Throughput of Commercial Photographic Camera Lenses for Use in Astronomical Systems

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ABSTRACT

We present measurements of the spectral response function of commercially-available Nikon 35mm photographic camera lenses for use in astronomical instrumentation. Our motivation for this work stems from the fact that several astronomical imaging systems have been deployed or proposed using this type of commercial lens. We have performed measurements of the relative and absolute spectral response function of five commercially-available photographic lenses. These measurements show that these lenses generally have > 50% throughput across the entire optical window of $400\text{nm} < \lambda < 800\text{nm}$.

Keywords: optical instrumentation, commercial-off-the-shelf system, photographic lens, lens throughput

1. INTRODUCTION

An important design requirement of astronomical instrumentation can be the relative percentage of the total light that reaches the detector after interacting with all the optical elements of the instrument, otherwise known as the optical throughput. This optical throughput can be measured as a function of wavelength, giving the spectral response function of the optical system. By knowing the spectral response function of all the optical components in an astronomical instrument, it is possible to characterize the total throughput of the ensemble, ensuring that the planned instrument meets its intended science goals. After the instrument design, the spectral response function of the lens can be used in conjunction with the response of the other optical elements in the system to create exposure time calculators that account for throughput loss, ensuring adequate signal-to-noise for science observations.

Commercially-available photographic camera lenses have been used by several experiments as readily available optical systems that could be used for a variety of science cases from the search of exoplanets[1,2] to the study of distant galaxies.[3] Some applications of commercially-available photographic camera lenses includes their use as "telescopes" that perform wide-field imaging surveys (examples include KELT[4] and AggieCam[5]), instruments that require multiple optical systems (examples include Dragonfly,[3] aTmCam,[6] and RAPTOR[7]), and even as optical subsystems inside instruments where cost is a significant factor in lens selection (AggieSpec[8]).

In this paper we present the relative and absolute spectral response function of five commercially-available Nikon 35mm photographic camera lenses which may be used for astronomical instrumentation at optical wavelengths ($350\text{nm} < \lambda < 1000\text{nm}$).

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Ground-based and Airborne Instrumentation for Astronomy VI, edited by Christopher J. Evans, Luc Simard, Hideki Takami
Proc. of SPIE Vol. 9908, 99085C · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2233723

2. LENSES TESTED

We tested a range of photographic camera lenses with a variety of focal lengths and $f/\#$'s to facilitate a variety of possible uses for optical astronomical instrumentation.

- Nikon NIKKOR 50mm focal length, $f/1.2$ Ai-S Manual focus lens (Manufacturer Part# 1435, KEH Model# 220889, Manufacturer Serial Number 341916)
- Nikon NIKKOR 85mm focal length, $f/1.4$ Ai-S Manual focus lens (KEH Model# 220996, Manufacturer Serial Number 201422)
- Nikon NIKKOR 135mm focal length, $f/2.0$ Ai-S Manual focus lens (KEH Model# 220689, Manufacturer Serial Number 213775)
- Nikon NIKKOR 180mm focal length, $f/2.0$ Ai Manual focus lens (KEH Model# 220736, Manufacturer Serial Number 369304)
- Nikon NIKKOR 200mm focal length, $f/2.8$ Ai Manual focus lens (KEH Model# 220751, Manufacturer Serial Number 740127)

All of these lenses were acquired from secondhand camera lens supplier KEH[9] as "previously used". All but the Nikon NIKKOR 50mm focal length, $f/1.2$ Ai-S Manual focus lens are currently out of production. We have provided the KEH Model number of all lenses in our sample in order to facilitate purchase of these lenses for astronomical instrumentation. Serial numbers can be used to identify lenses of a similar model.

3. SPECTRAL RESPONSE FUNCTION INSTRUMENT SETUP

3.1 Measurements with PreCal

The spectral response functions of the lenses were measured using the PreCal system, the prototype of the DECal[10,11,12] calibration instrument used to calibrate the Dark Energy Camera.[13] Figure 1 shows a photograph of the total PreCal system as used in the lab. The PreCal system uses a monochromator to produce light of a narrow bandwidth. Light is sourced from a quartz lamp which is then reflected off a diffraction grating on a computer-controlled turntable into a tunable slit. By controlling the incidence angle and diffraction angle on the grating and the width of the slit, we can select a small window of wavelength space to project for calibration

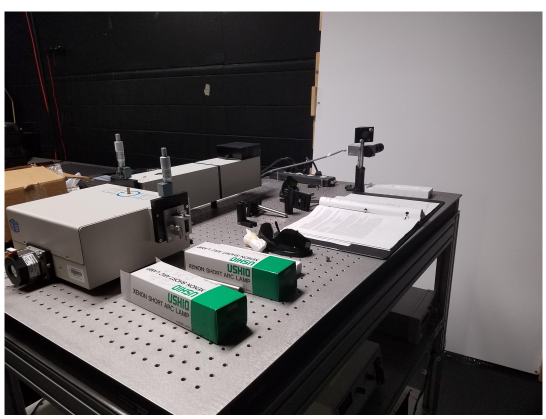

Figure 1. Image of the PreCal calibration system. The system is composed of a Czerny-Turner type monochromator manufactured by OBB. Light from the monochromator is projected onto a Lambertian surface (seen in the back right) which is then focused by the test lens and imaged by an SBIG ST-8300M CCD. A separate NIST-calibrated photodiode also pointed at the screen is used to monitor the amount of light reflected by the screen, providing an accurate measurement of the spectral response of the imaging system being studied.

purposes. For the purposes of this characterization, we selected a wavelength window of 10nm to enable relatively quick scans with sufficient light output from the monochromator.

This "monochromatic" light is projected upon a Lambertian surface. Images of the reflected light are focused by the lens being tested and recorded with a Santa Barbara Instrument Group (SBIG) ST-8300M CCD. The lens being tested was set to ∞ focal length and at its lowest available $f/\#$. Data from the PreCal system is reduced using IRAF. Each image taken using the PreCal system is dark frame subtracted, and the mean number of counts of each image is measured.

A National Institute of Standards and Technology (NIST)-calibrated photodiode pointing at the same surface is used to monitor the amount of light entering the optical system. A photon flux is derived from photodiode voltage using the NIST-provided calibration data. The mean number of counts of an image taken at a particular wavelength is divided by the photon flux at that wavelength as measured by the photodiode, decoupling the output of our monochromator source lamp from the spectral response function.

In order to decouple the spectral response of the SBIG ST-8300M CCD from that of the lenses tested in our study, we performed a PreCal scan of the CCD alone. The relative scan of the CCD was scaled by the SBIG-provided specification for the peak quantum efficiency of the detector, 56%, and is presented in Figure 2.

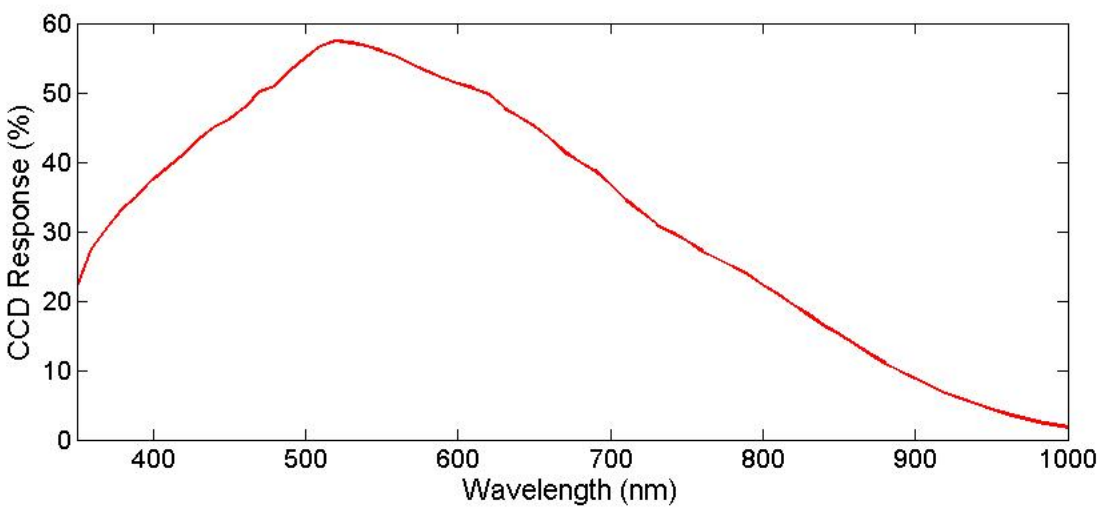

Figure 2. PreCal-measured response of the SBIG ST-8300M CCD. This CCD was used without a lens to image the PreCal Lambertian surface. The relative responsivity measured by PreCal was scaled by the peak quantum efficiency of this detector as found in SBIG's technical specifications. This was used to decouple the lens throughput from the responsiveness of the CCD.

3.2 Absolute Throughput Measurement

In order to place the relative PreCal spectral response measurements on an absolute scale, a Gentec-E Solo-2 laser power meter with a NIST-calibrated Si photodiode was used in conjunction with a set of ThorLabs laser diode modules with wavelength outputs of 405nm, 635nm, 650nm, 670nm, and 780nm. An on-axis optical system was devised where laser light was incident on the center of the lens after $\sim$ 60cm of travel through air. The beam was passed through a 1mm wide iris located 55mm from the first element of the lens. The Si photodiode was placed at approximately the back focal point of each lens, tilted slightly so that any lens dependent back reflections would not artificially increase the measurement of power. Measurements of laser power were taken with and without the tested lens in the path of the beam. The power measured by the Si photodiode with the laser turned off was subtracted from each measurement as background. The measured power of the laser with the lens in the beam path was divided by the measured power of the unimpeded beam, providing a percent measurement of the power loss due to the transmission of the Nikon lens.

As with the PreCal scan of relative throughput, for the measurements of absolute throughput, the Nikon lenses were set to ∞ focal length and at their lowest available $f/\#$.

There are multiple sources of systematic error that could have affected the laser throughput measurements. The background level of the dark room where these tests were performed contributed 2% of the total power detected by the Si photodiode. The measured power of the laser was not entirely stable at short time scales (< 30 seconds), varying on order of 1–2%. In order to determine how much scattered light was entering our system, we performed measurements of the lens at its lowest $f/\#$ and at its highest $f/\#$ (when the internal iris of the lens had limited the aperture as much as possible). The difference between these two measurements was $\sim 1\%$. We also attempted to reduce back-scattering off the reflective surface of the photodiode, which may have also contributed an error of $\sim 1\%$. Finally, we attempted to quantify any difference in throughput depending on the direction of light traveling by measuring the transmission of the lens when the front element was the first interface of the light and when the back element was the first interface; this yielded an average difference in throughput of $\sim 3\%$. With these sources of error, we therefore estimate the error of the laser absolute throughput measurements to be $\sim 4\%$.

4. SPECTRAL RESPONSE FUNCTION OF COMMERCIAL PHOTOGRAPHIC LENSES

We present the spectral response functions of the commercially-available photographic lenses tested in this study. In order to decouple the spectral response of the CCD from the lens, we divide the PreCal-measured spectral response function of the combined lens and CCD system with the PreCal-measured response of the CCD from Figure 2. We present the relative spectral response function of each lens in Figure 3. Each spectral response function in Figure 3 is normalized by the peak throughput of the lens. We show the results of the laser throughput measurements in Table 1.

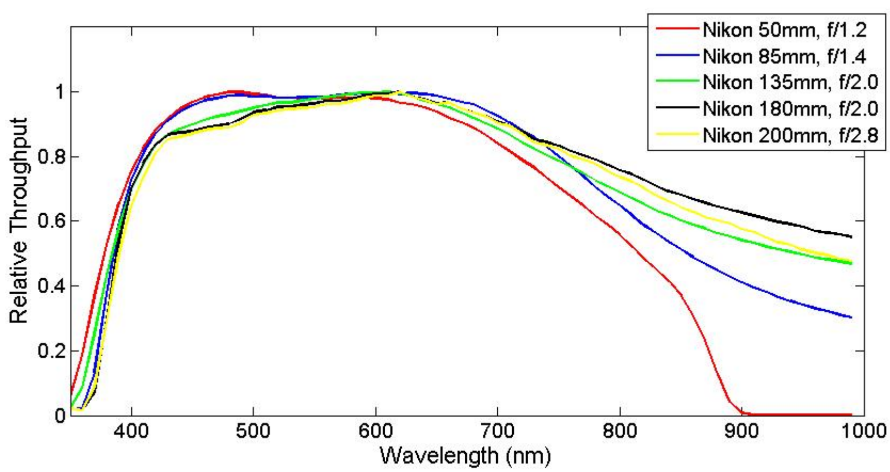

Figure 3. Relative throughput of all lenses tested in this study scaled such that the maximum throughput of each lens is 1.

In order to determine the absolute throughput of each lens, a scaling factor was determined using the laser throughput measurements at 405nm, 635nm, 650nm, and 670nm, and 780nm by dividing the measured absolute throughput from the lasers by the measured relative throughput from PreCal. The mean of these scaling factors for all wavelengths was used to scale the relative throughput measurements to the absolute throughput. We

Laser Diode Model	Wavelength (nm)	With Lens (mW)	Unimpeded Beam (mW)	Percent Throughput
		Nikon 50mm focal length, $f/1.2$		
CPS405	405nm	0.56	0.84	66.7%
CPS182	635nm	2.07	2.18	95.0%
CPS184	650nm	1.80	1.99	90.5%
CPS186	670nm	1.65	1.79	92.2%
CPS192	780nm	1.36	1.66	81.9%
		Nikon 85mm focal length, $f/1.4$		
CPS405	405nm	0.56	0.84	66.7%
CPS182	635nm	2.02	2.18	92.7%
CPS184	650nm	1.75	2.18	88.4%
CPS186	670nm	1.61	1.78	90.4%
CPS192	780nm	1.23	1.64	75.0%
		Nikon 135mm focal length, $f/2.0$		
CPS405	405nm	0.64	0.95	66.0%
CPS182	635nm	1.17	1.21	96.7%
CPS184	650nm	1.40	1.49	94.0%
CPS186	670nm	0.99	1.04	95.2%
CPS192	780nm	1.18	1.53	77.1%
		Nikon 180mm focal length, $f/2.0$		
CPS405	405nm	0.63	0.95	66.3%
CPS182	635nm	1.10	1.14	96.5%
CPS184	650nm	1.12	1.21	92.6%
CPS186	670nm	1.06	1.12	94.6%
CPS192	780nm	0.76	0.95	80.0%
		Nikon 200mm focal length, $f/2.8$		
CPS405	405nm	0.60	0.95	63.2%
CPS182	635nm	1.08	1.14	94.7%
CPS184	650nm	1.12	1.22	91.8%
CPS186	670nm	1.05	1.12	93.8%
CPS192	780nm	0.73	0.91	80.2%

Table 1. Results of the laser throughput measurements performed on the 5 lenses in this study. We utilized the laser throughput measurements to scale the PreCal relative spectral response function to an absolute scale. Based on other tests of systematic effects on this measurement, we estimate the error in our throughput to be $\pm 4\%$.

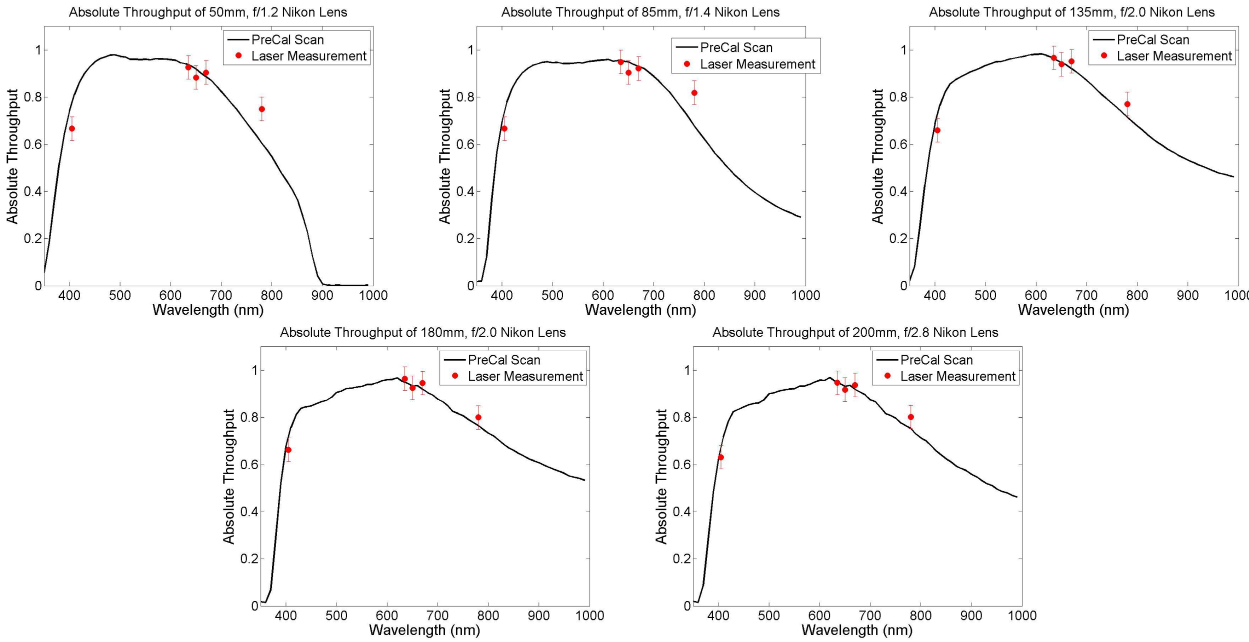

Figure 4. Measured absolute throughput by laser throughput tests using 405nm, 635nm, 650nm, 670nm, and 780nm laser diodes and a NIST-calibrated laser power meter. Lines show the PreCal-measured relative throughput of each of the lenses tested in this study scaled to the absolute laser measurements.

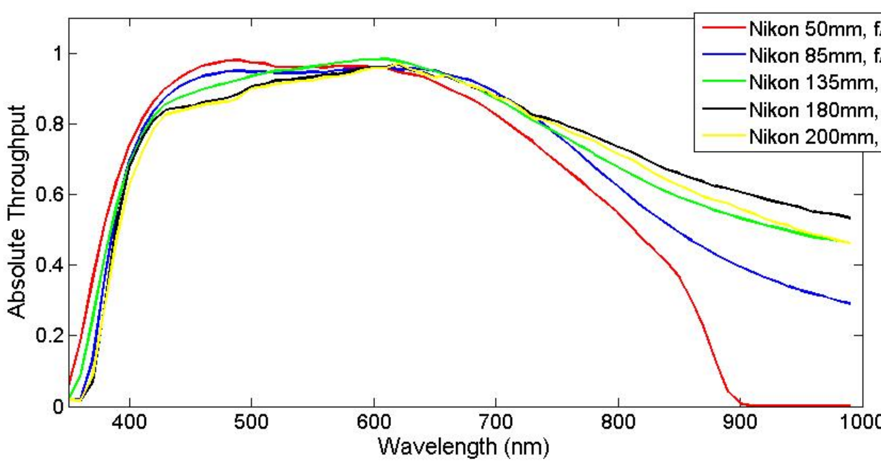

Figure 5. Absolute throughput of all the lenses measured in this study. Each absolute throughput was determined by scaling each PreCal-measured relative throughput to the mean of absolute throughput at 405nm, 635nm, 650nm, 670nm, and 780nm as determined by laser throughput analysis.

plot the absolute throughput of all the lenses tested in this study in Figure 4 and Figure 5. We additionally plot the absolute throughput measurements from the laser power tests for comparison in Figure 4. We note that for 400nm $< \lambda <$ 800nm, the absolute throughput is $> 50\%$ for all of the lenses. The Nikon 135mm focal length, $f/2.0$ lens, the Nikon 180mm focal length, $f/2.0$ lens, and the Nikon 200mm focal length, $f/2.8$ lens have absolute throughput $> 50\%$ for 400nm $< \lambda <$ 1000nm.

5. DISCUSSION

These lenses show similar relative throughput profiles from 400nm $< \lambda <$ 800nm. All lenses but the Nikon 50mm focal length, $f/1.2$ lens transmit light at wavelengths above 900nm. From Figure 5, we note that the absolute throughput remains $> 50\%$ for all of the lenses within wavelength ranges 400nm $< \lambda <$ 800nm.

Though this study does not consider image quality, our previous work[8] has shown that the Nikon 180mm focal length, $f/2.0$ lens and the Nikon 200mm focal length, $f/2.8$ lens have a FWHM of $< 15\mu$m when imaging stars. We have also found previously that the image quality did not degrade as a function of distance from the center of the CCD. We expect all five of these lenses to have similarly good imaging quality. This previous result, combined with the current analysis described here, suggests that photographic camera lenses are a viable solution to astronomical instrumentation needs.

Perhaps most importantly, we have developed a system and a methodology by which we can measure the spectral response of any optical system for use in astronomical instrumentation. More generally, we can perform these tests for any lens and any detector using both the PreCal system and the laser throughput analysis. With this capability, we can make more-informed decisions as to the suitability of lenses to meet instrument design requirements.

6. CONCLUSIONS

In order to facilitate the use of commercially-available photographic camera lenses in astronomical instrumentation, we have developed an experimental process by which we can measure the relative and absolute spectral response function of several different Nikon lenses. In measuring the relative throughput of these lenses, we have observed no sharp losses in transmission across 350nm $< \lambda <$ 1000nm. We have determined the absolute throughput of these lenses and have found that these particular lenses possess $> 50\%$ throughput from 400nm $< \lambda <$ 800nm.

ACKNOWLEDGMENTS

Texas A&M University thanks Charles R. '62 and Judith G. Munnerlyn, George P. '40 and Cynthia Woods Mitchell, and their families for support of astronomical instrumentation activities in the Department of Physics and Astronomy. The authors would also like to thank T. Li and D. Grant for useful assistance and conversations.

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