

## MIT Open Access Articles

*Quantum efficiency measurement of the Transiting Exoplanet Survey Satellite (TESS) CCD detectors*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** Krishnamurthy, A., J. Villaseñor, C. Thayer, S. Kissel, G. Ricker, S. Seager, R. Lyle, et al. "Quantum Efficiency Measurement of the Transiting Exoplanet Survey Satellite (TESS) CCD Detectors." Edited by Howard A. MacEwen, Giovanni G. Fazio, Makenzie Lystrup, Natalie Batalha, Nicholas Siegler, and Edward C. Tong. *Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave* (August 5, 2016).

**As Published:** <http://dx.doi.org/10.1117/12.2232244>

**Publisher:** SPIE-Intl Soc Optical Eng

**Persistent URL:** <http://hdl.handle.net/1721.1/116362>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of Use:** Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.



# PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

## Quantum efficiency measurement of the Transiting Exoplanet Survey Satellite (TESS) CCD detectors

A. Krishnamurthy, J. Villaseñor, C. Thayer, S. Kissel, G. Ricker, et al.

A. Krishnamurthy, J. Villaseñor, C. Thayer, S. Kissel, G. Ricker, S. Seager, R. Lyle, A. Deline, E. Morgan, T. Sauerwein, R. Vanderspek, "Quantum efficiency measurement of the Transiting Exoplanet Survey Satellite (TESS) CCD detectors," Proc. SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, 99042W (5 August 2016); doi: 10.1117/12.2232244

**SPIE.**

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

# Quantum efficiency measurement of the Transiting Exoplanet Survey Satellite (TESS) CCD detectors

A. Krishnamurthy<sup>1,2</sup>, J. Villaseñor<sup>2</sup>, C. Thayer<sup>2</sup>, S. Kissel<sup>2</sup>, G. Ricker<sup>2</sup>, S. Seager<sup>1,2</sup>,  
R. Lyle<sup>2</sup>, A. Deline<sup>3</sup>, E. Morgan<sup>2</sup>, T. Sauerwein<sup>2</sup>, R. Vanderspek<sup>2</sup>  
Massachusetts Institute of Technology<sup>1</sup>, MIT Kavli Institute<sup>2</sup>, University of Geneva<sup>3</sup>

## ABSTRACT

Very precise on-ground characterization and calibration of TESS CCD detectors will significantly assist in the analysis of the science data from the mission. An accurate optical test bench with very high photometric stability has been developed to perform precise measurements of the absolute quantum efficiency. The setup consists of a vacuum dewar with a single MIT Lincoln Lab CCID-80 device mounted on a cold plate with the calibrated reference photodiode mounted next to the CCD. A very stable laser-driven light source is integrated with a closed-loop intensity stabilization unit to control variations of the light source down to a few parts-per-million when averaged over 60 s. Light from the stabilization unit enters a 20 inch integrating sphere. The output light from the sphere produces near-uniform illumination on the cold CCD and on the calibrated reference photodiode inside the dewar. The ratio of the CCD and photodiode signals provides the absolute quantum efficiency measurement. The design, key features, error analysis, and results from the test campaign are presented.

## Keywords

CCD, detectors, characterization, quantum efficiency, instrumentation, TESS

## 1. INTRODUCTION

The Transiting Exoplanet Survey Satellite (TESS) [Ricker et al., 2014] is an Astrophysics Explorer mission selected by NASA for launch in 2017. The primary objective of TESS is to search for planets transiting bright dwarf stars with  $I_c \lesssim 13$  that facilitate follow-up measurements of planet masses and atmospheres. TESS is expected to discover a thousand or more planets that are smaller in size than Neptune, including dozens of Earth-sized planets by performing differential time-series photometry during a two-year all-sky survey. TESS will observe from a 13.7-day elliptical orbit around the Earth. TESS will employ four wide-field optical charge-coupled device (CCD) cameras with a band-pass of 650 nm – 1050 nm to detect temporary drops in brightness of stars due to planetary transits. All four cameras are mounted onto a single plate. The camera assembly consists of an f/1.4 custom lens assembly with seven optical elements, a CCD detector assembly and associated electronics. The CCD detector assembly consists of four deep-depletion back-illuminated MIT Lincoln Laboratory CCID-80 devices. Each CCID-80 device consists of 2048 x 2048 imaging array and 2048 x 2048 frame store regions, with 15 x 15  $\mu\text{m}$  pixels. The 2x2 array of CCDs is contained within 62 x 62 mm area with a 2 mm gap between the CCDs. The electronics consist of three compact double-sided printed circuit boards, each 12 cm in diameter. Each camera will acquire a new image every 2 seconds. The surface of one of the lens elements has a long-pass filter coating to enforce the band-pass cutoff at 650 nm. The spectral response at the red end is limited by the quantum-efficiency curve of the CCDs with sensitivity to wavelengths up to 1050 nm.

## 2. BACKGROUND

Early CCD cameras used front-illuminated CCD detectors that received light on the gate side of the device causing significant light loss due to partial absorption and partial reflection of the light from the collecting surface. In order to increase the quantum efficiency of the CCDs, back-illuminated CCD devices were developed. TESS will use the deep depletion CCDs developed by MIT Lincoln Laboratory [Suntharalingam et al., 2016]. In order to characterize their performance more accurately over the redder wavelengths at which the TESS cameras operate, precision absolute QE measurements are required.

Quantum efficiency (QE) is the percentage of photons that produces charge carriers. A combination of QE and CCD gain yields the sensitivity of the CCD signal. The precision measurement of absolute quantum efficiency of the CCD detectors, especially over the redder wavelengths is a crucial part of the characterization process because it will hugely aid in detecting transits around M stars. A higher QE over the redder wavelengths will yield a higher photon count and a higher signal, and thus higher planetary detections [Sullivan et al., 2015]. The quantum efficiency along with read noise is one of the most important parameters of the photometric noise budget for TESS. Precision characterization of absolute QE will greatly reduce the uncertainty of the mission output by enabling accurate modeling of star flux, photometric data points and projected count rates.

The design goal of the present work is to develop a precision optical test bench capable of automated absolute quantum efficiency measurements over the spectral range of 650-1050 nm with an absolute error of less than 2%. This will help refine the prediction accuracy of the models especially over redder wavelengths where QE of the CCD drops precipitously and hence, transit detections are highly dependent on the photon count rate. Light source selection and stabilization, filter selection, reference detector calibration and placement are some of the important factors that affect a very sensitive measurement like absolute QE. In order to accurately interpret the signals obtained from the CCD, precision gain measurements are performed. The quantum efficiency of the CCD is given by the ratio of the signal produced by the CCD to the incoming current measured by the calibrated photodiode. Poletto et al., 1997 and Groom et al., 2006 have previously performed absolute QE characterization with an absolute error of 3%-6% and 3.6% respectively. The present work builds on similar principles as in Groom et al., 2006 but with more precise light stabilization, gain measurement, and reference photodiode calibration to achieve the design goal.

### 3. PRECISION OPTICAL TEST BENCH

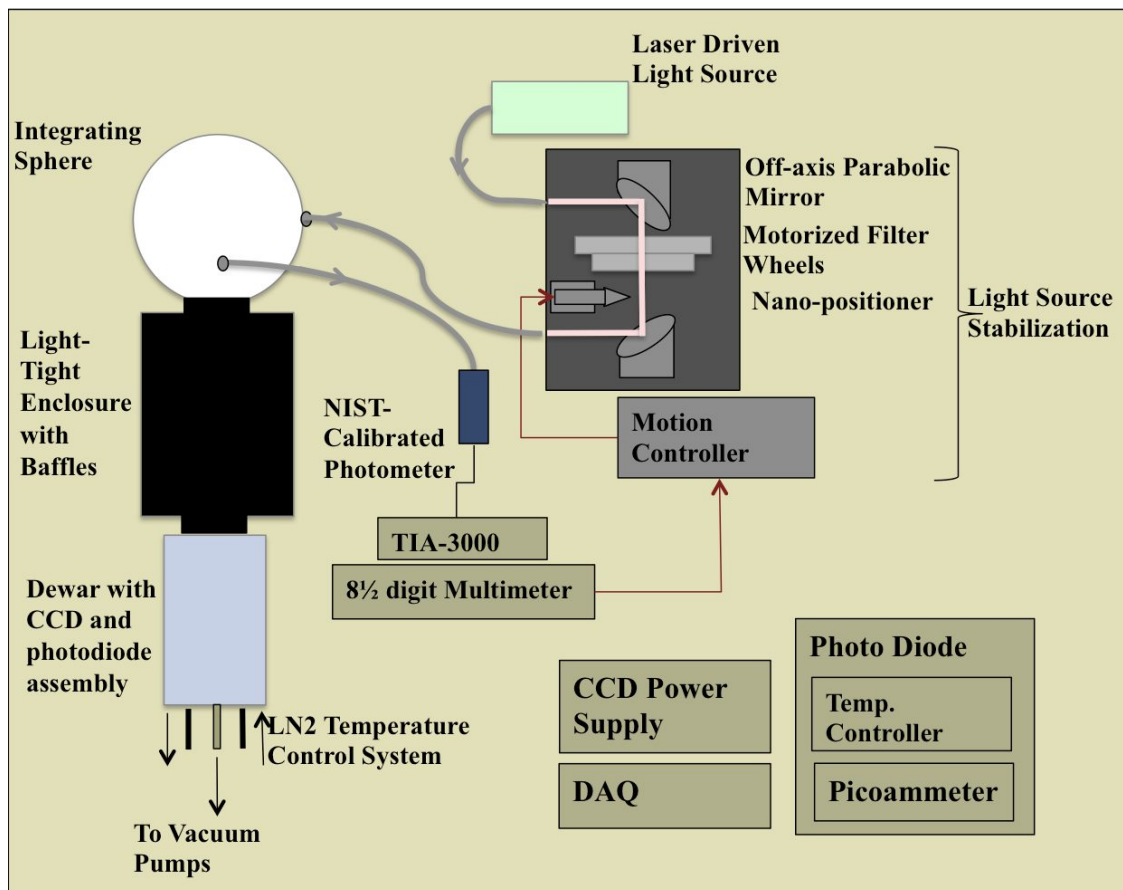


Figure 1: Precision optical test bench for the characterization of absolute quantum efficiency.

The experimental setup, illustrated in Figure 1, consists of a vacuum dewar with a single MIT Lincoln Lab CCID-80 device mounted on a cold plate that is maintained at the operating temperature of  $-70^{\circ}\text{C}$  to reduce the dark current to a negligible level. A calibrated reference photodiode is mounted next to the CCD and maintained at the calibration temperature of  $25^{\circ}\text{C}$ . The CCD electronics package consists of two compact printed circuit boards that are located beneath the cold plate. Eleven hard-coated 12.5-mm diameter band-pass filters over the range of 650 nm – 1064 nm with 10-nm bandwidth, and one 1000 nm filter with 25-nm bandwidth are used for accurate wavelength selection. A very stable laser-driven light source is integrated with a closed-loop intensity stabilization unit to control variations of the light source down to a few parts-per-million when averaged over 60 s. Light from the stabilization unit enters a 20-inch integrating sphere. The output light from the sphere produces near-uniform illumination on the cold CCD and on the calibrated reference photodiode inside the dewar. A picture of the test setup is shown in Figure 2.

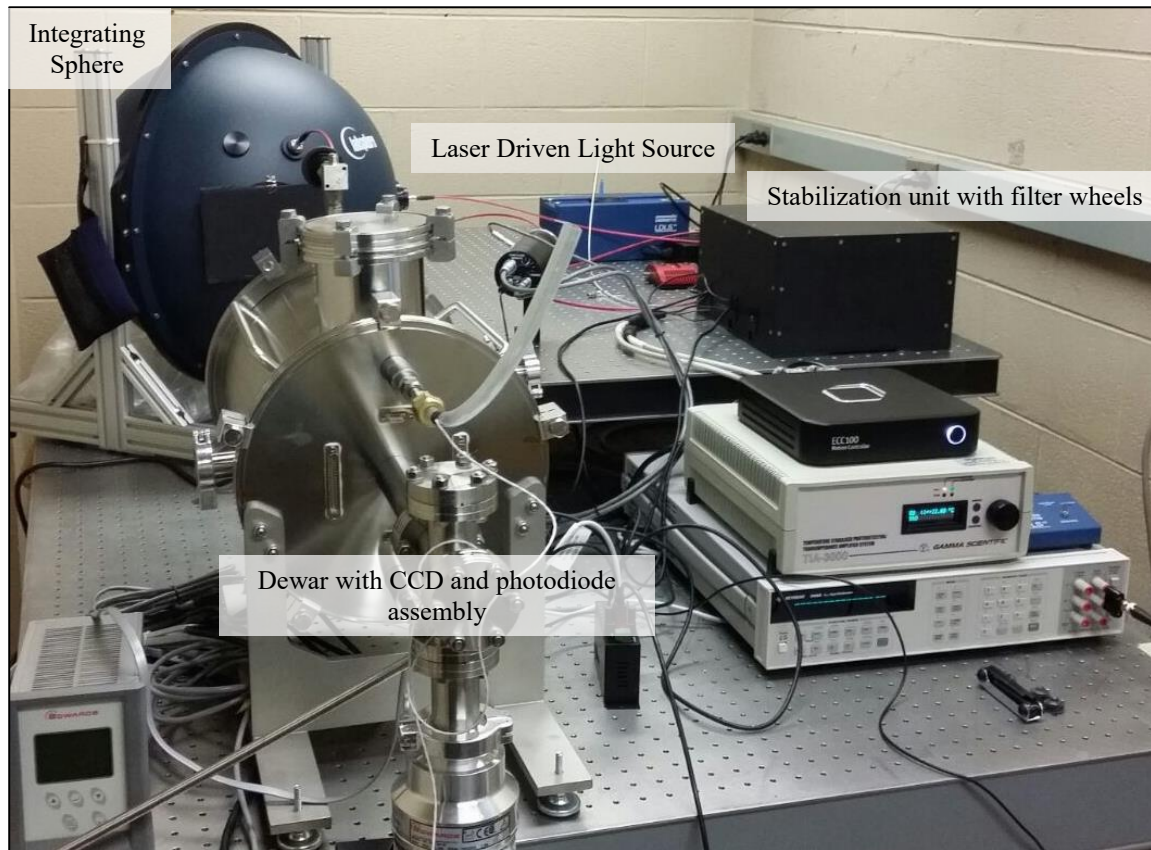


Figure 2: Picture of the precision QE test setup.

### Light Source

The Energetiq Laser-Driven Light Source (LDLS) technology consists of a CW laser that is focused with a high numerical aperture lens into a fused silica bulb filled with high-pressure inert gas. A traditional arc lamp igniter creates the plasma, which absorbs the highly focused laser beam that is heated to very high temperatures of 10,000 K. In traditional arc and deuterium lamps, the brightness and lamp lifetime are limited by the use of electrodes and decrease by almost 50% over 1000-2000 hours. The electrodeless LDLS technology creates small, high brightness plasma that allows efficient light collection, a very broad spectral range of 190 nm - 2400 nm, and long lamp life of over 9000 hours. The variation of spectral power with wavelength for the LDLS is shown in Figure 3.

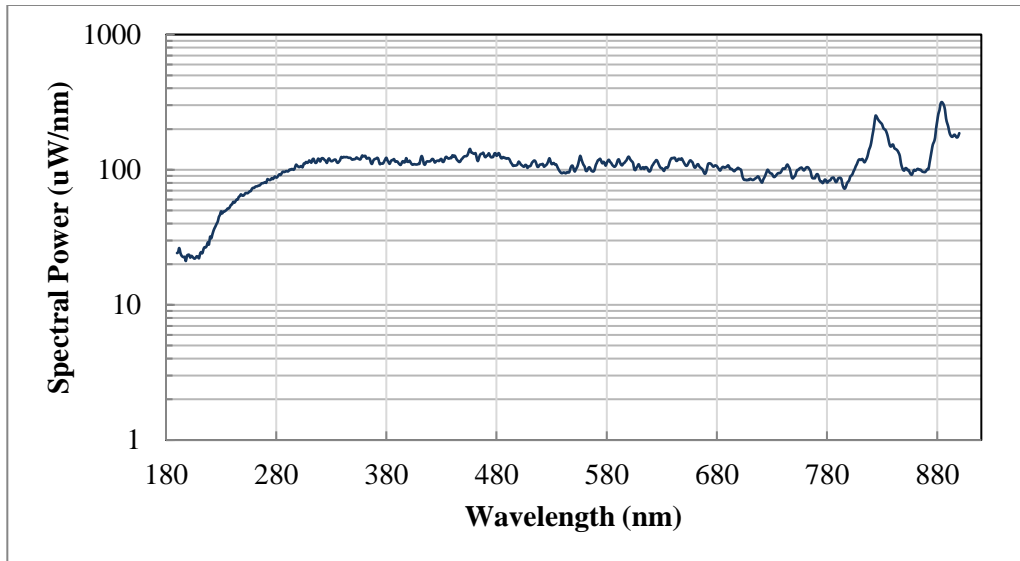


Figure 3: Typical performance of the Energetiq LDLS EQ-99XFC with the 450  $\mu\text{m}$  diameter, 0.22 NA, 1 m long fiber (data provided by Energetiq).

### Filter Wheels

Careful wavelength selection is performed using a 12-position Thorlabs motorized filter wheel with 0.5 inch hard coated bandpass filters from Edmund Optics that provide deeper blocking and higher transmission (>90%) compared to traditional coated filters. Eleven hard-coated 12.5-mm diameter band-pass filters over the range of 650 nm – 1064 nm with 10-nm bandwidth, and one 1000 nm filter with 25-nm bandwidth are used for accurate wavelength selection. A 6-position motorized filter wheel with 1-inch absorptive neutral density filters are used to control the intensity of the light entering the integrating sphere and the dewar with the CCD and reference photodiode assembly.

### Light Stabilization Unit

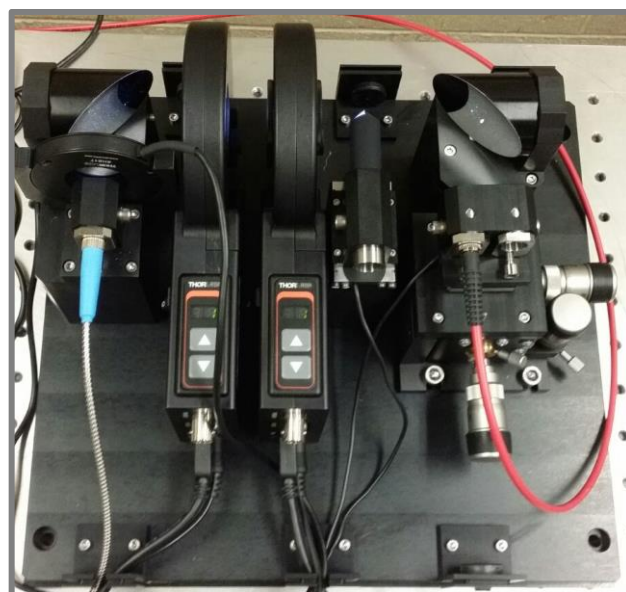


Figure 4: Super Stable Source (SSS) Stabilization Unit.

The light stabilization unit that is integrated with experimental setup to stabilize the LDLS light source is a patented development by the Characterising ExOPlanetS (CHEOPS) Team at the University of Geneva [Wildi et al., 2015]. It consists of two off-axis parabolic mirrors along with a knife-edge attenuator and optical fibers mounted on nano-positioners with a precision of few nm, as shown in Figure 4. A reference measurement by the NIST-calibrated precision photometer mounted on the integrating sphere is used to control the movement of the attenuator into the beam in a feedback loop thus controlling the flux intensity of the light entering the sphere and stabilizing the beam.

### Integrating Sphere

The 20-inch custom-built integrating sphere from LabSphere is an optical component consisting of a hollow spherical cavity with its interior covered with a diffuse white reflective coating called Spectrafect with 98% reflectance over the spectral range of 600 nm – 1100 nm. It has a 1-inch inlet port, 4-inch outlet port and a 1-inch diagnostic port. Light rays incident on any point on the inner surface are, by multiple scattering reflections, distributed equally to all other points thus preserving power and destroying spatial information producing diffuse light at the outlet. The port fraction i.e. the ratio of the area of the outlet to the inlet ports must be less than 0.05 for high uniformity (> 98%) of light exiting the integrating sphere.

### Dewar Design

The dewar assembly consists of a custom-built stainless steel chamber that is 14 inch in length and 10 inch in diameter with a 7.37 inch optical quartz window. The CCD and reference photodiode assembly are mounted on a ¼" thick 6061 Aluminum cold plate attached to the front of an annular liquid Nitrogen reservoir. The CCD electronics are placed behind the CCD and photodiode assembly.

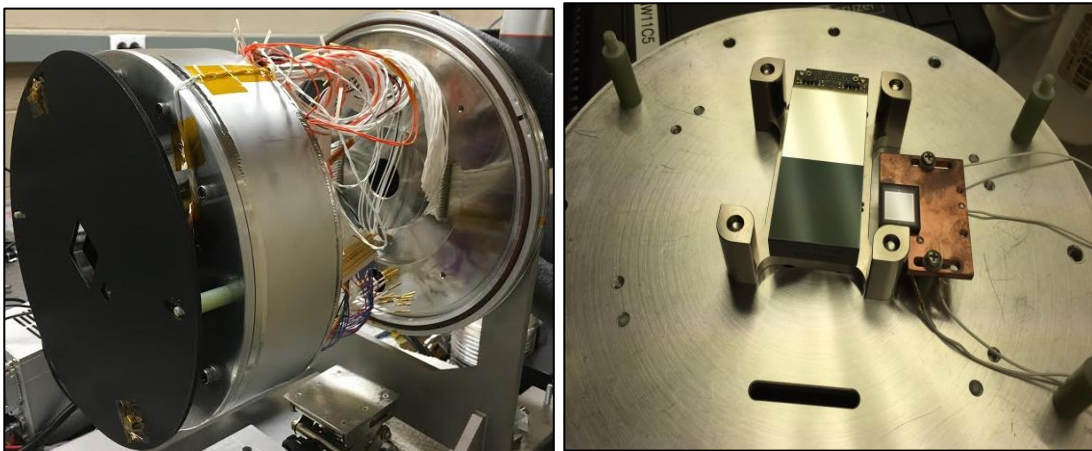


Figure 5: [Left] Dewar with the LN2 reservoir and [Right] CCD and reference photodiode assembly.

The CCD and the calibrated reference photodiode are mounted next to each other on the cold plate in the same focal plane (as shown in Figure 5) to measure the incoming and outgoing signal simultaneously. The precision photodetector in the light stabilization setup is used to cross-calibrate the reference photodiode to improve the accuracy of the measurements. The CCD is maintained at the operating temperature of  $-70^{\circ}\text{C}$  while the reference photodiode is maintained at the calibration temperature of  $25^{\circ}\text{C}$  using a 5W heater mounted on the bottom of the copper plate. The calibrated reference photodiode used is the Hamamatsu S1337-1010BQ with sensitivity over the required spectral range as shown in Figure 6.

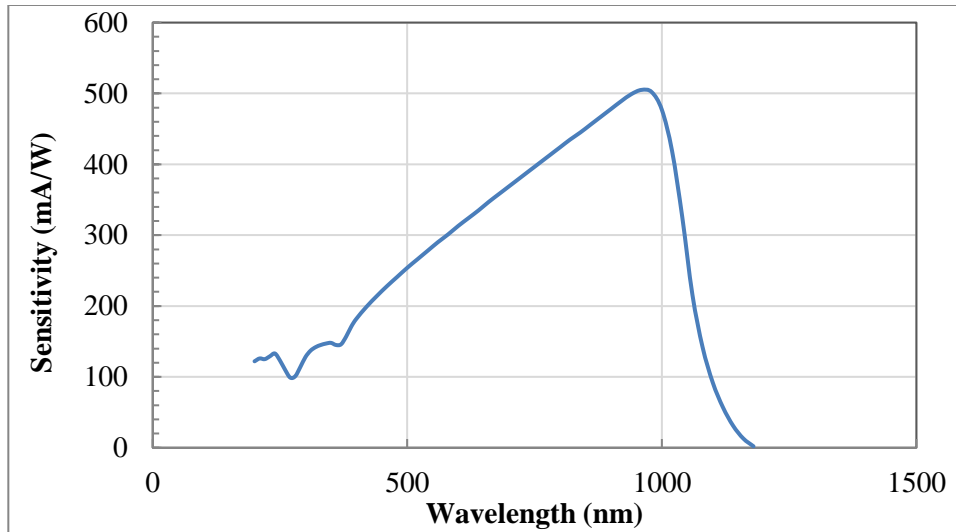


Figure 6: Reference calibrated photodiode sensitivity plotted against wavelength.

## 4. RESULTS AND DISCUSSION

### LDLS Flux Stabilization

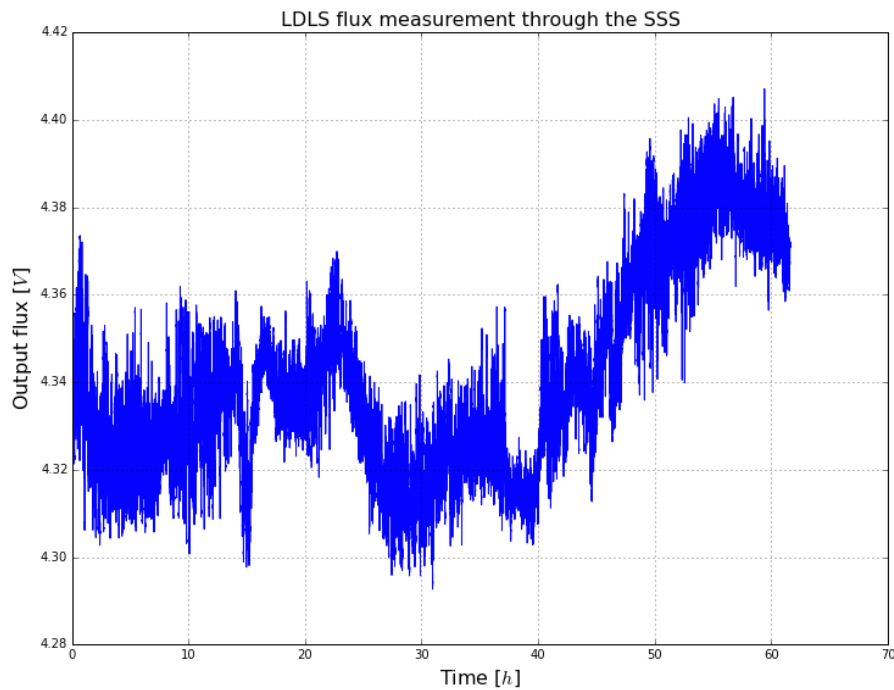


Figure 7: Instantaneous variation of output flux from the LDLS measured over time before stabilization.

The variation of the flux from the LDLS is measured using a photometer system consisting of a photodetector and multimeter as shown in Figure 7. The instantaneous variation of the LDLS is only about 1-3%, which is further stabilized by the Super Stable Source (SSS) stabilization unit that controls the fluctuations down to a few parts per million. The photometer system has a temperature stability of 0.003 K over 24 hours with a measurement uncertainty of about 5 ppm at 15 Hz.



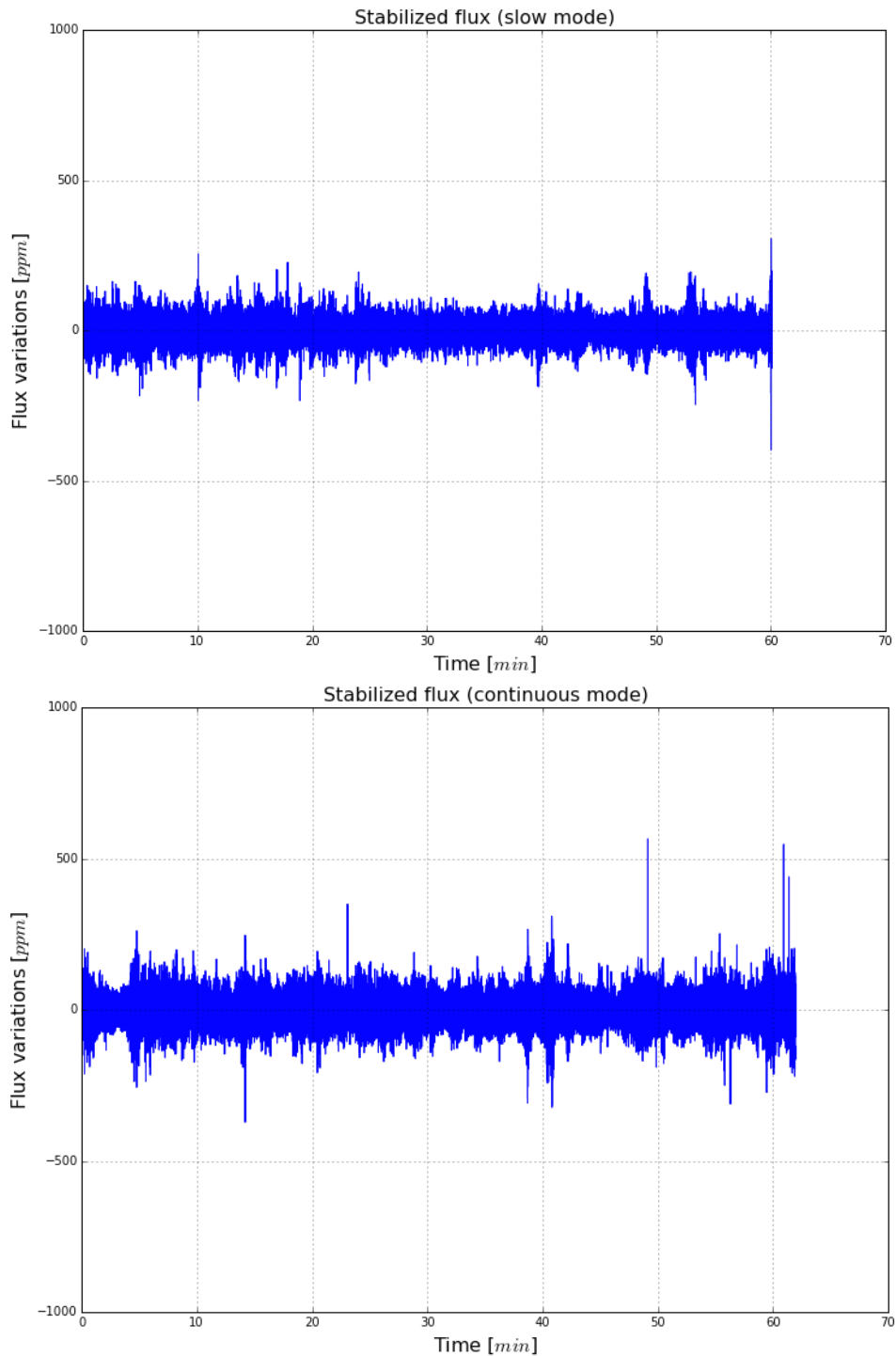


Figure 8: The stabilized LDLS flux measured by the photometer system in closed loop using the slow mode (above) and continuous mode (below).

The closed loop stabilization stage operates in two modes; a slow mode that commands the attenuator and waits for it to reach the required position before measuring the next point, and a continuous mode where the photometer system measures the flux without waiting for the attenuator to reach the point previously commanded. The slow mode yields a stability of 4.95 ppm and the continuous mode yields a stability of 3.57 ppm when averaged over 60 s. The slow mode was used to stabilize the LDLS at each wavelength before recording the QE measurements.

## Gain Measurements

The gain is the conversion factor between the electrons collected in the CCD and the Analog-to-Digital readout Units (ADU). Gain is dependent on the temperature of the CCD, and is measured using the  $\text{Cd}^{109}$   $K_\alpha$  and  $K_\beta$  peaks. Using the known energies of the X-ray peaks ( $K_\alpha = 22.1$  keV,  $K_\beta = 25.0$  keV), and the conversion of eV/e<sup>-</sup> for Silicon [Groom et al., 2006], we fit a line to the peaks whose slope gives the gain conversion factor [Schloze et al., 1996]. The gain measured is  $6.99 \pm 0.01$  e<sup>-</sup>/ADU.

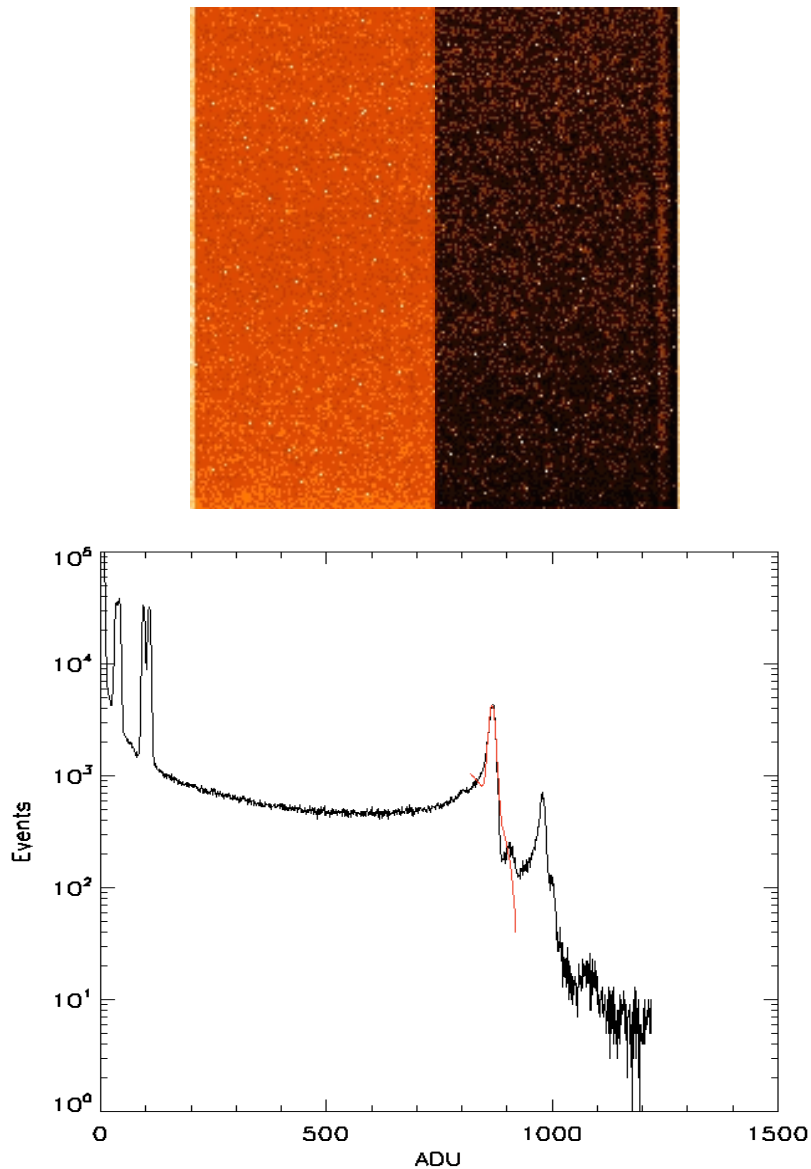


Figure 9: A  $\text{Cd}^{109}$  source is used to create X-ray events (above) and X-ray peaks for  $\text{Cd}^{109}$  (below).

## QE Measurements

Figure 10 shows the preliminary QE measurements obtained from the precision optical test setup. A flight-grade engineering CCD along with pre-flight electronics was used for the experiments.

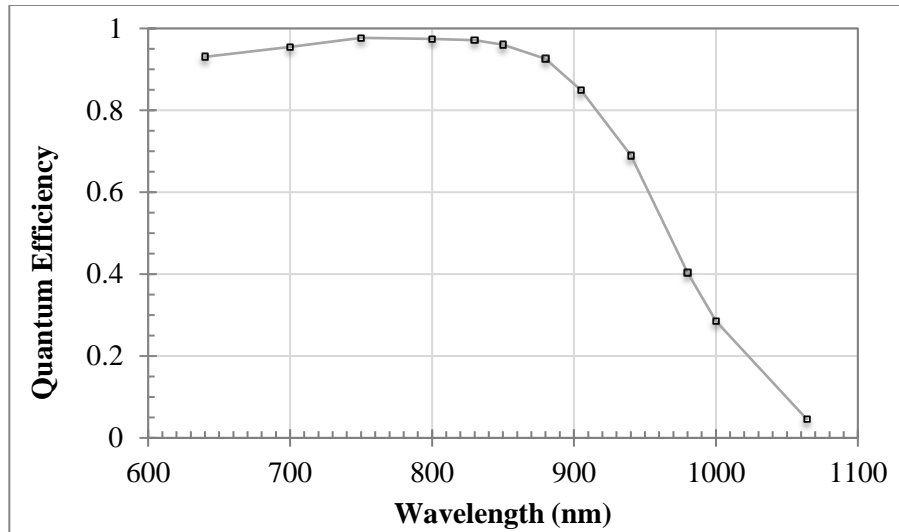


Figure 10: Quantum efficiency measurement for the TESS flight-grade engineering CCD with electronics.

The operating temperature of the CCD was  $-70\text{ }^{\circ}\text{C}$  and the exposure time was 2 s. A dark box was installed between the integrating sphere exit port and the CCD to obtain near-uniform illumination of the CCD and to eliminate light leaks. A set of baffles inside the black interior was used to prevent secondary reflections from entering the dewar. Sources of error like out-of-bandpass leakage from filters, light leaks, second-order reflections, and noise in the reference photodiode measurements were investigated and found to be negligible.

### ACKNOWLEDGEMENTS

This work is supported by NASA under the contract number NNG14FC03C.

### REFERENCES

- [1] Ricker, G. R., Winn, J. N., Vanderspek, R., et al., "The Transiting Exoplanet Survey Satellite," *J. Ast. Inst. Sys.* 1, 014003 (2015).
- [2] Suntharalingam, V., Prigozhin, I., Young, D. J., et al., "Deep depletion CCD detectors for the transiting exoplanet survey satellite," *Proc SPIE* 9915, 9915-28 (2016).
- [3] Poletto, L., Boscolo, A., Pelizzo, M.G., Placentino, L. and Tondello, G., "Quantum efficiency measurement on a CCD detector in the 0.3-to 1100-nm spectral region," In *Optical Science, Engineering and Instrumentation'97*, pp. 617-624 (1997).
- [4] Groom, D.E., Bebek, C.J., Fabricius, M., Karcher, A., Kolbe, W.F., Roe, N.A. and Steckert, J., "Quantum efficiency characterization of LBNL CCD's: Part I. The quantum efficiency machine. In *Electronic Imaging 2006*, pp. 60680F-60680F (2006).
- [5] Scholze, F., Rabus, H., and Ulm, G., "Spectral responsivity of silicon photodiodes: high-accuracy measurement and improved self-calibration in the soft x-ray spectral range," *Proc. SPIE* 2808 (1996).
- [6] Sullivan, P.W., Winn, J.N., Berta-Thompson, Z.K., Charbonneau, D., Deming, D., Dressing, C.D., Latham, D.W., Levine, A.M., McCullough, P.R., Morton, T. and Ricker, G.R., "The Transiting Exoplanet Survey Satellite: Simulations of planet detections and astrophysical false positives," *The Astrophysical Journal*, 809(1), p.77 (2015).
- [7] F. Wildi, A Deline, B. Chazelas, "A white super stable source for the metrology of astronomical photometers," *SPIE* 9605-63 (2015).