The PANOPTES project: discovering exoplanets with low-cost digital cameras

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ABSTRACT

The Panoptic Astronomical Networked OPtical observatory for Transiting Exoplanets Survey (PANOPTES, www.projectpanoptes.org) project is aimed at identifying transiting exoplanets using a wide network of low-cost imaging units. Each unit consists of two commercial digital single lens reflex (DSLR) cameras equipped with 85mm F1.4 lenses, mounted on a small equatorial mount. At a few $1000s per unit, the system offers a uniquely advantageous survey efficiency for the cost, and can easily be assembled by amateur astronomers or students. Three generations of prototype units have so far been tested, and the baseline unit design, which optimizes robustness, simplicity and cost, is now ready to be duplicated. We describe the hardware and software for the PANOPTES project, focusing on key challenging aspects of the project. We show that obtaining high precision photometric measurements with commercial DSLR color cameras is possible, using a PSF-matching algorithm we developed for this project. On-sky tests show that percent-level photometric precision is achieved in 1 min with a single camera. We also discuss hardware choices aimed at optimizing system robustness while maintaining adequate cost. PANOPTES is both an outreach project and a scientifically compelling survey for transiting exoplanets. In its current phase, experienced PANOPTES members are deploying a limited number of units, acquiring the experience necessary to run the network. A much wider community will then be able to participate to the project, with schools and citizen scientists integrating their units in the network.

Keywords: Exoplanets, Robotic Telescopes, Photometry

1. INTRODUCTION

The PANOPTES project[1] (Panoptic Astronomical Networked OPtical observatory for Transiting Exoplanets Survey) goal is to establish a world wide network of automated cameras to monitor a large fraction of the sky to detect exoplanet transits. Unlike previous research-grade exoplanet transit surveys, PANOPTES consists of a large number of individual low-cost units, each sufficiently simple and inexpensive to be built and operated by citizen scientists, amateur astronomers, and schools. PANOPTES thus serves both as a research and an outreach project. While its primary focus is to perform a wide exoplanet transit survey, data collected by PANOPTES can be used for other purposes, such as variable stars studies, supernovae detection, and asteroid tracking.

PANOPTES units, described in this paper, are designed to be easy to duplicate, low cost, and yet reliable. They can be operated remotely by users, or robotically for the exoplanet transit survey. All PANOPTES development (hardware and software) follows the open-source software development model, and the PANOPTES group includes both professional astronomers and citizen scientists.

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In Section 2, we describe the main choices made for the PANOPTES unit design, especially the adoption of commercial low-cost digital single lens reflex (DSLRs) cameras as detectors. The two main technical challenges for the project are discussed in the next two sections: hardware reliability (§3) and precision photometry (§4). The baseline PANOPTES unit design is described in §5.

2. WHY DIGITAL CAMERAS ?

2.1 Survey efficiency vs. cost

In addition to being widely accessible, commercial digital cameras, when equiped with a low F/ratio lens, are the most cost effective solution to build up survey efficiency. The PANOPTES unit consists of two DSLR cameras, each equiped with a 85mmF1.4 lens. The total hardware cost (cameras, lenses, equatorial mount, computer equipment, power, weather monitoring, all mounting hardware) is currently estimated at \$5,100. Each camera offers a 10x15 deg field of view (FOV) with a 60mm aperture. The etendue per \$ of the 2-camera unit is therefore 170 $m^2 deg^2 M\$^{-1}$. A 1-camera version of the PANOPTES unit would offer 101 $m^2 deg^2 M\$^{-1}$, while a 4-camera version would be 259 $m^2 deg^2 M\$^{-1}$. We have adopted the 2-camera version as our baseline to keep the cost per unit, and its size/complexity easily manageable. PANOPTES's 170 $m^2 deg^2 M\$^{-1}$ is significantly more advantageous than other wide-field surveys. Large wide field telescope, such as LSST or Pan-STARRS, offer 1 to 5 $m^2 deg^2 M\$^{-1}$. Systems using large format CCD cameras on commercial small telescopes are also in single digit $m^2 deg^2 M\$^{-1}$. The advantage of more professional systems using larger telescopes is that they offer higher angular resolution (typically 10x to 20x better than possible with PANOPTES' 8 arcsec pixels).

PANOPTES' high survey effiency, and therefore its ability to identify and study many exoplanet transits, relies on a large number of units to be simultaneously operated. We are aiming at wide participation by professional astronomers, citizen scientists and schools, and have therefore designed the units to be affordable, yet reliable and simple to assemble.

2.2 Detector characteristics

We have measured the detector characteristics for a DSLR camera equiped with the 85mmF1.4 lens baselined for the PANOPTES system. Results are shown in Table 1 for a Canon 500D camera. More recent detectors, such as will be used for PANOPTES units, offer similar performance.

Table 1. Measured detector characteristics

	ISO 100	ISO 200	ISO 400	ISO 800	ISO 1600
Readout noise [ADU]	10.9	11.6	13.94	19.87	32.27
Gain [e-/ADU]	1.36	0.68	0.34	0.17	0.09
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
Minimum exposure time (no Moon)	258 s	74 s	26 s	13.5 s	8.8 s
Number of exposures per hr	13.95	48.6	138.5	266.7	409.1
Saturation level [e-/frame]	22282.2	11141.1	5570.6	2785.3	1392.6
Saturation level [e-/hr]	3.1e5	5.4e5	7.6e5	7.4e5	5.7e5

DSLR cameras offer low readout noise performance, allowing PANOPTES units to operate at the photon noise limit on the sky background. Line 5 of the table lists the exposure time, for each ISO setting, for which the readout noise matches the photon noise on the sky background during dark time (no moon) in a site free of light pollution. For each ISO setting, the number of exposures per hr is then given on line 6, assuming no overhead between exposures.

The last line of the table shows, for photon-noise limited operation of PANOPTES, the saturation limit as a function of ISO setting adopted. The highest saturation limit (and therefore best dynamical range) is achieved by co-adding exposures taken at ISO 400 or ISO 800, with individual exposures of approximately 20 sec (@ ISO 400) and 10 sec (@ ISO 800). In practice, this optimal exposure time cannot be sustained for a long survey: at 20 sec per exposure, 10 hr observation per night, the shutter lifetime (rated at 100000 to 200000 exposures) corresponds to 100 nights of observation. Single frame exposure time is therefore a compromise between shutter lifetime and dynamical range . The imaging system currently operates at ISO 100 with exposure times longer than 200 sec in dark time to optimize shutter lifetime, and operation without shutter is being explored. At ISO100, 120sec, saturation is reached on the best frames for $m_V \approx 11$. PANOPTES is ideally suited to detect exoplanet transits around stars between $m_V \approx 13$ and $m_V \approx 11$.

2.3 Image quality

Each image offers a 10 x 15 degree field of view, with 8 arcsecond pixels. A sample image is shown in Figure 1, illustrating the large number of stars visible in each raw frame.

3. PANOPTES PROTOTYPES, LESSONS LEARNED

Project PANOPTES stated in late 2010 with the deployment of prototype 1, a single-camera unit, at the Mauna Loa observatory in Hawaii, USA. Robotic operation started in early 2011. Prototype 2 upgraded the system to two cameras and a more sturdy mounting to the ground. In 2013, prototype 3 was deployed, and is still in use. This last prototype uses four cameras, and was used to test choice of lenses and impact of near-IR blocking filter on photometry. In prototype 3, 2 cameras are equiped with Canon 85mmF1.2 lenses and 2 cameras are equiped with the lower cost 85mmF1.4 Rokinon lens. Each group of 2 cameras is further subdivided with and without near-IR blocking filter. Our findings are that (1) the image quality of the lower cost 85mmF1.4 Rokinon lens is almost as good as the Canon lens, and it is therefore a more attractive choice for PANOPTES, and (2) photometric precision is largely unaffected by the presense of the near-IR blocking filter. Considering the high cost of the Canon F1.2 lens relative to other hardware in the system and the fact that removing the near-IR blocking filter requires experienced manpower, these tests led us to adopt the 85mmF1.4 lens with the near-IR blocking filter as the baseline for PANOPTES units.

The nearly 4 years of prototypes operation has also been essential to design a PANOPTES baseline unit that is sufficiently reliable for robotic use. Reliable operation of a DSLR system without a protective dome (which would have greatly increased cost, footprint and complexity) was successfully demonstrated. This requires enclosing cameras in a weatherpoofed box and sealing gaps and connectors on the mount. This also allowed the PANOPTES team to develop and test observatory control algorithms, including tracking model refinement from previous images, observation scheduling, and reliable weather monitoring.

4. PRECISION PHOTOMETRY

As shown in Figure 3, commercial digital cameras such as the ones used for PANOPTES obtain color images through a set of filters on top of the detector pixels. Half of the pixels are green-sensitive, one pixel out of four is red-sensitive, and one pixel out of four is blue-sensitive. The pixel color layout is readily visible on PANOPTES raw images (Figure 3, right). This layout is a serious challenge to precision photometry, as stars' measured brightness and colors are a function of where the star image falls on the detector. Simple aperture photometry is therefore not applicable in this case, and we have developed a custom algorithm to extract precision photometry from PANOPTES units.

4.1 ALGORITHM

Our photometric algorithm aims at performing a differential flux measurement between the target and a well-chosen reference constructed from the same images: other stars in the field are used to construct a reference against which the target star is compared. Choosing the optimal of PSF(s) used for comparison with the target star is essential to compensate for error terms correlated with other sources (variable extinction due to clouds and airmass, color effects, detector non-linearity, and more importantly detector sampling/color effects).

Our approach to solving these challenges relies on an image-based identification of suitable reference PSFs. The wide field image delivered by the system offer a large number of potential reference targets. We perform

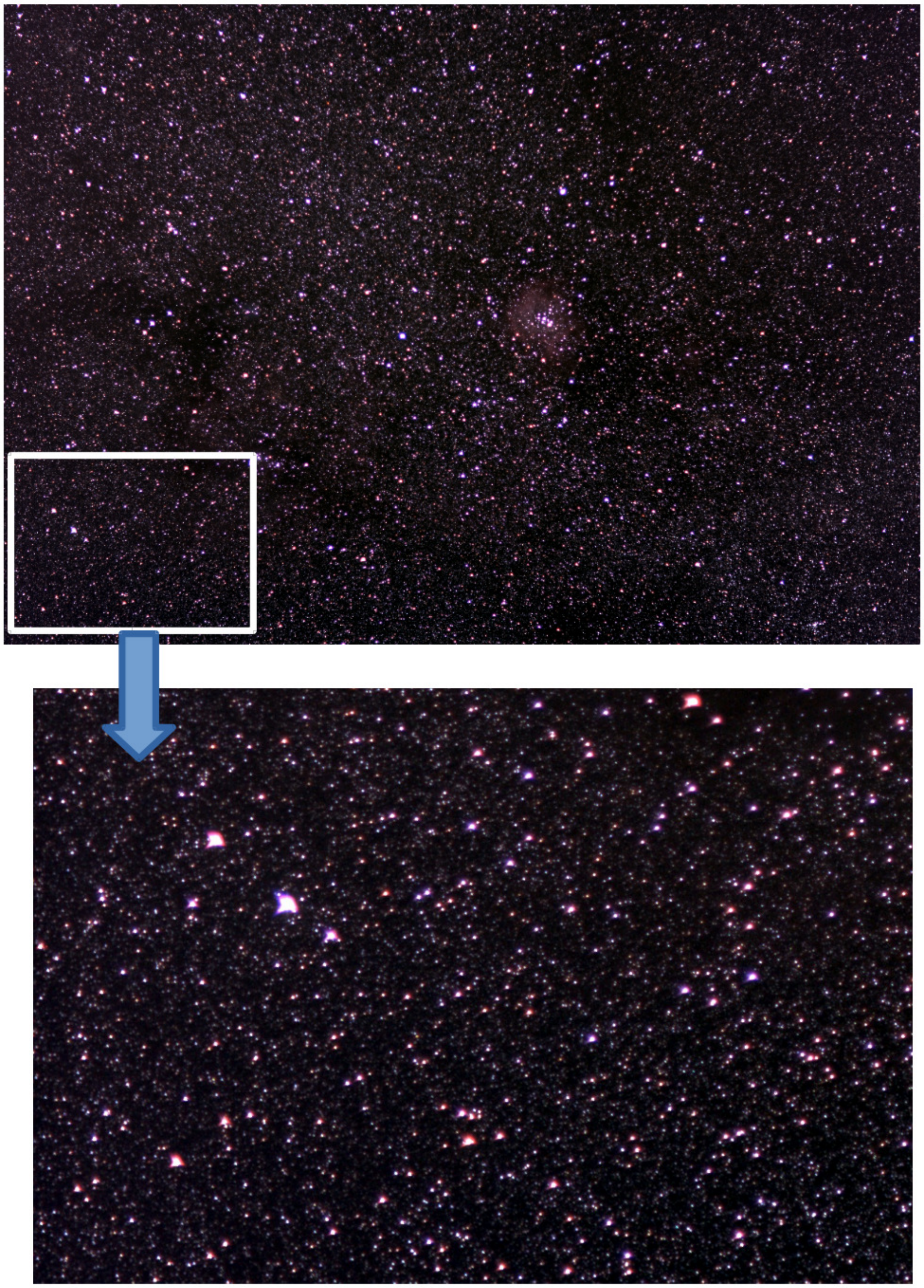

Figure 1. Sample 300 sec unprocessessed image (top). The lower right portion of the image is shown with higher magnification (bottom), showing moderate image quality degradation at the edge of the 10x15 deg field of view.

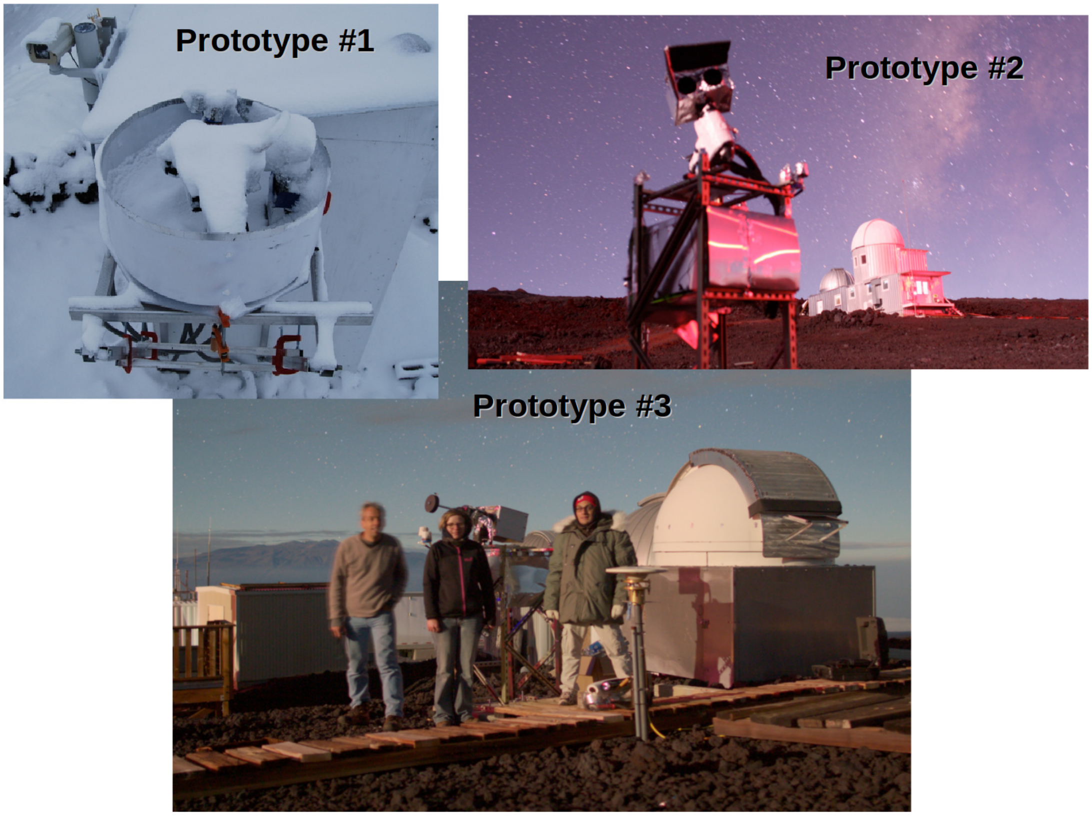

Figure 2. PANOPTES prototypes. Top left: first prototype, based on a single camera. Top right: Dual-camera prototype. Bottom: 4-camera prototype, currently still in operation.

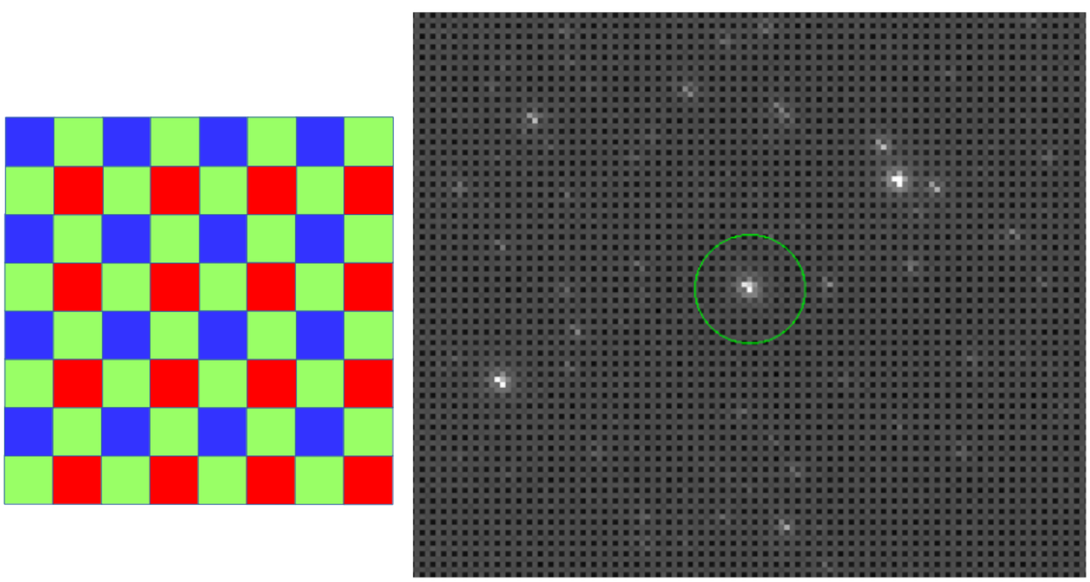

Figure 3. Detector color pixel layout for a DSLR camera (left) and detail of a PANOPTES raw image (right).

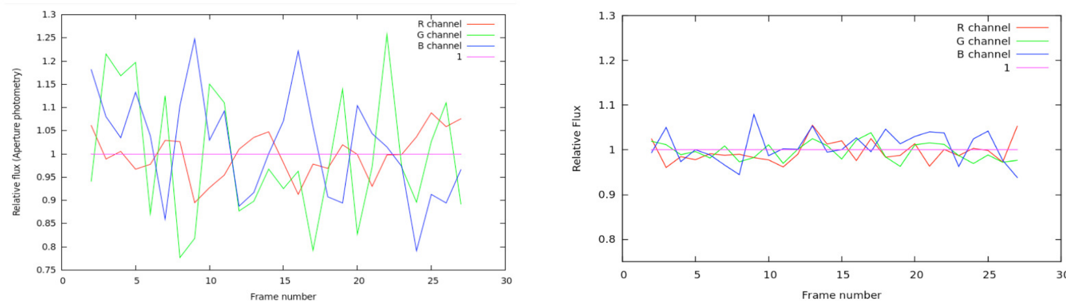

Figure 4. On-sky demonstration of the photometry algorithms developed for PANOPTES. While sandard aperture photometry (left) does not calibrate strong pixel sampling effects, an algorithm using PSF morphology (right) approaches the fundamental limits imposed by photon noise and scintillation.

image cross-correlations between our target and other stars in the field to select PSFs which have the intensity distribution amount pixels as the target for each image of the sequence. This step implicitly selects PSFs that have the same color, experience the same optical aberrations, fall on the same fractional pixel position and experience the same local detector defects as the target, without having to compute explicitly these parameters. An optimal linear combination of selected candidate PSFs is then performed to construct a template against which the target images are compared to produce the photometric light curve. While similar schemes have previously been applied to lightcurves, the strong pixelization issues in our system require image-level processing before a lightcurve is created.

4.2 ON-SKY VALIDATION

Figure 4 shows how the image correlation-based algorithm (right) compares with conventional aperture photometry (left) for a $m_V = 9.4$ star observed by PANOPTES prototype system. A set of 60-sec exposures was processesed using both approaches, and shows that the image correlation-based approach successfully calibrates PSF sampling effects. The photometric precision is about 2% for a 1-min exposure per color, and approaches the fundamental limit imposed by photon noise and scintillation (in this data set, photon noise was strong due to a bright Moon).

5. BASELINE UNIT

We are now building a "baseline" unit, incorporating all the lessons we learned from the three prototypes and which will be completely open source, both in its hardware and software. The baseline unit will be well documented, so that other groups can easily build their own unit. The first PANOPTES baseline units are currently in final stages of development, aiming for duplication and deploymement at the end of year 2014.

5.1 HARDWARE

The PANOPTES baseline unit uses two Canon EOS SL1 cameras in a small weatherproof enclosure, mounted on a iOptron IEQ30 equatorial mount. The 85mmF1.4 lenses offer 10x15 deg FOV. The unit includes weather and cloud sensing to support robotic operation, and runs on a 12V battery which is continuously charged by AC power. This offers resilience against power failures.

Figure 5 shows how the two cameras and lenses fit within the enclosure (left). The assembled unit (right) shows that only the front of the lenses is open to the outside, and is pointing down during daytime or bad weather.

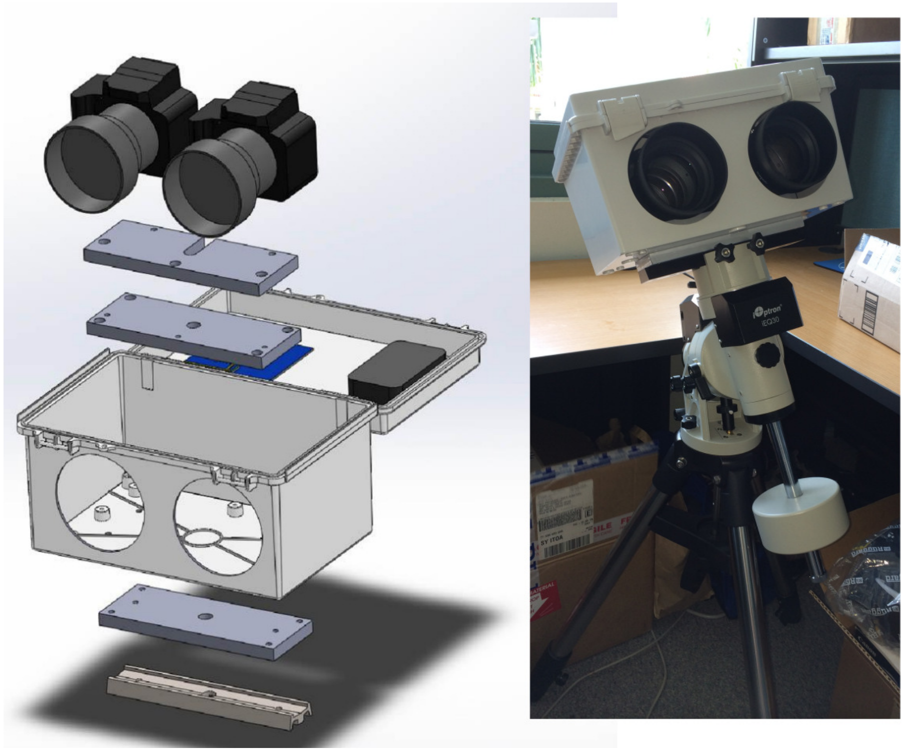

Figure 5. PANOPTES baseline unit design. Left: Camera housing design. Right: Assembled unit.

5.2 SOFTWARE

A new observatory control software, the Panoptes Observatory Control System (POCS), is being written using object oriented python. The POCS software will leverage existing astronomical and scientific packages such as astropy,[2] pyephem,[3] and IQMon.[4] POCS will operate as a state machine where the system will move between a few well defined states (see figure 6). A goal of the project is to keep the software as simple as possible so that it will be accessible to users to read and modify as needed. To that end POCS will not support several components or features that are common in more general observatory control systems such as enclosure control (PANOPTES does not use an enclosure), focus control (we have established that the focus stability is sufficient), and guiding. In addition, POCS will support only a few brands/types of mounts and cameras. POCS is an open source, community developed program. The code and documentation are available on github.[5]

6. CONCLUSION AND FUTURE DIRECTIONS

The baseline unit is being finalized, and we will start deployment of PANOPTES units in late 2014. We are currently seeking experienced amateur astronomers and professional astronomers to join PANOPTES and deploy the first set of baseline units, therefore building a community of PANOPTES users that can then support and assist a wider number of less experienced users. Development of an automatic photometry pipeline for PANOPTES will be the next high priority task, as the proof-of-concept algorithm needs to be integrated in an robust and automatic software.

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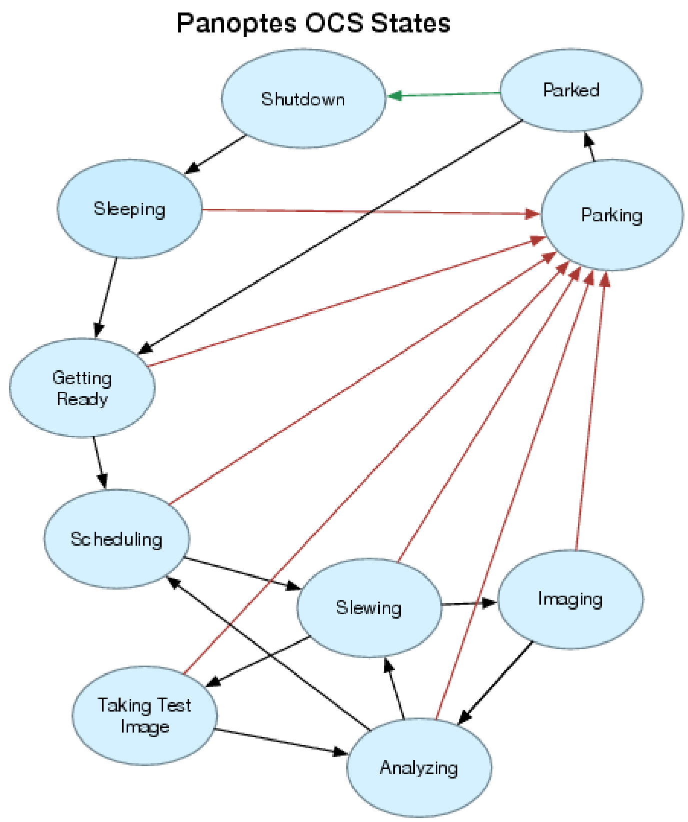

Figure 6. PANOPTES Observatory Control System (POCS) flow diagram.

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