DeltaRho + QHY600 Release Notes
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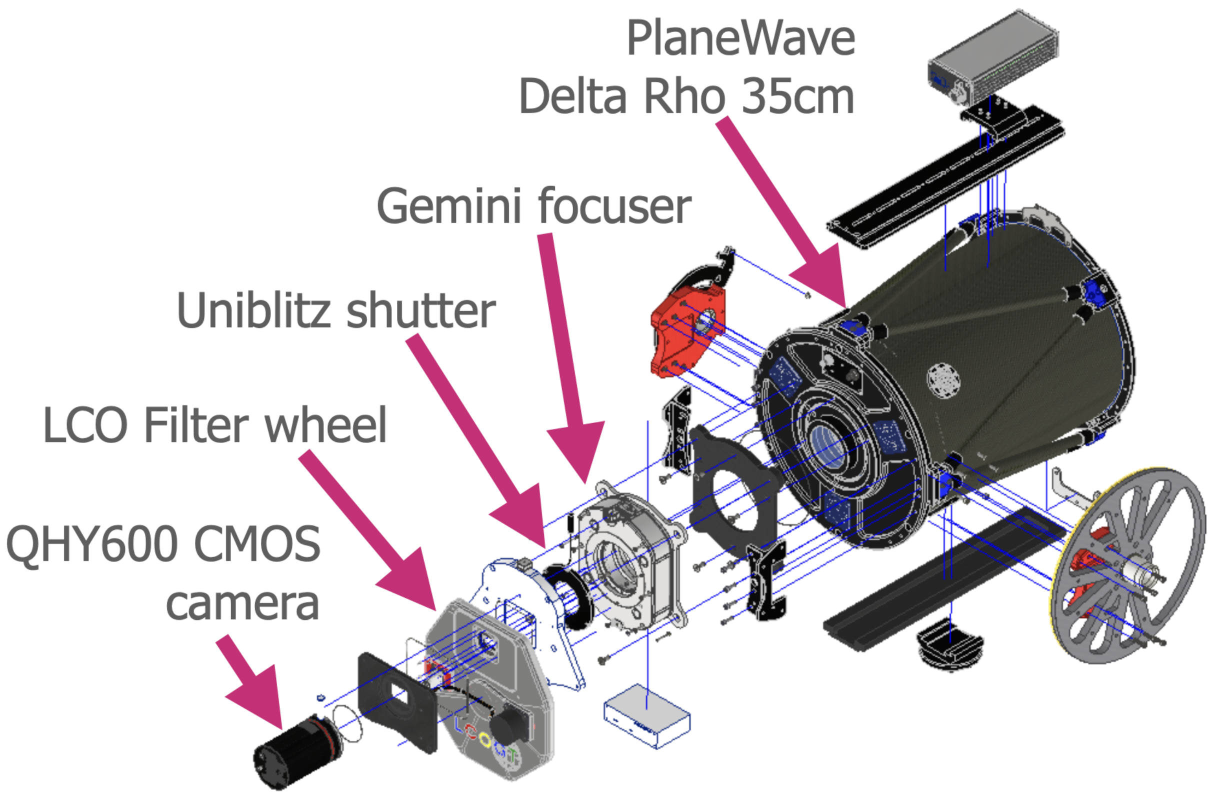


Background

The 0.4m telescopes, equipped with SBIG STL6303 imagers, have provided thousands of images for hundreds of LCO's education and science users. However, as we have reported over the years, the telescopes suffer from nagging problems. Specifically: secondary mirror control errors (in electronics and hardware) that lead to poor collimation and focus stability. In addition, the SBIG imagers have reached the end of their serviceable lifetimes and have revealed the mysterious photometric nonlinearity that we reported in 2021 and 2022. LCO engineers have gone to extraordinary lengths to service the 0.4m telescopes and their attendant SBIGs. The hours invested in their maintenance is comparable to the 1m network, even though their astronomical return is less. Now, *due to the generous support of the Moore Foundation*, we are able to replace these systems entirely. This document provides pertinent information that users of the 0.4m+SBIG systems should know about the new telescopes and cameras.

Quick Summary

- The Meade optical tubes are being replaced with Planewave DeltaRho 350 Optical Tube Assemblies. The SBIG STL6303 CCD cameras are being replaced with QHY600 CMOS cameras.

- The pixel scale is 0.7 arcsec/pixel. The full field of view is 1.9° x 1.2° on the sky. A readout mode restricting the region-of-interest to the central 30x30 arcmin is available. The central readout mode is intended for time series observations of compact sources.

- Because of the camera's small pixels and CMOS limitations, the full well is about 44,000e^-. The readnoise is about 3e^-. As with all CMOS detectors, the camera is affected by random telegraph noise.

- Relative to the 0.4m+SBIG systems, the DeltaRho+QHY600 systems have greater throughput in the up[1] and gp bands. The throughput is less for redder bands.

- The stability of the focus and collimation of the DeltaRho+QHY600 systems reveals the intermittent tracking errors caused by the telescopes' mounts. To mitigate the effects of these errors, **we recommend that observations of fainter objects use exposure times <120 seconds and stack images afterward**. The low read noise of the CMOS cameras makes stacking viable.

- Publications using data acquired with the DeltaRho telescopes should adhere to LCO's acknowledgement policy and include the following statement:

  "**This paper used observations made with Las Cumbres Observatory's education**

[1] At LCO, the SDSS u' g' r' and i' filters are called up, gp, rp, and ip, respectively, to avoid software complications when parsing apostrophes (').

network telescopes that were upgraded through generous support from the Gordon and Betty Moore Foundation.”

Details of key system components

Telescope

The new telescopes’ optical tube assemblies are DeltaRho 350 OTAs from Planewave. The primary mirrors are slightly smaller (0.35 m) than on the Meade telescopes (0.40 m).

Filter wheel

The new systems use the same filter wheels. The filter set includes:

- all of the filters that were available in the 0.4m+SBIG systems: up, gp, rp, ip, zs, w, B, V, as well as an aluminum blank (“opaque”) and an “air” position;
- Hα, O[III], and S[II] narrow (6.7 nm) band filters;
- an Exoplanet filter that cuts off light blueward of 500 nm.

The clear / air position of the filter wheel is not offered for observations.

Focus unit

The system is equipped with a Gemini focusing rotator, but the rotator is not connected due to the risk of mechanical interference. The focuser is mounted with the instrument package rather than at the telescope’s secondary mirror, which contrasts with the 0.4m+SBIG systems. The optical system is very fast (f/3), and small focus adjustments have a large effect. For the default focus curve, we use focuser offsets from +0.075 mm to -0.075 mm.

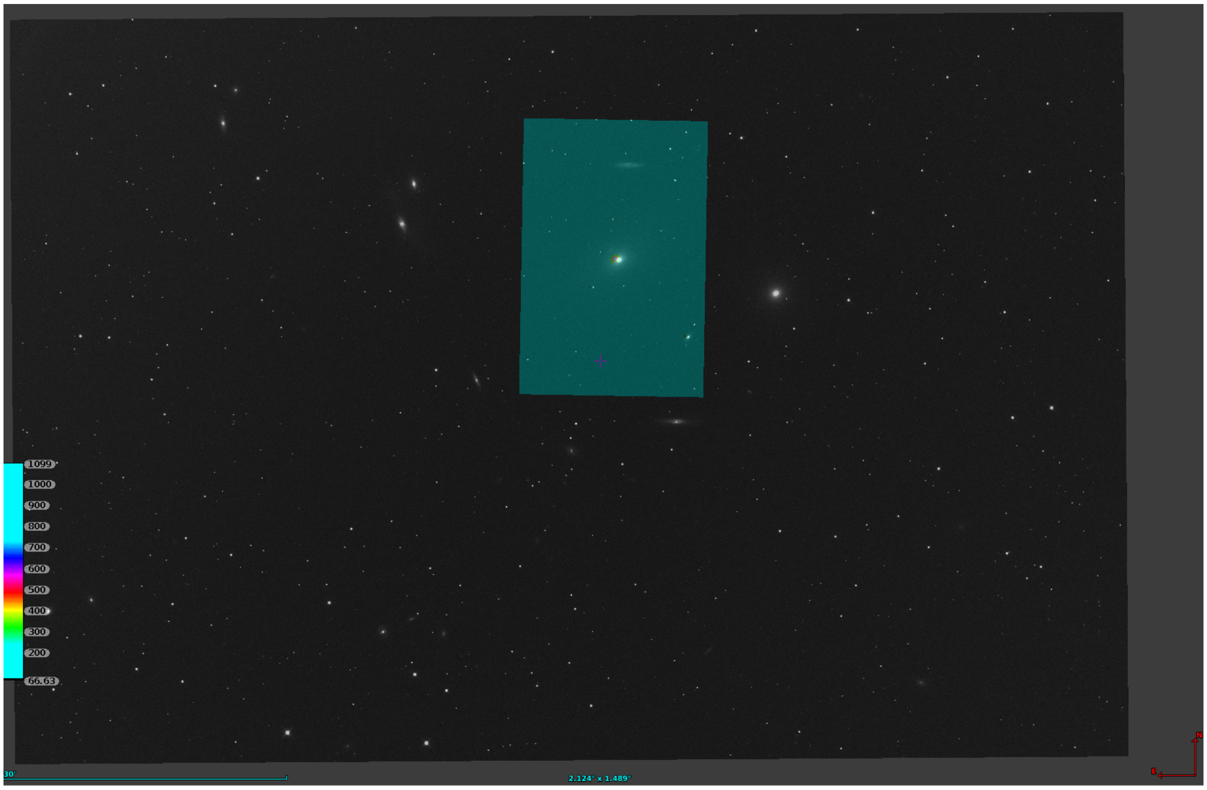
For defocused observations (e.g. of exoplanet transits around bright stars), we recommend exploring (with test exposures) defocus offsets around 0.075 mm first.

Imager

The new cameras are QHY600 CMOS cameras from QHYCCD.

Field of view

The camera orientation places North up and East left in both hemispheres. The field-of-view is 1.9° (E-W) x 1.3° (N-S). This field-of-view is much larger than the previous 0.4m+SBIG system (29’ x 19’), as shown in the figure below. The DeltaRho+QHY600 image is the background; the 0.4m+SBIG field-of-view is superimposed in teal.



Detector Characteristics

The pixel scale is 0.73 arcseconds/pixel.

The QHY600 is set to Readout Mode #1 (High Gain Mode) with Gain Setting = 0. The resulting detector characteristics are:

Gain	0.7 e^-/ADU
Readout noise	3 e^-
Saturation limit	64000 ADU (>44000 ke^-)

The Readout Mode and Gain Setting are selected to prioritize a low read noise (3 e^- vs. 7.5 e^-) over a larger full well (up to ~80 ke^-).

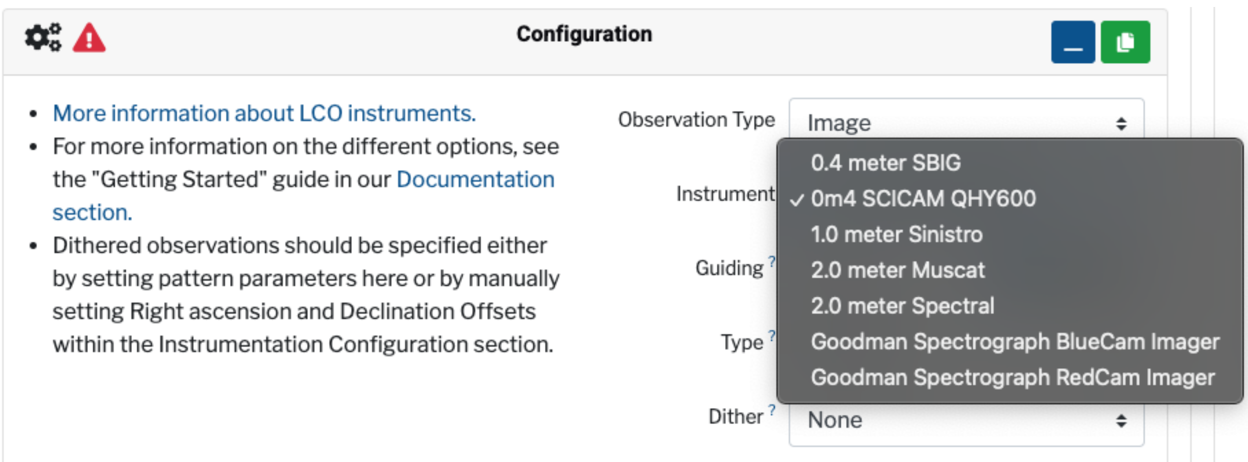
Two readout modes are configured:

- **full_frame**. The full 1.9° x 1.2° frame for wide-field imaging. The images are large! The readout overhead is < 6 s.

- **central30x30.** Unbinned, central 30' x 30' frame for time series exposures. This is approximately the same field-of-view as the SBIG cameras. The readout overhead is < 3 s. *There is no overscan in the central30x30 readout mode, and the BIASSEC keyword is set to N/A.*

Requests in the Observation Portal

Requests to observe with the DeltaRho+QHY600 systems should be submitted to the LCO Portal's web interface and API, just like requests to observe with other LCO instruments. In the Configuration section of a request, the new `instrument_type` option is *0M4-SCICAM-QHY600.* In the Location section, the `telescope_class` option remains *0m4*.



During the DeltaRho telescope rollout, the old (0.4m+SBIG) and new (DeltaRho+QHY600) systems will operate in parallel. Users who are assigned hours on the 0.4m network during the 2023A/B semesters will be granted hours on both instrument types. Users who have been allocated hours in Time Critical (TC) mode should pay special attention to which instrument type is available at which site during TC events.

Data Products: Banzai-processed images

QHY600 data are processed by the BANZAI pipeline. Typical image sizes are listed in the table below. Users should be aware of the computing requirements needed to process the images and should balance their science requirements with the requested field of view.

	full_frame (default)	central30x30
Raw, uncompressed	118 MB	12 MB
Raw, fz-compressed	46 MB	3.7 MB
BANZAI, uncompressed	526 MB	49 MB
BANZAI, fz-compressed	132 MB	13 MB

The calibration frames used for BANZAI processing are acquired in both readout modes and are available to all users in the science archive.

Random Telegraph Noise

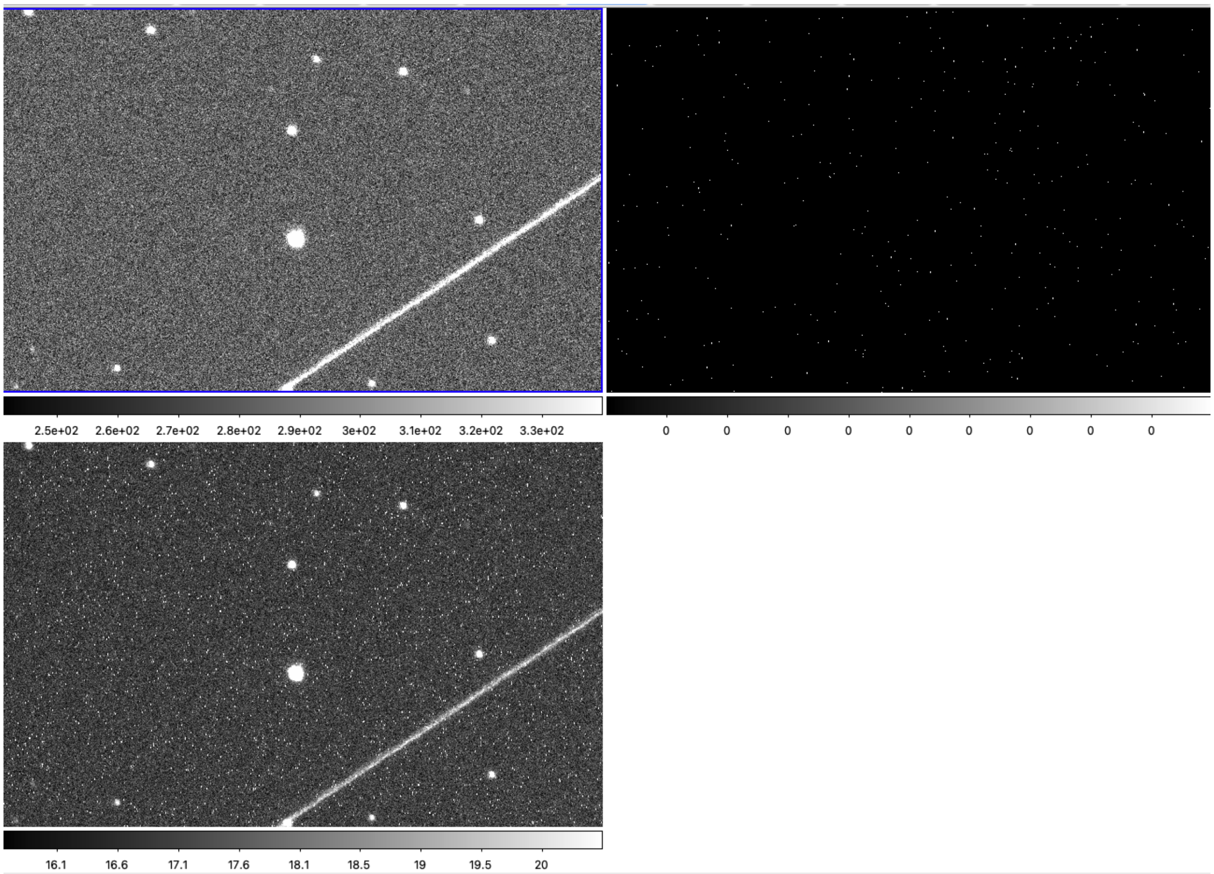
Because the QHY600 cameras use CMOS detectors, they are subject to random telegraph noise, where some pixels have excessive noise with a tri-modal distribution that can be 20 electrons wide. This is apparent in low background level images as a "salt and pepper" like noise, and can be mitigated by, e.g., stacking several exposures.

CMOS cameras in professional astronomy are fairly new, and there is no clear consensus yet on how telegraph noise is to be treated. As a first step, we have decided to include the per pixel noise behaviour in LCO CMOS images so advanced users can improve the noise model of their photometry.

Each BANZAI-processed image already includes a noise map, i.e. a map of the propagated readout noise and photon shot noise at each pixel. This map is stored in the FITS extension named "ERR". Traditionally, for CCD cameras, this noise map has been seeded with a single readnoise value for the entire image. For CMOS cameras, this noise map is seeded with a per pixel noise value, see our CMOS noise map documentation[2] for more details and limitations of the noise modelling.

The extensions of a BANZAI-processed image ('SCIENCE' for the science image, 'BPM' for the bad pixel mask, and 'ERR' for the noise propagation map) are illustrated in the figure below.

[2] See https://cmos-noise-map.readthedocs.io/en/latest/index.html



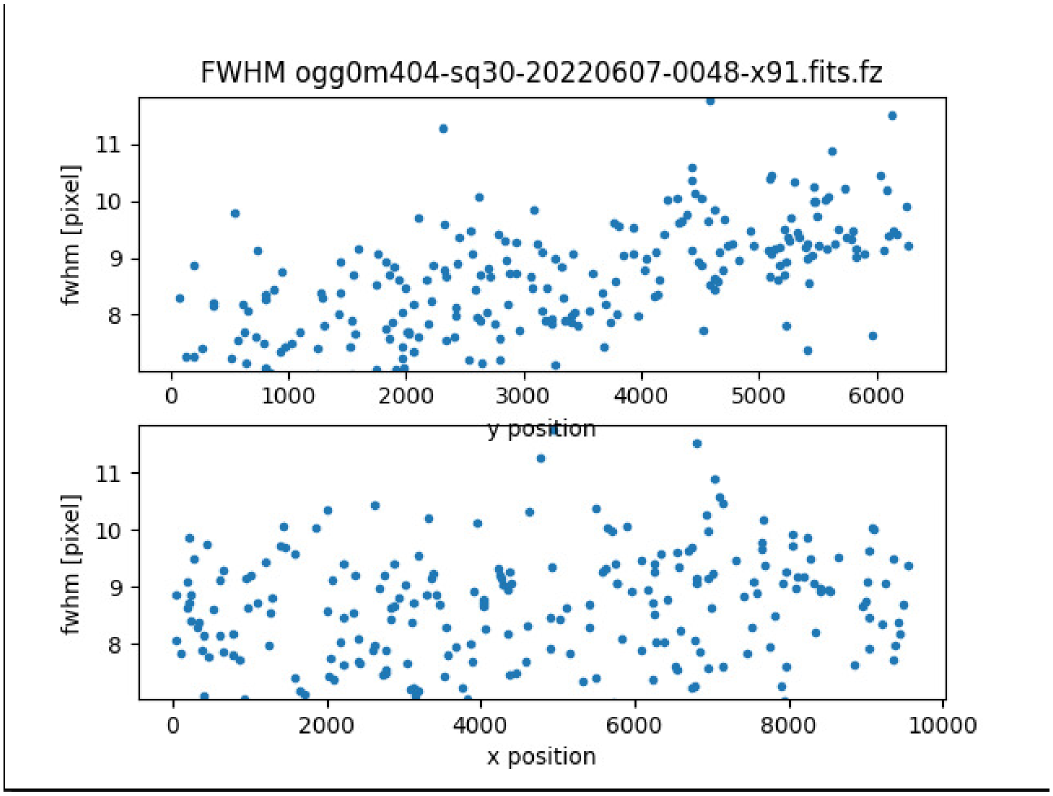
:

Upper left: processed image. Upper right: bad pixel mask. Lower left: The per-pixel noise derived from read noises and shot noises from bias, darks, flats, and the exposure itself.

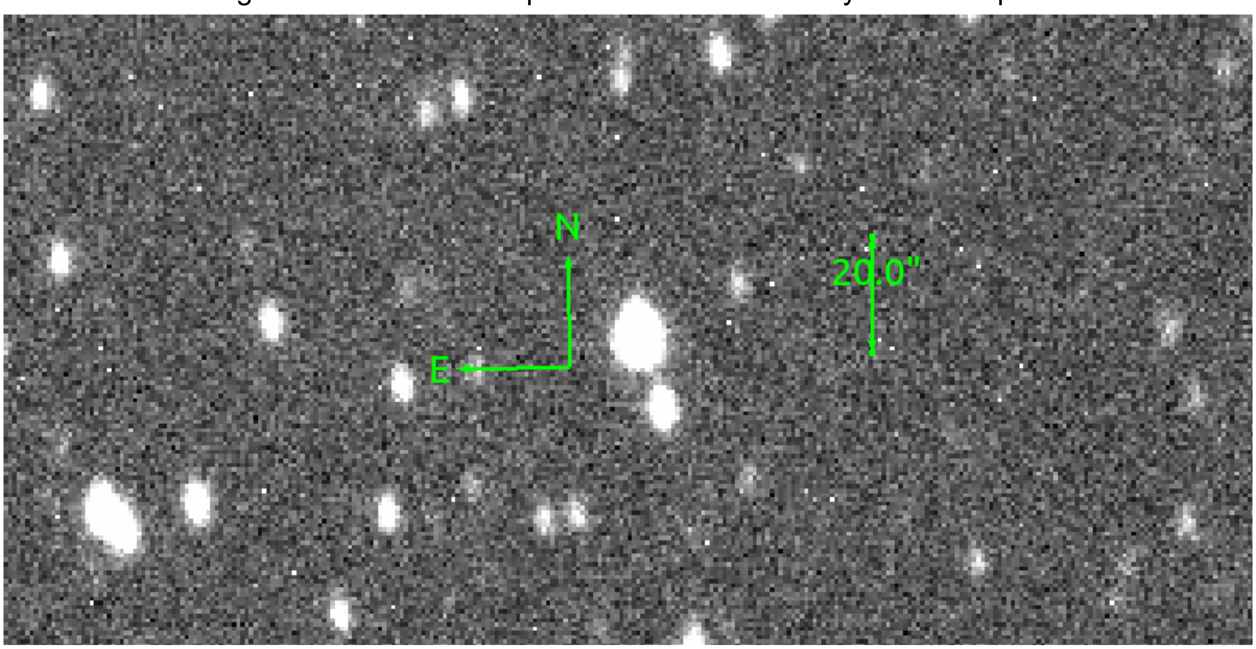
On-sky performance:

Image quality

The focus and collimation of the DeltaRho telescopes are stable. In a deliberately defocused image with “donut-shaped” PSFs, the FWHM of the PSFs metric vary by about 2 pixels, or 2 * 3.76 µm, across the field-of-view. With an f/3 focal ratio, this corresponds to a height difference of 2 * 3.76 µm ÷ 3 = 2.5 µm.

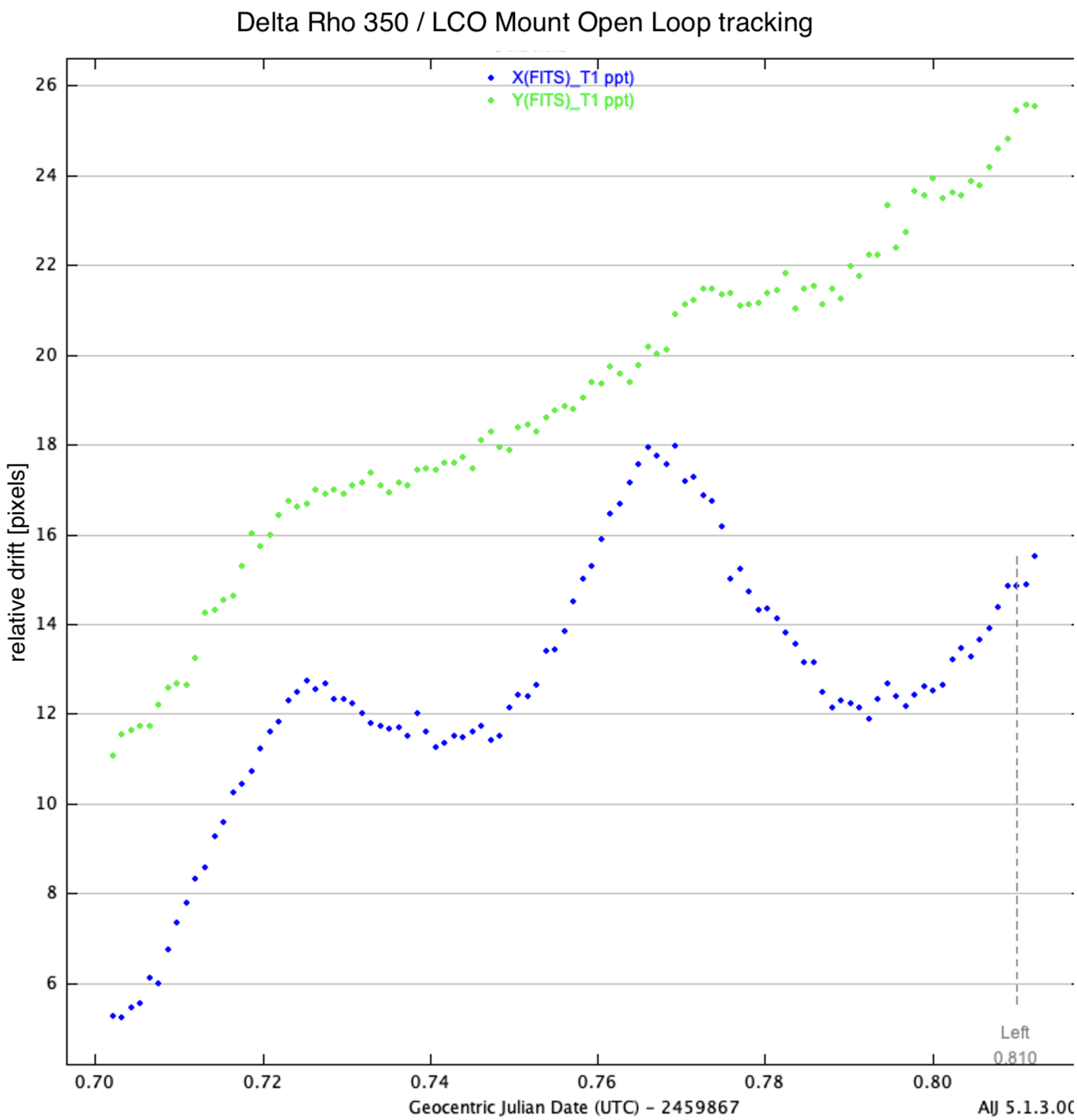


On some nights, the PSFs appear elongated in the N/S direction (see figure below), which we attribute to tracking errors of the telescope mount exacerbated by the wind speed and direction.



Tracking

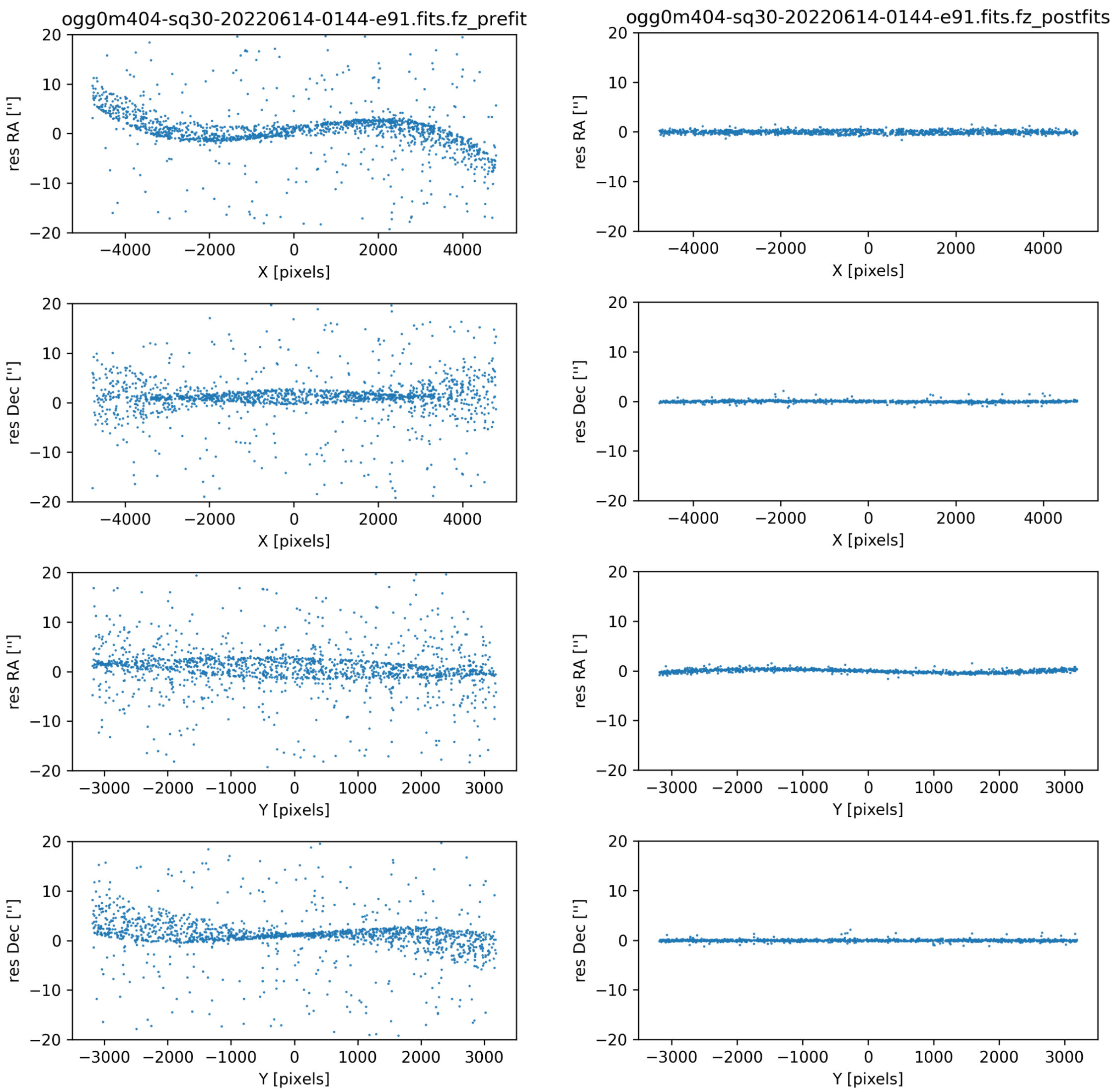
Limitations to tracking stability are imposed by the telescopes' C-ring mount. Unguided images exhibit a drift of up to 20 arcseconds over a few hours. Occasionally, the drift occurs within a few minutes. Until we identify the cause of the intermittent "fast drift", **we recommend that users always enable telescope guiding (i.e. self-guided images). Moreover, we recommend that users avoid long exposure times and instead stack multiple shorter (<2 minutes) exposures, to observe fainter targets.** An example of the drifts imposed by the telescope mount is shown in the figure below[3].



[3] This example shows the drift *after* the grease in the tail bearing was replaced.

Image geometry & distortions

As a wide-field, fast telescope, the DeltaRho is affected by image distortion. A linear WCS solution to full frame QHY600 images yields residuals in the corners on the order of 10 to 15 arcseconds. Adding a 3rd order polynomial (SIP) correction will reduce these residuals significantly. The plot below shows the improvements in the residuals (differences between star positions and the WCS-modeled positions) from when the image is fit with a linear WCS solution (left column) to when it is fit with a 3rd-order-polynomial-corrected WCS (right column).



Currently (March 2023), BANZAI-processed images will only provide a linear WCS solution, but a higher order corrected WCS can easily be calculated with the command line tools of astrometry.net:

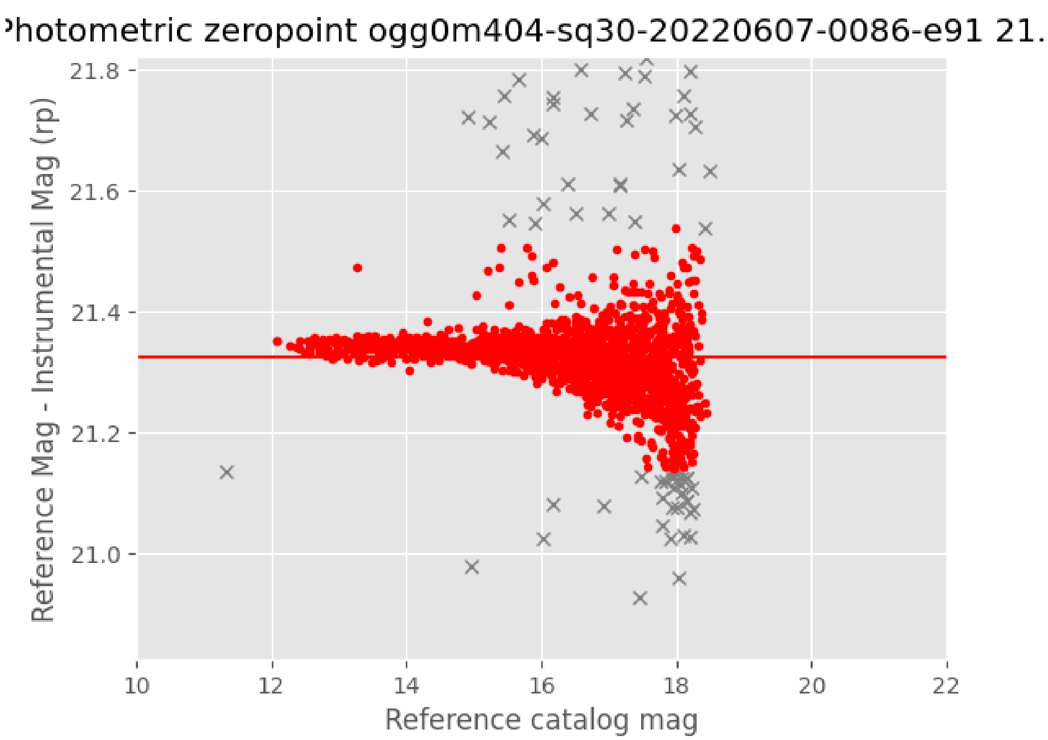
```
solve-field -t3 -no-plots [imagename.fits]
```

Depending on the computer speed and the richness of the field, the processing of astrometry.net can take several minutes per image. To compensate for the distortion in a stack of images that were obtained in a dither pattern, astrometry.net provides the wcs-resample tools:

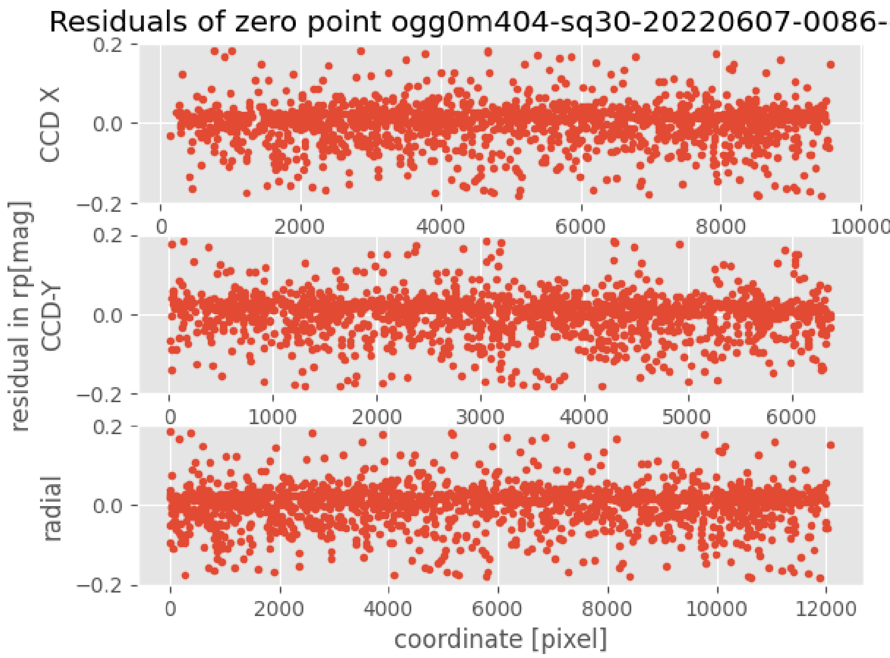
```
wcs-resample [input image] [reference image wcs] [outputimage]
```

Photometry

The photometry of stars behaves linearly over the range of magnitudes. The figure below shows the uniformity of photometric zero points as a function of catalog magnitude for stars in an example image. We have not found evidence for the photometric nonlinearity that impaired some of the SBIG cameras.



The figure below shows the residuals in SDSS-r’ magnitudes (y-axis) as functions of the x coordinate (top panel), y coordinate (middle panel), and radial distance from field center (bottom panel) for a particular image. Plots like this one have been created for multiple images and show that zero points are homogeneous over the field of view.



Throughput

We compare the collecting areas of the DeltaRho and the 0.4m telescopes, taking the central obscuration into account:

$$((0.35/2)^2 - (0.196/2)^2) \ / \ ((0.406/2)^2 - (0.127/2)^2) = 0.56.$$

Thus, we expect the DeltaRho telescopes to deliver about half of the photon flux of the Meade telescopes, which corresponds to a zero point decrement of 0.63 mag. Wide-field telescopes need a larger secondary!

A comparison of the measured photometric zeropoints between the 0.4m and DeltaRho systems is in the table below. The zeropoints (zp) are in units of log(e-/s). The airmass is assumed to be 1.

Filter	zp SBIG kb82	zp QHY600 sq30	Δ (mag)	Rel. Sensitivity
up	16.11	17.5	+1.4	3.6
gp	21.4	21.8	+0.5	1.6
rp	21.5	21.2	-0.3	0.75
ip	20.75	20.1	-0.65	0.55
zs	19.4	18.4	-1	0.4

The lower photon collecting ability of the telescope is countered by a much better-matched pixel scale with a lower readnoise going down from 14 e^- to 3 e^-. For faint targets and low surface brightness objects, we expect a net gain in S/N.

Users should be aware that the zeropoints given above and those assumed in the LCO Exposure Time Calculator are for telescopes with freshly cleaned optics under transparent skies. In practice, dust deposition and differences in atmospheric transparency can easily degrade those values by 0.3 mag. Before submitting requests for long sequences of exposures, we advise users to request test exposures.

Links

- Description of DeltaRho 350 + QHY600 on the LCO website.