

Cloud Computing with Context Cameras

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Abstract.

We summarize methods and plans to monitor and calibrate photometric observations with our autonomous, robotic network of 2m, 1m and 40cm telescopes. These are sited globally to optimize our ability to observe time-variable sources.

Wide field “context” cameras are aligned with our network telescopes and cycle every ~ 2 minutes through BVR*i*z’ filters, spanning our optical range. We measure instantaneous zero-point offsets and transparency (throughput) against calibrators in the 5-12m range from the all-sky Tycho2 catalog, and periodically against primary standards. Similar measurements are made for all our science images, with typical fields of view of ~ 0.5 degrees. These are matched against Landolt, Stetson and Sloan standards, and against calibrators in the 10-17m range from the all-sky APASS catalog. Such measurements provide pretty good instantaneous flux calibration, often to better than 5%, even in cloudy conditions.

Zero-point and transparency measurements can be used to characterize, monitor and inter-compare sites and equipment. When accurate calibrations of Target against Standard fields are required, monitoring measurements can be used to select truly photometric periods when accurate calibrations can be automatically scheduled and performed.

1. Introduction

Las Cumbres Observatory Global Telescope (LCOGT) is equipping a global network of 2m, 1m and 40cm telescopes with homogeneous instrumentation. Our goal is to provide maximally available monitoring of time variable sources, from solar system to extragalactic objects, and ranging in brightness from about 7-20m. Ideally we would like to provide accurate relative light curves with accurate absolute photometric calibration for all our imaging data, but the latter would preclude observations in non-photometric conditions, and would require a large overhead of standard observations that would take time away from the many programs that do not require such absolute accuracy.

Many observations of time-variable sources are able to achieve very high relative photometric precision, typically to a few mmag, by comparison with stars within the target field. Observations of exoplanet transits for example do not require absolute flux calibration, and in many cases results are quite insensitive to variable atmospheric transmission, or filter passband. Similar statements may be made for other time variable observations such as micro-lensing events, but in this case data from several sites, instruments and passbands are likely to be combined, so reasonable flux calibration of the different data sets enables more reliable combinations and comparisons.

More demanding applications include SN light curve observations, where accurate flux calibration to 1% or better is required, to minimize the effects of observational error on derived cosmological parameters. These accurate calibrations can be performed *post-facto* on target fields, after light curves of interesting targets have been determined with good relative accuracy. A number of target fields requiring accurate flux calibration can be combined into a single calibration program during photometric periods.

We are therefore trending towards a two-stage approach for our photometric calibrations. The first stage includes automatically measuring a zero-point magnitude offset to better than 10% (goal $\leq 5\%$) for all images, based on available calibrators within each observed field. Measured zero points and rms errors are attached to each FITS header, and can be added to instrumental mags (eg. as MAG_ZEROPOINT in *sextractor*¹) to provide calibrated magnitudes to within the recorded error.

The second stage, for more accurate photometric calibration but of fewer targets, requires the observer to propose specific targets and methodology to derive detailed calibrations for these target fields. In the latter case, LCOGT can provide the continuous monitoring to indicate when photometric conditions prevail, and when these demanding calibrations should be automatically scheduled.

2. All-Sky Catalogs

It has become common practice to provide rapid and automatic World Coordinate System (WCS) fits to astronomical images, usually by reference to the USNO-B or NOMAD catalogs (Zacharias et al. 2004). We perform WCS fits with *astrometry.net*² for instantaneous or “flash” reductions, and with *wcsfit* within the ORAC-DR pipeline (Bridger et al. 1998) for final data products. With the advent of comprehensive all-sky photometric catalogs, it is a short step to add pretty good automatic photometric calibration. Our experience is that this can be accurate to a few percent, even in quite cloudy observing conditions.

The Tycho2 catalog (Høg et al. 2000) contains ~ 2.5 M stars around the sky, with an average density of ~ 60 stars per square degree, and a useful magnitude range from 3-12mag. It is well suited to wide-format devices such as SkyProbe (Steinbring et al. 2009), and the 3-degree wide Context cameras described here. The Tycho2 catalog provides native passbands in B_T and V_T . Cousins R-mags can be added from NOMAD (Zacharias et al. 2004) as can infrared JHK_S bands from the 2MASS survey (Cutri 1998). Fitted magnitudes in any desired system passbands can be obtained by matching a best-fit library spectrum to the catalog passbands. A version of automatic flux calibration utilizing Tycho2 was proposed in Pickles & Depagne (2010).

The number and magnitude range of the Tycho2 catalog provide relatively sparse automatic flux calibration within typical cassegrain images covering less than one degree, and their magnitude range is too bright for many telescopes. Large survey cameras such as PTF in the Northern hemisphere can automatically calibrate against extensive Sloan survey data (Ofek et al. 2012). In a few years the Gaia mission (E. Pancino, this conference) promises to provide a dense all-sky astrometric and photometric catalog to satisfy different telescope apertures, and image fields.

¹<http://www.astromatic.net/software/sextractor>

²<http://astrometry.net>

Fortunately the AAVSO Photometric All-Sky Survey (APASS³, A. Henden, this conference) now provides over 40M stars across most of the sky. APASS DR6 provides good flux calibrators at a typical density of over one thousand stars per square degree, in the 10-17mag range, and accurate to about 3% in passbands BVg'r'i'. Spectral matching to BVg'r'i' and corresponding 2MASS JHK_s magnitudes, again enables synthetic mags to be calculated for other desired passbands. We have started using the APASS DR6 catalog on our science images and find excellent results. We typically find ≥ 50 matching stars in our current 15x15 arcmin frames (to be increased to 27x27 arcmin), resulting in a measured zero-point rms (for stars of varying brightness and color) in the range 3–5% for un-flatfielded observations, and often better than 3% for flat-fielded data, in atmospheric conditions varying from clear to quite cloudy.

3. Extinction and Transparency

Here we use the term “Extinction” to refer to clear atmospheric extinction that is measured over a reasonable time (≥ 1 -night) to vary linearly with airmass. Extinction caused by Rayleigh scattering, ozone, and aerosols in an atmospheric shell around the Earth is then considered to be well behaved, or “photometric” for that period, with coefficients of extinction per airmass (per passband) that are well defined and measurable. Extinction calibrations may also include color terms to match observed to standard passbands, and may include terms to allow for variable atmospheric absorption or emission features that affect one or more passbands.

The term “Transparency” here quantifies any conditions, including cloudy weather or conditions of significant non-photometric atmospheric variability. Transparency varies from a maximum of 100% (photometric if maintained over a significant period) to much lower values, and becomes unmeasurable below about 10%. Useful observations can still be obtained when the transparency is as low as 20–30% however. Transparency calculations here allow for the nominal clear-atmosphere extinction per passband and airmass, where the extinction coefficients can be calculated from Hayes & Latham (1975), or calibrated by on-sky measurements.

4. Telescope Throughput

Telescope optical throughput includes reflectivities of mirrors, transmission of corrective optics and filters, and QE of detectors, all of which can vary (slowly) with time. Figure 1 is a screenshot showing the attenuation of an A0 V spectrum (magenta) by various components extracted from our database: mirrors (standard reflectance curve in red, measured single-mirror reflectance from 380–760 nm in blue, scattering in green), a smooth atmospheric transmission (brown) calculated from Hayes & Latham (1975) for 1.3 airmasses at an elevation of 2200m, filter transmissions (black) and CCD QE (cyan).

³<http://www.aavso.org/apass>

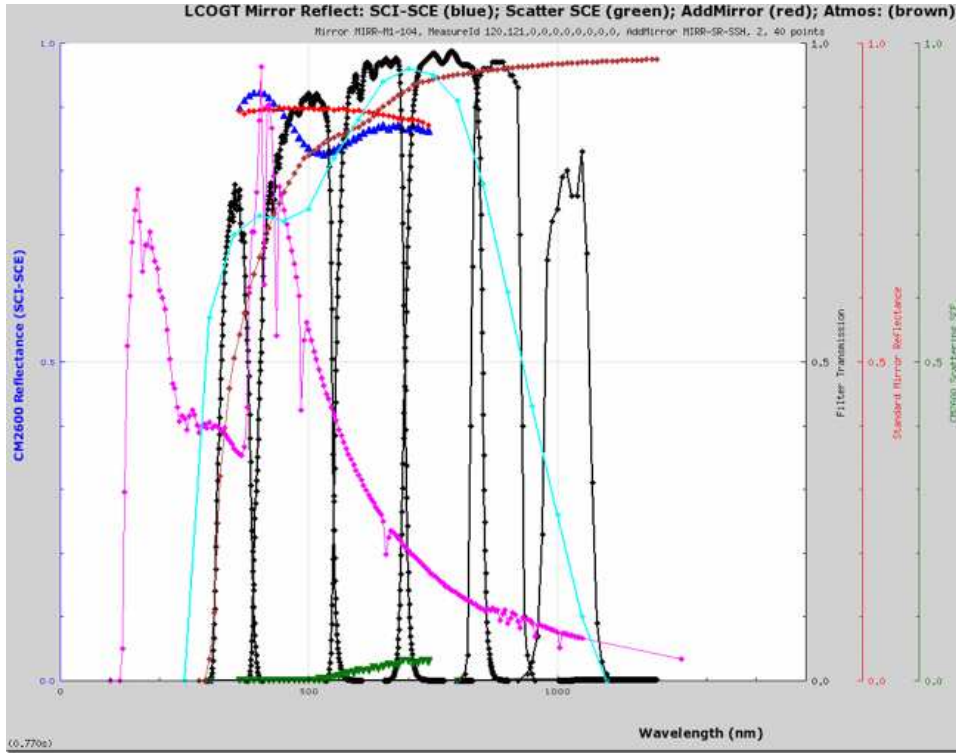


Figure 1. Throughput measurements from our database.

5. Filters and System Passbands

We have designed and ordered custom filters from Astrodon, to optimally match UBVRI standards (Landolt 2009), Landolt (this conference) and Stetson⁴. We were able to match our system UBVRI passbands to those of Bessell (1979, 1991); Maiz Apellaniz (2006) that provide the best matches to Landolt standards (with minimized color corrections) when convolved with calspec flux-calibrated spectra (Pickles 2010).

We have adjusted our Sloan primed passbands slightly from those listed for the USNO 40-in telescope⁵. Our g_L filter has its blue edge shifted redwards to 405nm. Our g_L red edge and r_L blue edge were optimized to exclude the night-sky OI 5577 Å feature. Our z_{SL} , y_{SL} filters are chosen to match the short red-cutoff Pan-Starrs z_S , y_S filters⁶. Our w_L filter matches the wide combination of g+r+i. LCOGT ugrizy_L system passbands (smooth atmosphere, telescope, filter, detector) are shown on the left of Figure 2 for u_L , g_L , r_L , i_L , z_{SL} , y_{SL} in blue, compared with Sloan USNO-40 primed filters (black) and UKIRT/VISTA Z_V , Y_V (filter only) in red.

⁴<http://www3.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/community/STETSON/standards/>

⁵<http://www-star.fnal.gov/ugriz/Filters/response.html>

⁶http://svn.pan-starrs.ifa.hawaii.edu/trac/ipp/wiki/PS1_Photometric_System

It is not possible to match observed to standard system passbands precisely, because of variations in telescope throughput, atmosphere and detector QE. It is possible to model (and check by measurement) the color differences that result. We have convolved LCOGT and Sloan primed system passbands against a set of standard spectra and computed the color difference as a function of color. These are shown on the right in Figure 2. For detailed on-sky comparisons, we compare against Sloan standards from Smith et al. (2002, 2005); Tucker et al. (2006); Davenport et al. (2007).

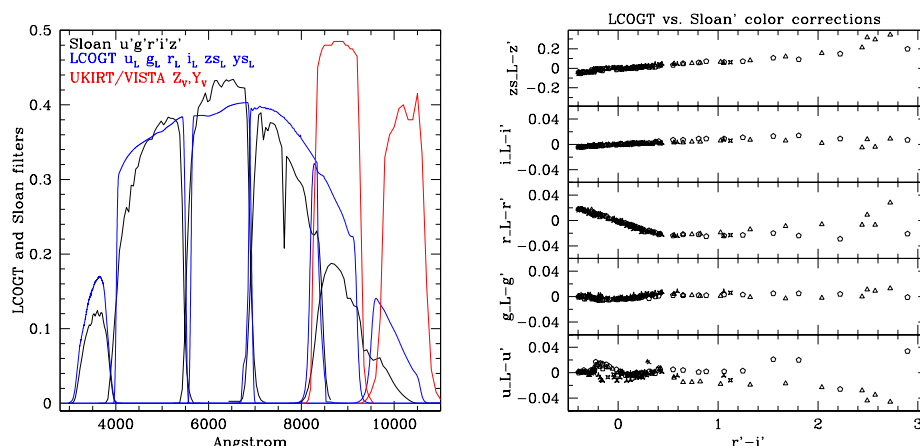


Figure 2. LCOGT filter passbands and modeled color corrections

6. Flat-fielding and Baffling

Removal of the instrument signature should remove pixel-to-pixel variations, zonal effects including vignetting, and variable QE response to uniform illumination. After signature removal a star should give the same flux and instrumental magnitude anywhere in the detector field. But errors in the flat-field system, illumination and color differences between the sky illumination and flat-field, and scattered (stray) light from imperfect baffling can all lead to residual response variations in the 1–3% range across the detector. These effects need to be understood, minimized and calibrated. We were able to reduce this effect significantly on our 2m telescopes by improved light baffling (Rosing and Tufts, in preparation). We have devoted considerable attention to designing good 1m telescope baffles, and minimizing ghosting (Haldeman et al. 2010), and to designing a uniform flat-field illumination system for all our telescopes (Haldeman et al. 2008).

7. Context Camera and Results

The context camera results illustrated here use a Nikon 400mm f/2.8 lens with 5-position filter wheel and SBIG 6803 CCD. This results in 3072x2048 images with 4.7-arcsec pixels, and a 4x2.7 degree field of view. Figure 3 shows such a device mounted on the south side of a 1m telescope mirror cell, coaligned with the 1m telescope point-

ing. We are also testing other camera setups, on independent mounts, that can service multiple pointings⁷.

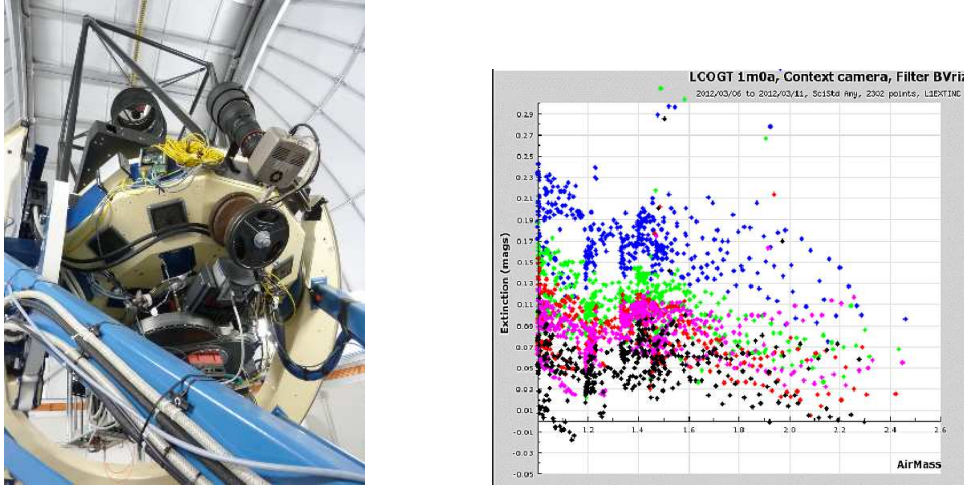


Figure 3. Context camera mounted on our 1m telescope in Santa Barbara and extinction measurements vs. airmass

The context camera cycles through its 5 filters (BVR*'i'z'*) in about 2-minutes. Each frame is WCS fitted, calibrating stars within the pointing area⁸ are coordinate matched with observed stars in each image to within a small tolerance (~ 3 -arcsec), usually resulting in ≥ 100 matches. For each image the differences between *sextractor* instrumental and catalog magnitudes in the relevant passband are calculated, and a mean and rms formed. Because of vignetting in the system, the un-flat-fielded context data typically have about 15% rms, but flat-fielded or simply un-vignetted images typically have $\leq 5\%$ rms. The highest values of these differences correspond to clear, possibly photometric weather; lower values to cloudy conditions. Measurements are displayed in real-time on the system, and stored in a database.

An example of these results for a 6-night period in March from our facility in Santa Barbara is shown as a screenshot from our database to the right in Figure 3. Extinction in magnitudes is plotted against airmass for B–blue, V–green, r’–red, i’–magenta and z’–black. Measured extinctions show trends with airmass in each color, but none of these data indicate photometric conditions. Photometric nights are rare in Santa Barbara, particularly at our facilities close to UCSB, at low elevation, and close to the sea.

We have installed a Context camera at our recently deployed 1-m at McDonald Observatory, and will extend them with 1m telescope deployments this year to our sites at CTIO (Chile), SAAO (South Africa) and SSO (Australia). Our goal is to accumulate data and calibrations with a view to characterizing each site, and automatically detecting photometric periods.

⁷<http://lcogt.net/network/0.4m>

⁸<http://lcogt.net/ajp/findstars>

8. Conclusion

Wide-field Context cameras are well suited to monitoring the changing atmosphere at astronomical sites. They provide quick, automatic and reliable calibrations of transparency. More importantly for our purposes, they can automatically detect and signal photometric conditions when they prevail. At these times detailed calibrations of extinction coefficients, and of important target fields, can be scheduled with network telescopes.

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