Achieving high precision photometry for identifying transiting exoplanets with a low-cost robotic DSLR-based imaging system

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We describe a low cost high precision photometric imaging system, which has been in robotic operation for one year on the Mauna Loa observatory (Hawaii). The system, which can be easily duplicated, offers a 150 sq deg field with two 70mm entrance apertures. We describe the design of the system and show early results, and describe a new data processing technique developed to overcome pixelization and color errors. We demonstrate on-sky photometric precision approaching fundamental error sources (photon noise and atmospheric scintillation) and conclude that our approach is ideally suited for exoplanet transit survey with multiple units.

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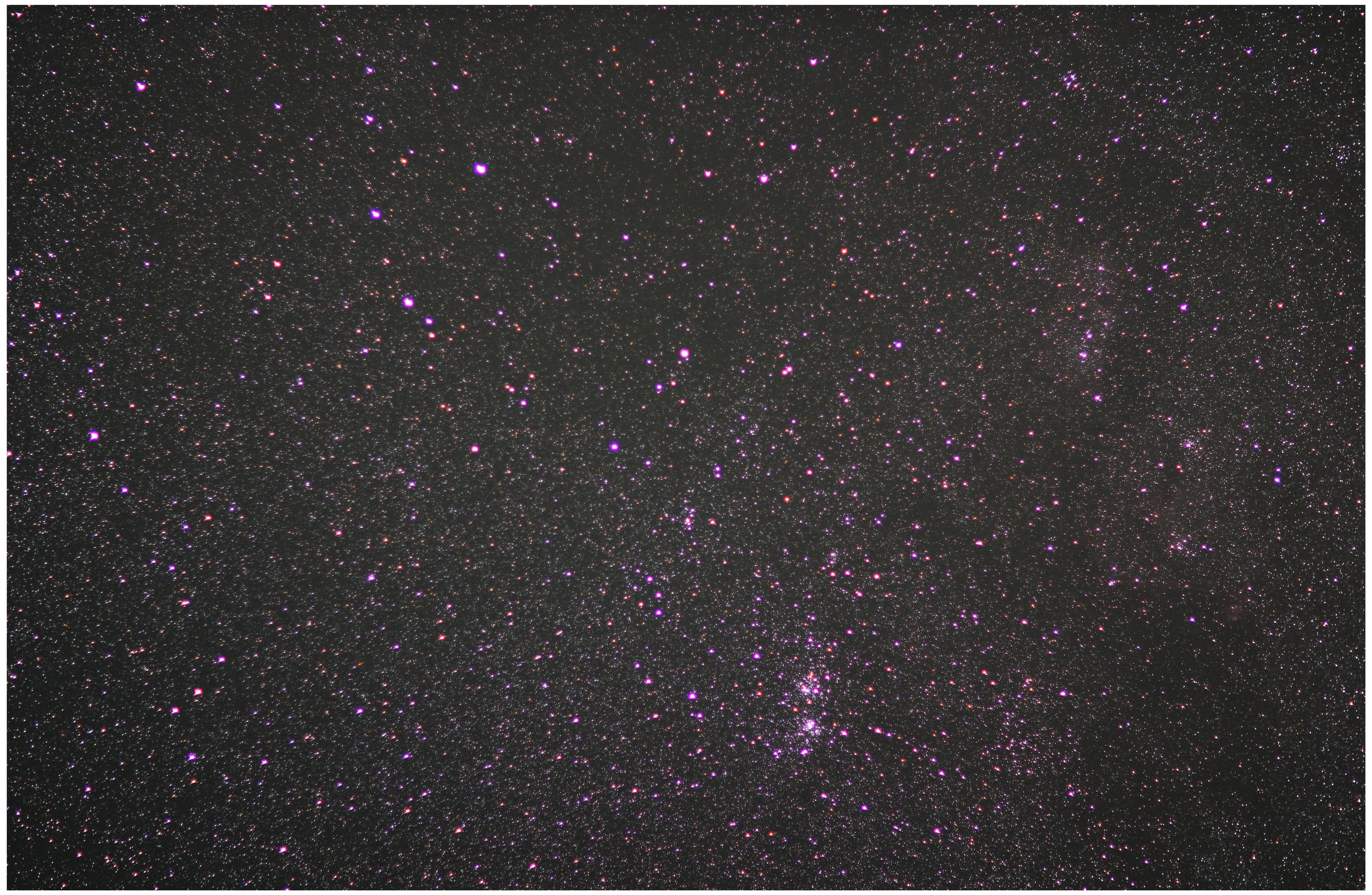


Example RAW frame, no processing , 287 sec exposure at ISO 100

Project Goals

High efficiency exoplanet transit survey
Efficiency defined here as science performance/$

Why many small aperture units is better than few large aperture units ?
(1) Small aperture offers the best efficiency ($/etendue) by using mass-produced commercially available hardware
(2) It is possible to reach the fundamental limits of photometric precision (photon noise, scintillation) on small aperture, while it is very difficult on large apertures
(3) Noise between different units is uncorrelated (different pointing errors, detectors, atmospheric conditions etc...) → gain as sqt(Number of units)
(4) It is easy to scale by duplicating small apertures
(5) Minimum cost and complexity for a single unit allows schools/amateur astronomers to participate
(6) Multiple units offers reliability against single unit failure

Low cost, high reliability hardware

All hardware and software is publicly available
Open source code

Easy to duplicate & improve
Make it possible for schools and amateur astronomers to build and operate units
→ can be grown in global network would
→ high potential for outreach and participation of citizen scientists & students to exoplanet discoveries

System overview

Field of view	150 square degree per camera (10 x 15 deg)
Aperture	70mm for each camera
Pixel size	8" and 10"
Detector	CMOS color detectors, 15 and 18 Mpix
Sensitivity	Photon noise limited, m_V ~ 15.5 point source sensitivity in 4mn

	ISO 100	ISO 200	ISO 400	ISO 800	ISO 1600
Readout Noise [ADU]	10.8959	11.6364	13.9445	19.8761	32.2658
Gain [e-/ADU]	1.36	0.68	0.34	0.17	0.085
Readout Noise [e-]	15.8	7.91	4.74	3.38	2.74
(RON=photon noise) level [ADU]	161.5	92.08	66.11	67.16	88.49

Location: Mauna Loa observatory, Hawaii
Weather sealed system, no dome (points down during bad weather, daytime)
High reliability software, enters safe mode if unexpected behavior is experienced

Optics : Canon 85mm F1.2 lens (x2)
Detectors: Canon DSLR 500D and 550D
Equatorial Mount, stepper motors
Basic weather monitorig (temperature, humidity, cloud detector, wind speed)

Intelligent pointing and tracking model: system learns optimal tracking rates as it acquires images

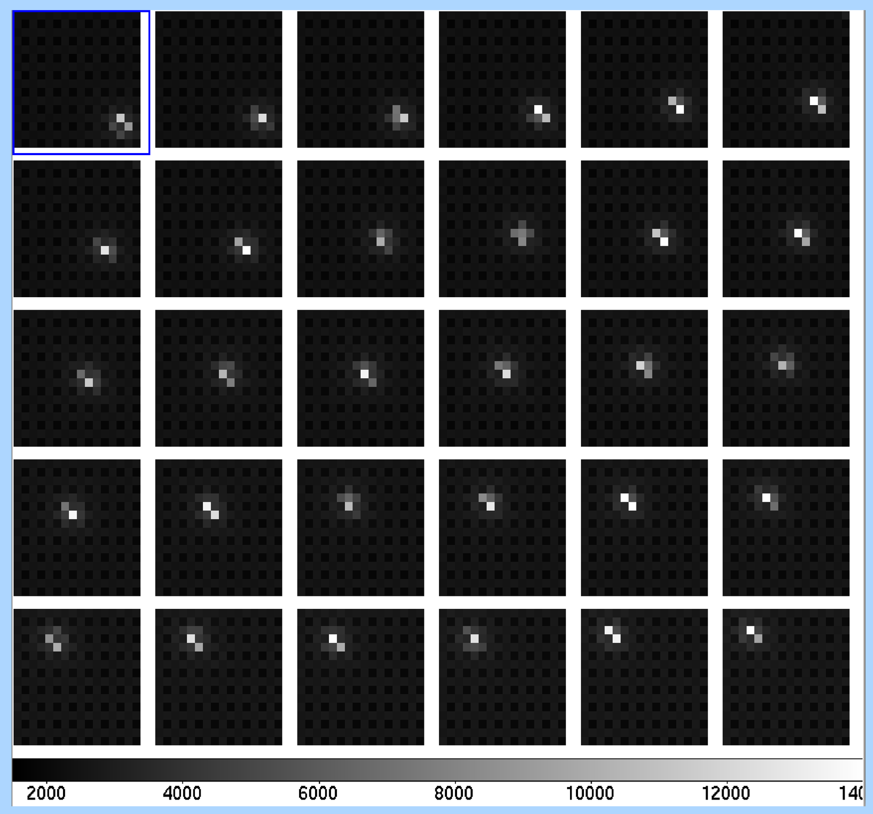
All images are photon-noise limited on sky background (zodiacal light + airglow)

LOW COST: ~$10k per sq meter sq deg of etendue
HIGH RELIABILITY achieved by combination of simplicity and use of mass-produced items

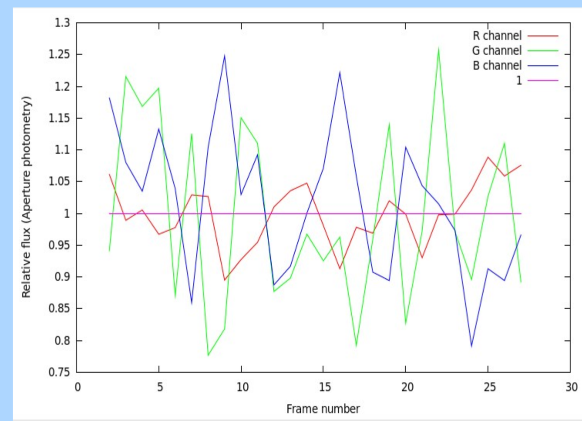
Achieving high photometric precision with RGB CMOS arrays

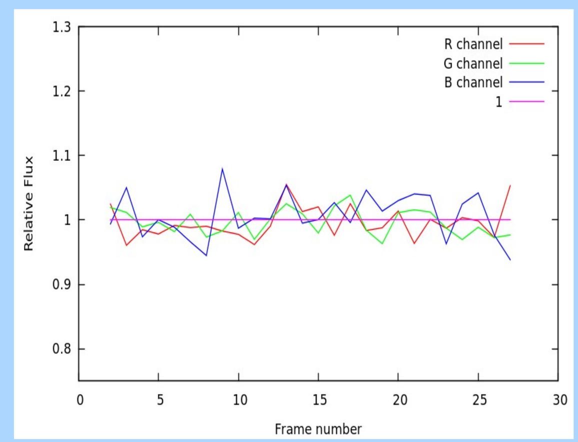
Each image contains ~20000 high SNR PSFs
→ for each target, there are several suitable reference stars that experience the same effects as the target (same color, same fractional pixel position, same local detector defects, same optical PSF aberrations)

Careful selection of such reference stars is used to buld a template, as follows:
(1) identify best 50 reference stars
(2) build linear combination of the 50 reference PSFs that best match the sequence of target PSFs, WITHOUT TRYING TO FIT THE TRANSIT SIGNAL TO BE EXTRACTED
(3) subtract linear combination from target PSFs
(4) repeat steps (2) and (3) for each transit parameters tested (period, duration), and record for each set of these parameters the best estimate of the transit depth.



sequence of 1-mn exposures
(note strong drift in early data)





We have demonstrated photometric precision approaching fundamental limits.
Top left: aperture photometry
Top right: our algorithm
(table below is for 1mn exposure time, single camera, m=9.4 star)

Error term	R channel	G channel	B channel	Notes
Atmospheric Scintillation	0.3%	0.3%	0.3%	
Photon Noise	2.79%	1.00%	2.24%	mV=9.35, includes background contribution (bright time, r=40arcsec mask)
Readout Noise	0.40%	0.23%	0.71%	
Flat field error	0.5%	0.4%	0.5%	Error term irrelevant with good tracking
Total (expected)	2.88%	1.14%	2.42%	
Achieved	**2.48%**	**2.04%**	**3.51%**	

Current status, future plans, how to get involved ?

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Current status:
- Hardware working reliably
- percent-level photometric precision over 1 mn exposure demonstrated
- Known transits have been observed and detected
- Survey has been started to identify new transits (staring at single field)

System is well dcumented (hardware / software) on website: http://www.naoj.org/staff/guyon/09allskysurvey.web/content.html
We are inviting amateur astronomers, schools, to work with us and build additional units and help develop system (hardware, software)