

### 3.1. Camera Assembly

Each camera system is based on an f/1.2 Canon EF-mount DSLR lens, with focal lengths chosen to provide fields of view of hundreds of square degrees, and sufficiently small pixels (in the tens-of-arcseconds range) to allow precision photometry of $m_V < 10$ stars without significant crowding effects. The lenses image onto Kodak KAF-16803 CCDs packaged in a Finger Lake Instrumentation (FLI) PL-16803 camera. A FLI CFW-4-5 filter
wheel provides five filter positions for 50 mm square filters. The
Canon lens’ built-in focus hardware cannot be easily accessed
without connection to a Canon camera, and manual focusing of
these very fast lenses did not provide sufficient image quality.
To allow precision focusing under remote computer control
we added an FLI Atlas focuser to the optical system. The
camera systems are controlled over a USB link by a compact
Linux-based server located inside their thermal enclosures. The
completed imaging system is compact, measuring a total of
230 × 230 × 175 mm and weighing 6.5 kg.

3.2. Enclosure, Window, and Thermal System

To ensure survivability of the electronics and other compo-
nents, and to provide sufficient heating to remove snow and
ice, the camera thermal enclosures were required to maintain
an internal temperature of 5°C in temperatures lower than −40°C
and in wind speeds up to 10 m s⁻¹. We designed heated enclo-
sures based on the Pelican 1610 case, an equipment shipping
case which consists of a waterproof polypropylene copolymer
enclosure. We drilled a 3.5 inch diameter hole on the upper
surface for the camera aperture; a 3 mm-thick AR-coated glass
window protected the camera lenses. Two small holes equipped
with bulkhead connectors provide inputs for AC power and Eth-
ernet connections. The entire case internal surface was insulated
by one-inch-thick neoprene/vinyl/buna-N foam rubber.

A high level of interior temperature stability was required to
provide sufficient focus stability for the small depth of focus of
our f/1.2 lenses. We based the case thermal control system on the
heating and air circulation system of a Dotworkz Systems D2-
RF-MVP CCTV enclosure which was used in an earlier camera
prototype. We modified the control electronics to allow control
by one-inch-thick neoprene/vinyl/buna-N foam rubber.

Pre-campaign testing of the systems was performed in a
freezer at −27°C, with wind simulation provided by small
fans. We found the enclosure’s thermal control systems could
maintain temperature inside the cases to ±0.5°C in conditions
approximating those found at the Ridge Lab site. On-site,
the systems were able to maintain the nominal 5°C internal
temperature in all conditions encountered (−30±5°C), except
when the wind speeds exceeded 10 m s⁻¹.

Precision photometry requires keeping the optical window of
the systems free of snow and ice during Arctic conditions. Our
testing in the Arctic, including days with high winds, blowing
snow and high levels of “diamond-dust” (fine ice particles)
demonstrated that the window was kept clear by the heating
system in all conditions encountered (Figure 4). The gentle
heating allowed the snow and diamond dust to sublime off
the camera enclosures rather than melting, reducing ice buildup
around the instruments.

3.3. Camera Mounting and Alignment

The cameras were aligned on the north celestial pole
by rotating the enclosures to face north and tilting them
to the required angle. An initial azimuthal alignment was
measured using a north–south line pre-determined via a
hand-held GPS receiver, and the system tilt was fixed using
a digital inclinometer. After initial pointing, fine alignment was
achieved by monitoring the position of the north celestial pole
in the acquired images. We used ratchet straps and shims to
mount the enclosures onto the grillwork on the Ridge Lab roof,
a design which proved stable for all the encountered conditions.

3.4. Camera Control Software and Data Storage

The camera systems were controlled by custom software run-
ning on Ubuntu–Linux-based computers inside each enclosure.
The software handled initial hardware tests, autofocusing, rou-
tine camera operations, and automatic transfer of acquired data
to the data server.

The autofocus routine was based on code used to focus the
Palomar Transient Factory camera (Law et al. 2009). First, the
camera steps through a range of focus positions. Star-like objects
in the field are extracted and have their FWHMs measured
using SExtractor (Bertin & Arnouts 1996). The resulting list
of objects is then filtered to exclude extended objects, cosmic
rays and other non-point-sources, a median FWHM is derived
for each focus position, and a parabola is fit to the resulting
focus position/FWHM curve. The DSLR lenses produce a
changing PSF across the field (see Section 5.1), including field
curvature which can interfere with simple autofocus routines
because different parts of the field can be in focus at different
positions. We found that restricting the focus routine to use
only the central 80% of the image and rejecting stars with high
(>1.5) ellipticity gave acceptable focusing for targeted zone of
continuous coverage in the center of the field.

The two camera systems each generated approximately 8 GB
of image data per hour. We transferred the data immediately after
acquisition onto two 2TB hard disks inside the Ridge Lab. The
satellite Internet connection at the site was sufficient only for test
and monitoring images to be transferred during observations; the
full survey data set was stored on USB external hard disk drives
for later analysis.

4. OBSERVATIONS AND DATA REDUCTION

Table 2 details the data taken during our 2012 February
campaign. Because the campaign was undertaken toward the
onset of arctic sunrise, twilight conditions were encountered
for a fraction of the day, allowing a total of 16 hr of
dark-sky observing in each 24 hr period. The cameras oper-
ated continually from 2012 February 14 to 2012 February 21,
a total of 152 hr of which 98 hr was dark. Thin-to-moderate clouds were experienced for approximately half the run, resulting in 0.5–2 mag of extinction and increased scattering during those periods.

To test different survey methods, we operated the two camera systems in slightly different ways. The 85 mm camera swapped sequentially between five filters between each exposure, providing near-simultaneous multi-color photometry. The 50 mm camera instead operated in a single fixed vidicon near-simultaneous multi-color photometry. The 50 mm camera operated in a single fixed filter. The filter bands of the 85 mm camera had poor image quality due to wedge angles in the filter glass; we continued observations in those filters for sky-brightness measurements only.

The cameras operated with an open-shutter efficiency of 71% for the 50 mm camera and 65% for the 85 mm camera, which had slightly increased overheads because of its filter changes. In total, the cameras collected 44,583 images, 1.36 TB of data.

4.1. Flat Fielding with Very-wide-field Cameras

Flat fielding with a fixed, autonomous camera system is potentially challenging. We tested four flat-fielding methods to inform subsequent instrument and survey design—conventional twilight flats, superflats generated from our full data set, imaging a flat white screen held above the cameras, and using thick clouds as flat fields.

4.1.1. Conventional Twilight Flats

Flat fields taken during twilight are susceptible to large-scale gradients caused by multiple scattering. These effects can generally be neglected for narrow-angle astronomical imaging, as long as extremely high precision is not required. In contrast, our wide-field twilight flats showed unacceptably large gradients. This, coupled with the several months during which twilight is not available at circumpolar observing sites, makes twilight flats unsuitable for these camera systems.

4.1.2. Superflats

The major contributors to the sky brightness measured by superflats generated from data taken in dark time are airglow, zodiacal light, and starlight. Zodiacal light and airglow vary across the sky; at a zenith angle of 12.5° (the edge of our narrowest field) the airglow is approximately 2.5% brighter than at the zenith, while the zodiacal light varies by approximately 10% across the range of ecliptic latitude covered by our cameras (Benn & Ellison 1998). Because of our cameras’ large pixels, the starlight contribution is larger than found in narrow-field astronomical images, and the repetitive nature of the sky rotation complicates the generation of precision superflats. For these reasons, we found that it was extremely difficult to generate precision superflats from our data set.

4.1.3. Screen Flats

“Dome” flats generated from screens in front of the camera are not susceptible to the problems encountered by twilight and super flats, although care is required to ensure a uniform illumination pattern. Achieving this is simple for our fast, small lenses. We found that a white card held in front of our cameras during late twilight was sufficient to generate high-quality flats (at a level sufficient for millimag photometry) for both our cameras and all filters.

4.1.4. Cloud Flats

Without a dome on which to place the screen, screen flats cannot be easily taken by a stand-alone remote camera system. An automated system to place screens over the cameras would be complex and potentially unreliable. For these reasons, we also attempted to test the use of thick clouds as a substitute flat screen. The thickest clouds during which we obtained data, with an extinction of ~3.5 mag, still had enough stars to complicate the generation of flat fields. Comparing the “cloud-flats” to the screen-generated flat, we also found variations in the sky brightness at the 1% level on scales of 5°–10°, likely induced by structures within the cloud layer. This could possibly be removed by averaging of a long-term cloud-covered data set, but the cloudy data we collected were not of sufficient length to test this.

4.1.5. Reliable Wide Field Camera Flats

Twilight and cloud-based flats appear to only be suitable for rough flat fielding with these wide-field camera systems. Although the sky-gradient effects of scattering, airglow, and zodiacal light could be removed at some level using their predicted across-field variations, it is difficult to generate clean flats with the stars in the field executing repetitive motions that puts them in the same pixels at the same time each day. Cloud-generated flats showed percent-level spatial changes that will be difficult to accurately remove without a long period of cloudy weather, and there is a possibility that the brightness distribution of low-level clouds could be systematically biased by local topographic features.

For these reasons, we elected to use the screen flats for subsequent analysis. Remote operation of these systems is challenging, although we note that the sealed optical system of our cameras and their very fast beams reduce the likelihood of changes in the flats. We did not detect any flat-field changes over the course of our survey, at the one part in 1000 level; it is likely that an occasional visit by a technician placing illuminated screens in front of the cameras would be sufficient to achieve precision flat fielding.

4.2. Data Reduction Pipeline

We implemented a Python-based data reduction pipeline to calibrate our images for photometry and astrometry. FITS files recorded by the cameras were first dark-subtracted and then flat fielded using the methods described above. The sources in each field were extracted using SExtractor (Bertin & Arnouts 1996) “mag-auto” apertures with modeling and subtraction of a background that was allowed to vary across the field.

4.2.1. High-efficiency Astrometric Calibration of Extremely Wide-field Images

The images produced by our lenses have a generally much higher degree of geometric distortion than those produced by

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6 The Ridge Lab is located near the north magnetic pole, ensuring that most auroral emission is over the southern horizon (Figure 1).
standard astronomical telescopes. We found that automatic astrometric calibrations typically used for wide-field surveys such as astrometry.net (Lang et al. 2010) and SCAMP (Bertin 2006) led to unacceptably poor astrometric solutions (~100 arcsec median astrometric error compared to catalogs in some regions of the image), even with high-order polynomial corrections. We found that splitting the individual images into 10–30 rectangular subsections allowed SCAMP to find an acceptable astrometric solution within each subsection based on the UCAC-3 catalog (Zacharias et al. 2010). However, each subsection required tens of seconds to extract the sources and find an astrometric solution. This results in whole-image processing times of several minutes, unacceptable for images taken at least four times each minute in two cameras.

To improve the processing times we developed a model to directly relate camera pixel positions and observation times to sky coordinates. Because the cameras’ optical axes were slightly misaligned with respect to the celestial pole, we modeled lens distortion terms in polar coordinates around one “optical” axis, and then the conversion to R.A. and decl. around a separate “celestial” axis. We modeled the lens distortion in the following way, based on the models first described in Conrady (1919) and Brown (1966):

\[ D = \sqrt{(x - x_c)^2 + (y - y_c)^2} \]  
\[ x_{\text{lens corr}} = (x - x_c)(1 + aD^2 + bD^4 + cD^6) \]  
\[ y_{\text{lens corr}} = (y - y_c)(1 + aD^2 + bD^4 + cD^6) \]

where \( x, y \) are the measured stars positions in pixels, \( x_c, y_c \) are the camera optical axis pixel coordinates, and the terms \( a - e \) are fit to the measured astrometry. To measure the model coefficients and optical axis coordinates we took 20 frames distributed throughout the nights, fully calibrated the frames using astrometry.net and SCAMP, and used a downhill simplex minimization to fit the coefficients to the calibrated astrometry. After correction of the pixel coordinates, the sky coordinates of the stars are calculated by converting the de-distorted pixel positions to sky coordinates with a tangent plane projection and then adding the sky rotation term corresponding to the observation epoch.

After initial modeling, we found that a fixed lens model did not adequately fit the data. An additional shift was required to model a slow change in the angle between the optical and celestial axes. The amplitude of the modeled shift is consistent with a 100 \( \mu \)m height change in one edge of the camera support structure and was maximal around midnight. We attribute this to the effects of changing temperature during the semi-twilight nights.

Verifying the full astrometric solution against a second set of calibrated images, we found that just based on the time of observation and the pixel position of the stars, sky positions were calculated to \( \approx 20 \) arcsec (\( < 1 \) pixel) accuracy across the entire image, with improved performance in the image centers. The full astrometric processing for the \( \sim 10,000 \) stars in each image takes a fraction of a second.

4.2.2. Efficient Millimagnitude Photometry with Extremely Wide-field Images

To obtain photometric zero points we modified the differential aperture photometry pipeline originally developed for the Palomar Transient Factory (Law et al. 2009) M-dwarf planetary transit search (Law et al. 2012). We associate an initial “rough-guess” photometric zero point with each image and using them generate light curves for each source. We then vary the zero points, using a simulated- annealing algorithm to minimize the averaged noise-weighted rms variability in all the light curves. The algorithm converges on the set of zero points which provide the most stable photometry for the largest number of sources in the field, and is thus robust to bias from astrophysical or instrumental variability in individual stars.

The slight misalignment between the cameras’ optical axes and the celestial pole (Section 4.2.1), and the small focal plane tilt (Section 5.1), leads to a slow change in size and shape of the stars’ PSFs as the sky rotates. We found that this was enough to induce few-percent-level changes in the post-zero-point-calibration stellar fluxes, for stars at the edges of the field where the PSF changes were largest. The resulting systematic flux error affects each star in a particular region of the image in the same manner and so can be removed with standard methods designed to remove light curve systematics. We use 15 iterations of SysRem (Tamura et al. 2005) to model and remove this systematic error for the ensemble of light curves.

After photometric calibration and systematics removal, we consistently achieved 1% level photometric performance in individual images over 12 hr timescales, and few-millimagnitude-level photometry when binning datapoints from 60 individual exposures together (Figure 6).

The expected single-exposure scintillation noise for at-zenith observations is approximately 6 and 8 mmag for the 85 mm and 50 mm lenses, respectively (Dravins et al. 1998; Young 1967). The scintillation noise estimates depend on the particular observing conditions at the site (to within \( \sim 50\% \); Young 1967), and we thus conclude that the cameras are achieving very close to scintillation-limited photometric precisions. We evaluate the photometric performance for planet-search purposes, including the level of correlated noise, in Section 5.3.

5. PERFORMANCE

In the below subsections, we detail the performance of the camera systems in the context of the requirements of a bright-star transiting exoplanet survey.

5.1. Image Quality

The lens point-spread functions (PSFs; Figure 5) are well matched to the camera’s pixel size in the center of the field, with round shapes and full-width at half maxima (FWHMs) of approximately two pixels. In both cameras, the PSFs increased in width toward the edges of the field (Figure 7), although at a slow enough rate to provide useful images up to the edges of the zone in which stars are continuously covered. A small tilt in the focal plane (\( \sim 5 \mu \)m across the CCD) is visible in each camera’s FWHM map, produced by a combination of the camera mounting hardware and the tolerance in the wedge angle of the filter glasses. The tilt did not significantly affect the image quality within the continuous coverage zone.

5.2. Camera Sensitivity

The cameras achieved their design sensitivity, with a typical 10 s exposure 5σ point-source limiting magnitude of \( m_v = 12.6 \) for the 85 mm lens. We measured the limiting magnitudes using stars observed in a Sloan Digital Sky Survey SEGUE field (Yanny et al. 2009), which was included in both our
cameras’ fields of view and allows us to approximately match filter responses for photometric calibration. At its highest point, the SEGUE field covers declinations from 82°3 to 85°1. Our cameras have somewhat lower image quality and increased vignetting at those altitudes than at the center of the fields. Correcting for these effects, the true limiting magnitude at the field centers is improved to $m_V \approx 13.6$.

Figure 8 shows the relative vignetting of our cameras as a function of the field position. The 85 mm lens reduces the light collection to approximately 50% of its maximum value by the edge of the camera’s zone of continuous photometric coverage, while the 50 mm lens has a more pronounced vignetting giving $\approx 35\%$ sensitivity at the edges of the chip.

5.3. Correlated Noise Performance

As shown in Figure 6, binning our single-exposure photometry allows few-millimagnitude precision for thousands of stars in the our fields of view. However, correlated (“red”) noise can greatly reduce the efficiency of planet detection even with apparently good photometric stability (e.g., Smith et al. 2006).

We evaluated the correlated noise performance of our camera systems by searching for unexpected behavior when binning the photometric data points to different timescales; a system with a high degree of correlated noise would show a precision improvement with binning which is slower than the expected $\sqrt{N_{\text{data points}}}$. To remove the possibility of obtaining spuriously good performance estimates by overfitting during the systematic noise reduction steps, we used a subset of our full data reduction pipeline, without the final photometry and systemic noise removal steps. We repeated the below tests with our full pipeline and obtained identical results.

Using the SExtractor extraction of the sources in our astrometrically calibrated images, we performed differential aperture photometry for four isolated stars near the center of our fields. We selected the target and three calibration stars to have magnitudes in our exoplanet survey range ($m_V = 7–9$), but with
care to keep their peak fluxes below \(\sim 20,000\) ADUs to avoid nonlinearity due to our CCD’s anti-blooming system (which engages at signals of \(\gtrsim 32,000\) ADUs). Within each night, we fit a second-order polynomial to the light curves to remove long-timescale residual systematic variations (typically at the 5 mmag level). The final photometric stability was measured from the rms variability in the resulting light curve.

Similarly to the full pipeline, we achieved an rms precision of 1.0% in individual 10 s exposures on the 85 mm camera, and 2.4% in \(r\)-band exposures with the 50 mm camera. The ratio of photometric performance for the two lenses is roughly as expected for measurements limited purely by photon and scintillation noises, suggesting only low-level extra sources of photometric error.

Binning the photometry to 10 minute exposures improved the photometric precision to 2–3 mmag (Figure 9), compared to an expected scintillation-limited precision of \(\approx 2\) mmag. In both cameras, the photometric precision improves the expected rate of \(\sqrt{N_{\text{data points}}}\) until at least 100 frames are binned together. The length of our data set from this campaign precludes a meaningful analysis of the effects of correlated noise on longer timescales, but the close adherence to the \(\sqrt{N_{\text{data points}}}\) relation is encouraging.
6. DETECTED VARIABLE SOURCES

We performed a search for variable stars and other astrophysically varying sources, both visually searching for obvious periodic sources, and testing automatic variable-source detection in a blind search for stellar variability and transit signals.

6.1. Bright Periodic Sources

Because our targets are bright ($m_V < \sim 10$), essentially all the high-amplitude variables in the field are already known. In an initial visual characterization of each light curve with evidence of a large amount of variability, we re-detected the Delta-Scuti star V377 Cep, and detected eclipses for the beta Lyr eclipsing binaries EG Cep and AZ Cam, the W UMa eclipsing binaries FN Cam and RZ UMi, and the Algol-type binaries W UMi, TY UMi, AY Cam and SV Cam. In Figure 10, we show a two-camera, three-color, 15 hr light-curve of the primary eclipse of W UMi, an $m_V = 8.5$ Algol-type eclipsing binary (e.g., Sahade 1945). Three primary and secondary eclipses of this 1.71 day period system were captured during our week-long observations.

6.2. Stetson-J Blind Detection of Variable Stars

We tested the ability to perform an automated stellar variability and transit search with the cameras, using known bright variable objects in our field to evaluate the detection efficiency. The General Catalogue of Variable Stars (GCVS; Samus et al. 2009) lists 119 variable stars within our field of view and magnitude limits ($5.0 < m_V < 10.0$). Most of these objects are rarely outbursting stars or long-period variables which are unlikely to have produced detectable variability during our observations. However, 28 stars have $<20$ day photometric periods (and so a reasonable chance of undergoing measurable variability within our observations), and have light curves which were flagged as clean of instrumental effects by our pipeline. All the known variables in the list have amplitudes which can be easily detected by our cameras.

We based the variability search on the Stetson-J statistic (Stetson 1996), which compares pairs of observations to search for variability which is correlated between datapoints. Compared to a simple rms-variability selection we found that Stetson-J is much less sensitive to the main source of false-positive variability in our data set: few-percent-level blending between closely separated sources, which affects approximately 2% of the stars in the field. Most of the stars in the field move by a large fraction of a pixel each frame, and thus the blending between closely separated stars can vary by large amounts ($>10\%$) frame-to-frame. The resulting mostly uncorrelated blending from frame-to-frame allows the Stetson-J statistic to exclude those sources as instrumentally rather than astrophysically variable.

To detect a source as variable we set a minimum Stetson-J statistic of 0.14, a value selected to exclude 98% of the sources in our field (Figure 11). Seven (25%) of the GCVS variable stars were detected as variable under this criterion. The light curves of the remaining GCVS objects were clean of obvious instrumental effects, but did not contain eclipses or other obvious astrophysical variability, suggesting the pipeline is efficiently and automatically detecting the objects that underwent eclipses or other variability during the observation period evaluated.

A visual inspection of the light curves of the other 119 high-variability sources revealed eight objects with signs of pulsations or other sinusoidal variability at the $<5\%$ level; five objects with possible single eclipses with 5%–20% depths (suggesting long-period systems); 43 sources with blending effects from nearby stars; and 63 objects with long-timescale variability that we cannot usefully classify as instrumental or astrophysical in the current data set. The planned full-winter Arctic data sets will allow confirmation of these possible longer-period variable stars and enable a full evaluation of stellar variability in this field on timescales up to several months.
6.3. Transit Search

We searched for individual planetary transits using the binned high-precision light curves shown in Figure 6. We calculated the expected Stetson-J transit signal by injecting simulated transit events (1%, 2 hr duration dips with ingress and egress periods) into our binned light curves. We found that individual transit events are securely detectable using the Stetson-J statistic for the brightest one-third of the stars in the data set ($m_V \lesssim 8.5$). Typical 1% depth transits produce Stetson-J values of 0.3 in the binned light curves of these bright objects, excluding the 97.5% of objects in the field which have lower values. A visual search of the 38 light curves with Stetson-J > 0.3 in the binned light curves revealed no likely transit-like events. The statistically significant detection of transit signals around the fainter stars will be feasible with a longer data set which allows the use of more sophisticated phased matched-filter-type transit-search algorithms that obtain much improved detection significances (e.g., Kovács et al. 2002; Tingley 2003).

7. DISCUSSION AND CONCLUSIONS

We have demonstrated the operation of two wide-field camera systems in the High Canadian Arctic, achieving the image quality and photometric precision necessary for the detection of transiting exoplanets around bright stars. Each camera’s data set contains light curves for $\approx 70,000$ stars, with $\approx 5000$ in each camera having sufficient SNR and being sufficiently uncrowded to search for transiting exoplanets.

In a data set from a full arctic winter, the probability of detecting at least three transits of planets in month-long orbits around solar-type stars is $\approx 70\%$ (Figure 2), while the geometric transit probability for those planets is a few percent. With few-millimag photometric precision the systems could detect exoplanets as small as Neptune transiting solar-type stars. The *Kepler-*derived few-percent occurrence frequencies for planets in that size and orbital period range (Howard et al. 2012) suggest that the AWCam systems, when operated during an entire arctic winter, would be capable of detecting up to five transiting exoplanets around stars brighter than $m_V = 9.5$.

7.1. A Concept for a 10,300 deg$^2$ Arctic Camera

Although wide field, the cameras described here only cover 3%–6% of the sky continuously accessible from the Ridge Lab in winter months. Larger sky areas can be covered with multiple cameras, but this requires extremely short exposures or a tracking mount to avoid star trails. One such concept under development, the Compound Arctic Telescope System (CATS; Law et al. 2012), places 19 cameras similar to the ones described into our binned light curves. We found that individual transit events are securely detectable using the Stetson-J statistic for the brightest one-third of the stars in the data set ($m_V \lesssim 8.5$). Typical 1% depth transits produce Stetson-J values of 0.3 in the binned light curves of these bright objects, excluding the 97.5% of objects in the field which have lower values. A visual search of the 38 light curves with Stetson-J > 0.3 in the binned light curves revealed no likely transit-like events. The statistically significant detection of transit signals around the fainter stars will be feasible with a longer data set which allows the use of more sophisticated phased matched-filter-type transit-search algorithms that obtain much improved detection significances (e.g., Kovács et al. 2002; Tingley 2003).

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REFERENCES

Agol, E., Cowan, N. B., Knutson, H. A., et al. 2010, ApJ, 721, 1861
Bakos, G. Á., Kovács, G., Torres, G., et al. 2007, ApJ, 670, 826
Bakos, G. Á., Noyes, R. W., Kovács, G., et al. 2004, PASP, 116, 266
Benn, C. R., & Ellison, S. L. 1998, NewAR, 42, 503
Berín, E. 2006, in ASP Conf. Ser. 351, Astronomical Data Analysis Software and Systems XV, ed. C. Gabriel, C. Arviset, D. Ponz, & S. Enrique (San Francisco, CA: ASP), 112
Berín, E., & Arnouts, S. 1996, A&AS, 117, 393
Bouchy, F., Udry, S., Mayor, M., et al. 2005, A&A, 444, L15
Brown, D. C. 1966, PgE, 32, 444
Brown, T. M. 2003, ApJL, 593, 125
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJL, 529, 45
Christian, D. J., Pollacco, D. L., Skillet, I., et al. 2006, MNRAS, 372, 1117
Collier, A. M., Guenther, E., Smalley, B., et al. 2010, MNRAS, 407, 507
Conrady, A. E. 1919, MNRAS, 79, 384
Crouzet, N., Guillot, T., Agabi, A., et al. 2010, A&A, 511, A36
Daban, J.-B., Gouvret, C., Guillot, T., et al. 2010, Proc. SPIE, 7733, 151
Demory, B.-O., Gillon, M., Deming, D., et al. 2011, A&A, 533, A114
Di Rico, G., Ragni, M., Dolci, M., et al. 2010, Proc. SPIE, 7737, 55
Dravins, D., Lindegren, L., Mezy, E., & Young, A. T. 1998, PASP, 110, 610
Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJL, 529, 41
Hickson, P., Carlberg, R., Gagne, R., et al. 2010, Proc. SPIE, 7733, 53
Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJL, 745, 20
Howell, S. B., Rowe, J. F., Dotson, J. W., et al. 2012, ApJL, 746, 123
Kovács, G., Zucker, S., & Mazeh, T. 2002, A&A, 391, 369
Lang, D., Hogg, D. W., Mierle, K., Blanton, M., & Roweis, S. 2010, AJ, 139, 1782
Law, N. M., Kraus, A. L., Street, R., et al. 2012, ApJ, 757, 133
Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, PASP, 121, 1395
Law, N. M., Sivanandam, S., Murouwinski, R., et al. 2012, Proc. SPIE, 8444, 56
Majeau, C., Agol, E., & Cowan, N. B. 2012, ApJL, 747, 20
Moore, A., Allen, G., Aristidi, E., et al. 2008, Proc. SPIE, 7012, 76
Moore, A. M., Ahmed, S., Ashley, M. C. B., et al. 2010, Proc. SPIE, 7733, 54
Moore, A. M., Aristidi, E., Ashley, M., et al. 2006, Proc. SPIE, 6267, 53
Pal, A., Bakos, G. Á., Torres, G., et al. 2010, MNRAS, 401, 2665
Pepper, J., Kuhn, R. B., Siverd, R., James, D., & Stassun, K. 2012, PASP, 124, 230
Pepper, J., Poppe, R. W., DePoy, D. L., et al. 2007, PASP, 119, 923
Pollacco, D. L., Skillen, I., Collier Cameron, A., et al. 2006, PASP, 118, 1407
Pont, F., & Bouchy, F. 2005, in Proc. Dome C Astron. and Astrophys. Meeting, ed. M. Giard, F. Casoli, & F. Paletou (EAS Publ. Ser. 14; Cambridge: Cambridge Univ. Press), 155
Sahade, J. 1945, ApJ, 102, 470
Samus, N. N., Durlevich, O. V., et al. 2009, Ycat, 1, 2025
Sato, B., Fischer, D. A., Henry, G. W., et al. 2005, ApJ, 633, 465
Smith, A. M. S., Collier Cameron, A., Christian, D. J., et al. 2006, MNRAS, 373, 1151
Steinbring, E., Carlberg, R., Croll, B., et al. 2010, PASP, 122, 1092
Steinbring, E., Ward, W., & Drummond, J. R. 2012, PASP, 124, 185
Stetson, P. B. 1996, PASP, 108, 851
Stevenson, K. B., Harrington, J., Fortney, J., et al. 2012, ApJ, 754, 136
Tamuz, O., Mazeh, T., & Zucker, S. 2005, MNRAS, 356, 1466
Tingley, B. 2003, A&A, 408, L5
von Braun, K., Boyajian, T. S., ten Brummelaar, T. A., et al. 2011, ApJ, 740, 49

Wang, L., Macri, L. M., Krisciunas, K., et al. 2011, AJ, 142, 155
Winn, J. N., Matthews, J. M., Dawson, R. I., et al. 2011, ApJL, 737, 18
Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377
Young, A. T. 1967, AJ, 72, 747
Zacharias, N., Finch, C., Girard, T., et al. 2010, AJ, 139, 2184