PHOTOMETRIC RESPONSE FUNCTIONS OF THE SLOAN DIGITAL SKY SURVEY IMAGER

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ABSTRACT

The monochromatic illumination system is constructed to carry out in situ measurements of the response function of the mosaicked CCD imager used in the Sloan Digital Sky Survey (SDSS). The system is outlined and the results of the measurements, mostly during the first six years of the SDSS, are described. We present the reference response functions for the five color passbands derived from these measurements, and discuss column-to-column variations and variations in time, and also their effects on photometry. We also discuss the effect arising from various, slightly different response functions of the associated detector systems that were used to give SDSS photometry. We show that the calibration procedures of SDSS remove these variations reasonably well with the resulting final errors from variant response functions being unlikely to be larger than 0.01 mag for g, r, i, and z bands over the entire duration of the survey. The considerable aging effect is uncovered in the u band, the response function showing a 30% decrease in the throughput in the short wavelength side during the survey years, which potentially causes a systematic error in photometry. The aging effect is consistent with variation of the instrumental sensitivity in the u band, which is calibrated out. The expected color variation is consistent with measured color variation in the catalog of repeated photometry. The color variation is \( \Delta(u - g) \sim 0.01 \) for most stars, and at most \( \Delta(u - g) \sim 0.02 \) mag for those with extreme colors. We verified in the final catalog that no systematic variations in excess of 0.01 mag are detected in the photometry which can be ascribed to aging and/or seasonal effects except for the secular u - g color variation for stars with extreme colors.

Key words: galaxies: photometry – surveys – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

A unique and unprecedented feature of the Sloan Digital Sky Survey (SDSS: York et al. 2000) is the wide field CCD imager (Gunn et al. 1998) which enables us to image 1.52 deg\(^2\) (the physical area size is 725 cm\(^2\)) of the sky at a time. The prime concern is the accurate characterization of the imaging efficiency across the five color passbands of the SDSS. For this purpose, we have constructed a monochromatic illumination system and installed it permanently in the imager enclosure. We have carried out detection efficiency measurements several times during the SDSS operation. This enables us to study the variation of the response function over the survey period. We have then compared photometry with the designed and/or measured characteristics of the imager in the laboratory, and with photometry of the associated telescopes with SDSS filters to qualify SDSS photometry.

This paper describes the monochromatic illumination system and the detector efficiency measurement, and presents the response function for the SDSS main imager which is used as the reference. We discuss the effect that is expected on SDSS photometry from seasonal, secular, and chip-to-chip variations of the response efficiency, and compare it with the actual data acquired by the survey after the routine photometric calibration. We also study response functions of the associated telescopes used in photometric calibrations for SDSS and study the effect on SDSS photometry from their slightly variant system responses. We believe that this helps us understand SDSS photometry better as well as serves as a useful guide for designing comparable systems in the instrumentation planned in the future.

The photometric system comprises five color bands, u, g, r, i, and z, that divide the entire range from the atmospheric ultraviolet cutoff at 3000 Å to the sensitivity limit of silicon CCDs at 11000 Å into five non-overlapping passbands, maximizing the bandwidth of each band to enhance the detection efficiency (Fukugita et al. 1996, hereinafter F96). The blue side of the g, r, and i passbands is cut off by colloidal color glass elements (GG400, OG550, and RG695, respectively) and their red side by short-pass interference multilayer (30–45 layers) coatings made of TiO\(_2\) and SiO\(_2\). The characteristics of the u filter is determined by ionically colored glass, BG38 and UG11, for the blue and red sides, respectively, while an interference coating made of Ta2O5 and SiO2 is applied to suppress the red leak that would otherwise appear at 6600–8000 Å. For the z passband, the blue side is cut off by colloidal color glass RG830, and the red side is open, naturally cut off by the silicon CCDs. CCD detectors for the main imager are thinned back-illuminated devices except for those for the z band which use thick front-illuminated devices, all procured from Scientific
Imaging Technologies, Inc. (SITe). An ultraviolet-enhancing antireflection coating was applied to the CCDs used for the $u$ band. The filters, directly cemented on the second quartz corrector of the Richey–Chrétien telescope, are placed just before the CCDs. The containers that house the filters and CCDs are vacuumized all the time for the duration of the survey except for necessary maintenance periods. The CCD that is used at the 50 cm Photometric Telescope (hereafter PT), which has been used to set the zero point of photometry and to monitor atmospheric extinction, and the CCD at the USNO 1 m telescope system, which was used to preset brightness of standard stars, are also UV-enhancing coated, thinned back-illuminated devices similar to the $u$ CCDs in the main camera.

We have measured the transmission of filters in the laboratory before their installation to the imager. The transmission was verified to be sufficiently close to the design, allowing for some variation in the cutoff wavelength up to 10–20 Å that arise from fluctuations in the commercially available glass elements (Schott, Mainz) and different batches of coatings (Asahi Spectra Co., Tokyo). The response of the CCD was measured at SITe but only at a room temperature. This curve was then modified at long wavelengths to fit the data obtained at operating temperature (about $-80^\circ$C) in our laboratory, using, however, coarsely sampled measurements. Synthesized response curves for the specific device used for PT were published in F96, which defines the original photometric system of SDSS. The response curves used for the survey with the 2.5 m telescope camera, therefore, are expected to differ by some extent from the one that defines the SDSS photometric system. The camera itself has six assemblies (called Camcols) of five detectors, one for each color (hence 30 CCDs and filters), and the six individual systems are, of course, not exactly the same as each other.

We also anticipated that the system response may be subject to seasonal variation (the CCDs are cooled, but the filters run approximately at the ambient temperature of the telescope enclosure) and possibly to aging effects. We have designed and constructed a monochromatic illumination system to characterize the wavelength response of all of the camera CCDs/filters, and have occasionally measured the system response during the duration of the survey to monitor the seasonal and secular effects.

After we began the operation of the 2.5 m telescope (Gunn et al. 2006) we found that the response functions deviated significantly due to an effect that was completely unexpected in the beginning. The filters are in vacuum, with the coated surface exposed. In vacuum, water molecules, which have been adsorbed into the voids in the relatively low-density evaporated films used in the filters, migrate away, lowering the refractive index of the films and moving the cutoff wavelength of the $g$, $r$, and $i$ filters blueward by about 2.3% (120 Å, 160 Å, and 175 Å, respectively). The same effect would also modify the red leak suppression of the $u$ filters. Laboratory measurements of this effect, motivated by the early measurements of the imager using the illumination system, are reported in M. Fukugita & K. Shimasaku (2010, in preparation, hereafter FS10). The result of our early measurement was given in Fan et al. (2001).

The preparation for the calibration work has been somewhat patchy, due to a pressing time schedule when the survey began and to a number of problems that surfaced in the early stage of observations. The basic system was defined in F96 for the combination of the filters and the CCD that were supposed to be used for the PT, originally intended to be used both to define magnitudes of the standard stars and to carry out the photometric calibration for the 2.5 m telescope, together with a daily monitor of atmospheric extinction. However, due to technical problems and a subsequent delay in installing the PT (called the Monitor Telescope at that time) photometry of the standard stars was actually carried out using the system at the USNO 1 m telescope in Flagstaff with a set of filters that were slightly different, due to manufacturing variations, from those for PT. The zero points for the USNO system were adjusted to the F subdwarf spectrophotometric standard BD+17°4708 in the PT system, as given by F96.

The 50 cm PT eventually installed at Apache Point Observatory (APO) has observed both standard stars, whose magnitudes were adopted from observations at USNO, and stars in secondary patches which were simultaneously measured by the 2.5 m main telescope and thus used as transfer fields. The brightness of stars in the secondary patches was measured with respect to the USNO brightness for the set of standard stars that define the zero point of SDSS photometry (Smith et al. 2002; Tucker et al. 2006), originally denoted as primed magnitudes (FS96). Further complications were caused by the fact that the set of filters used at PT was replaced in the middle of the survey (2001 August 18, Modified Julian Date (hereafter MJD) 52140) with a new set which was fabricated using a more modern technique of ion-assisted deposition coating. This is forced by the fact that we discovered that the old filters made with traditional evaporated coatings display changes with temperature and humidity, smaller than the changes observed going to a fully evacuated environment, but still substantial. These changes are almost certainly associated again with the adsorption of water in the low-density evaporated films. The ion-assisted films are much denser and do not show the effects, as we also confirmed in laboratory experiments. The filters with evaporation–deposition films show a temperature dependence in excess of what was anticipated from the temperature dependence of color glass. In vacuo, as in the 2.5 m imager, the evaporated films show no temperature effects, however.

This instability was also noted by Tucker et al. (2006) during their work on photometric standard stars at the PT, who attempted to remove the effect by using variable color terms (“b-terms”) so as not to affect the final results. The determination of these transformations and tracking them in time, however, is difficult and results in somewhat ambiguous photometric results. We thus decided to replace the PT filter set with a new one made with ion-assisted deposition coating, which makes the filter characteristics stable against environmental conditions. We designed the transmission of PT filters to fall between the one in vacuum and the one in air so that it can be close to the PT system in the dry air-purged environment with which some amount of the work had already been done.

We thus have used several systems that have somewhat different response functions to set up SDSS photometry. It is, therefore, important to examine that all relevant photometric response functions are sufficiently close to each other so that

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11 The red cutoff wavelength shifted by an unexpected amount, 42 Å for $g$, 58 Å for $r$, and 77 Å for $i$ redwards when temperature increases by 20° (FS10). They are about five times worse than the temperature dependence for the color glass used for the blue-side cutoff. These shifts were much more than anticipated and would cause a few hundredth of magnitude shift. As mentioned in the text above, a very dry condition would affect the coating surface and hence the character of transmission. The filter at PT is purged with very dry air. It is so dry that the transmission of filters has shifted halfway between the air and the vacuum. We realized that it is difficult to control the exact condition; this forced us to decide that we replace the filters with ones made with the new technique. We confirmed that this effect together with the temperature dependence disappears with filters fabricated by the ion-assisted deposition coating technique.
the resulting photometry defines a system at least with tolerable internal errors. This compels us to measure the response functions of PT (before and after the filter replacement), USNO and all 30 devices of the 2.5 m telescope imager, in addition to that used to define the original photometric system. We note that the fiducial response functions of the 2.5 m telescope imager have been made public through the World Wide Web at the SDSS site (SDSS public Web site 2001)\(^\text{12}\) using our measurements in 2000 December. In this paper, we present the newly estimated response function based on the entire measurements, but primarily resorting to those measured in the autumn of 2004 with more careful wavelength calibrations. The response function for the \(u\) band we shall present is significantly different from the one made public because of an unexpected large aging effect, but the other reference response functions we present differ little from the ones in the public Web site. Even with the response functions as much varied as in the \(u\) band, the effects on calibrated photometry in the SDSS output turn out to be tolerably small. We note in passing that though we will do all our calculations as if the SDSS photometry is an AB system, we will not address the very difficult problem of determining the AB zero-point corrections, which could well be as large as a few hundredths of a magnitude.

In Section 2, we present the design of the monochromatic illumination system. In Section 3, we present the results of the response function measurements, and present the new reference response function constructed therefrom. In Section 4, we consider the effects expected from the variation of response functions on photometry. We also discuss the response function of associated telescopes used to give SDSS photometry and errors in photometry when these slightly different systems are used. We also study the actual data, which are published in SDSS catalogs (Abazajian et al. 2003, 2004, 2005; Adelman-McCarthy et al. 2006, 2007, 2008) after processing and calibrations by the photometric pipelines with the aid of the monitor telescope pipeline (Stoughton et al. 2002; Tucker et al. 2006).

2. MONOCHROMATIC ILLUMINATION SYSTEM

The illumination system consists basically of a lamp, a monochromator consisting of a grating, order sorting filters and slits, an integrating sphere, and a photodiode to measure the flux of the illumination. This system can be moved accurately over the focal plane to illuminate any CCD in the camera, and also to illuminate a calibrated reference diode. The output of the integrating sphere is a few inches above the quartz corrector element which also serves as the mechanical substrate upon which the imager Dewars are mounted, about 10 inches above the focal plane (Gunn et al. 1998). The \(X\)-direction (the direction across different camera columns for the same color band) is controlled by a ball–screw stepping motor, while the \(Y\)-direction (the direction across five different color filters in a single Dewar) is manually controlled. Thus six CCDs with a given color band can be reached by remote control, but measuring different color bands requires manual intervention. Since the (manual) slit width must sometimes be changed when going from one color band to another anyway, this is not onerous. The illumination covers 250–1200 nm with the resolution \(R = \lambda / \Delta \lambda = 50–200\) for a 0.5–2 mm slit width. The lamp is a Philips quartz-halogen tungsten-filament (QTH) lamp of 150 W with the filament size 3 mm \(\times\) 5 mm. The flux is 5000 lm and the color temperature is 3400 K at 24 V. Its lifetime, 50 hr at 24 V, is increased to 500 hr when run at 20 V, at which voltage the color temperature is 3200 K.

The light is condensed with a mirror system and is then guided to a slit of the monochromator with adjustable width 1–20 mm by a triangular mask. The monochromator (JASCO CT-10) consists of four mirrors which make a collimated beam with a diameter of about 30 mm. The mirror focal length is 100 mm, with an approximate focal ratio of \(F/3\). A grating of 28 mm \(\times\) 28 mm with 1200 lines mm\(^{-1}\) is used to disperse the light with the spectral dispersion about 6.7 nm mm\(^{-1}\) at 600 nm. The grating is controlled by a stepping motor. The beam is guided through the outlet slit, whose width is set equal to that of the input slit, to the order-sorting filter, consisting of three filters, U-330 for 250–390 nm, L-37 for 390–680 nm, and R-64 for 680–1200 nm. The output light illuminates an integrating sphere (ORIEL) 8 inches in diameter, and a shutter is placed before the integrating sphere. The integrating sphere makes the illumination over the surface of a CCD as uniform as we can. The output is through a circular hole of 2 inches in diameter. The illuminating hole is placed vertically so that distance to CCD mimics the \(F/5\) beam of the telescope. A 61.7 mm thick aluminum block with a cylindrical hole of 2.5 inch diameter is attached to the illuminating hole, which works as a light guide. The inside of the cylinder is anodized so that it works as a light baffle. Figure 1 shows the entire unit.

The light flux is monitored by a photodiode (Hamamatsu Photonics, S2281) whose detection efficiency is accurately known. The sensitivity of the photodiode was measured by Hamamatsu Photonics from 200 nm to 1080 nm at a 10–20 nm interval. We may obtain the idea about the error of the sensitivity by replacing the photodiode with an alternative photodiode, which leads us to convince that it is no more than \(\approx 0.5\%\). The absolute sensitivity of the photodiode is verified by Japan Quality Assurance Organisation, showing that the accuracy is better than 0.6%–0.7% at 488.0 nm and at 835.1 nm, respectively. This photodiode is placed at the baffle of the cylinder hole of the block beneath the integration sphere. This is used to monitor the illumination flux, i.e. the efficiency of the CCD including the filter transmission is measured relative to the flux received at this photodiode.

The photodiode signals are converted into voltage with an AD743 operational amplifier, and data acquisition is done with National Instruments DAQ-700 at 1000 data points per exposure. The illumination apparatus and the photodiode data acquisition are controlled with National Instruments PCMCIA-GPIB. The entire measurement sequences are programmed and controlled by a LINUX computer in the SDSS control room, except for changing the manual stage positions, choosing a slit width and a lamp voltage.

The parameters of the monochromator are set as follows: the slit width is 0.5 mm for \(g, r, i\) bands, 0.75 mm for the \(u\) band, and 1.0 mm for the \(z\) band, which corresponds to the spectral resolution of 5.6 nm, 3.6 nm, 3.3 nm, 3.0 nm, and 5.5 nm for \(u, g, r, i, z\) bands, respectively. The QTH lamp works at 20.0 V for \(g, r, i, z\) bands, and 22.5 V for the \(u\) band. The exposure time is 2–100 s depending on the efficiency of the passband at the wavelength being measured so that the CCD output is 3000–30,000 electrons per pixel. Typical errors of repeated measurements were found to be less than \(\approx 0.5\%\) in efficiency.

We were not prepared to measure accurately the absolute detection efficiency at each measurement. We occasionally placed another photodiode at the distance the same as that

\(^{12}\) http://www.sdss.org/dr7/instruments/imager/filters/u.dat
to CCD to estimate the absolute detection efficiency. The absolute normalization of the detection efficiency we quote in the following section is obtained from such measurements, unless otherwise stated. We expect systematic errors of the order no worse than 10% in the absolute normalization, which is mainly due to geometrical uncertainty of the hardware setting. Relative efficiency was estimated with the photodiode placed at the integrating sphere. We scaled each measurement to that with the absolute measurement by adjusting it with an appropriate normalization factor.

Another important issue is the wavelength calibration. We measured the wavelength of the monochromatic illumination repeatedly with a portable fiber spectrometer, Asahi Spectra HSU-100S, which was calibrated against lines of an Hg+Ar lamp for the range 250–1000 nm. As a whole, we estimate that the wavelength accuracy of the monochromatic illumination is kept to an error less than \( \pm 3 \text{ Å} \), at least for the measurements with wavelength calibration carried out in 2004 July and after. In earlier measurements, we did not use the portable spectrometer, and the monochromator was directly calibrated with H\( \alpha \) and H\( \beta \) emissions from a hydrogen lamp; the position of the lamp could not be accurately controlled and was likely somewhat different from the original one for the quartz-halogen lamp and hence the wavelength calibration was not as accurate as it was with later measurements. In this paper, we correct early measurements using ones measured after 2004 July by matching the red-side cutoff, whose wavelength has been sufficiently stable in the vacuum chamber.

We note that the deviations of the incident angle of the light from exactly perpendicular cause a shift of cutoff wavelengths of the interference filter, as

\[
\Delta \lambda = \sqrt{1 - c_i \sin^2 \theta},
\]

where \( c_i = 0.62, 0.57, \) and 0.58 for \( g, r, \) and \( i \) filters, respectively, and \( \theta \) is the angle from perpendicular. This gives \( \approx 0.2\% \) in the wavelength, or 8–12 Å depending on the passband for \( \theta = 4^\circ \), corresponding approximately to the average over an \( F/5 \) beam with the secondary obscuration. Hence, the real transmission of the red-side cutoff in \( g, r, \) and \( i \) bands may systematically be shorter by 8–12 Å than with the parallel beam. Our illumination system produces an \( F/5 \) beam, however, without the secondary obscuration which gives \( \approx 0.1\% \) (4–6 Å) shifts. Hence, we still expect 4–6 Å shift for the red cutoff in \( g, r, \) and \( i \) band responses. This effect is not large, and is wavelength dependent within each bandpass. We do not correct for this effect in the present work, but include this into systematic errors.

The illumination of the monochromator covers roughly the whole size of the CCD, on which the flux varies only by \(< 8\% \). Some fringing pattern is visible in the red end of the \( i \)-band illumination, but it is at most 2%, and the effect can be small enough when an average is taken over some extended pixels. We set a region with the circular aperture of 100 pixel radius near the center for our measurements. The repeated measurements with exposures using the same setting give the median counts that agree within 0.5% (they are however mostly due to small flux variation of the QTH lamp, and are mostly absorbed when compared against the flux at the photodiode.).

Along with the measurement of the response functions, we occasionally measured gains of the detectors. A few pairs of the same exposures were taken with the same setup of the monochromator as the response function measurement, and the images were subtracted between the two and the standard deviations in counts were measured. The input fluxes in counts and the deviations then give the detector gain. The raw data for the response functions derived above were multiplied by the gains to obtain the quantum efficiency.

Figure 2 shows an example of the measurement of the quantum efficiency of a UV-enhancing coated thinned CCD without a filter, the specific device used for the PT. The solid points are obtained with the present monochromator illumination system.
Figure 2. Response function (quantum efficiency) of the ultraviolet-enhancing coated thinned back-illuminated CCD used at the PT. The solid points are the measurement with the present system, and the dashed curve is the quantum efficiency for the same CCD measured at SITe at a room temperature, but tilted using a laboratory measurement (open points) at a cooled, operating temperature, used in F96.

Table 1

| Date     | u  | g  | r  | i  | z  |
|----------|----|----|----|----|----|
| 2000 Jan.| 6  | 1  | 4  | 1  | 2–4,6|
| 2000 Apr.| 1  | 1  | 1,4| 1  | 1–2 |
| 2000 Dec.| 1–6| 1–6| 1–6| 1–6| 1–6 |
| 2001 Sep.| 1–2| 1–2| 1–2| 1–6|     |
| 2004 Jul.| 1–2| 1–6| 1–4| 1–3| 1–2 |
| 2004 Oct.| 1–5|    |    |    |     |
| 2005 May.| 2–4| 1  |    |    |     |
| 2006 Sep.| 5–6|    |    |    |     |
| 2006 Dec.| 1–6|    |    |    |     |
| 2008 May.| 1–6| 1–6| 1–6| 1–6| 1–6 |

Note. a The number stands for measured Camcol.

with the CCD cooled to operating temperature and the open points represent the data which were measured at SITe at room temperature but were warped to trace the broadband measurements at a working temperature in our laboratory for the same CCD. We see agreement between the two at 1%–2% accuracy, although the measurement in the UV is somewhat noisy. The latter is the curve we used in the characterization of the SDSS response function in F96.

3. THE MEASUREMENT

We have carried out measurements at 11 epochs before 2006 (and one in 2008); the journal is given in Table 1. The measurement is time consuming, and full measurements were not done at all the epochs, because of time constraints. The results are summarized in Figure 3 (u), Figure 4 (g), Figure 5 (r), Figure 6 (i), and Figure 7 (z). The response functions for the 2.5 m telescope main imager that we will take as the reference are shown by thick solid curves. They are obtained by averaging our measurements over six columns of detectors, obtained in 2004 October and November, as described below. When some measurements for specific columns are missing, we supplement the data from other measurements, after applying a correction for temperature effects. In order to take into account the reflection losses due to the primary and the secondary mirror of the telescope, we included reflection losses from two fresh aluminum surfaces, which modify the efficiencies by 20%–30% while change the shapes of the curves only slightly. The attenuation due to the first corrector lens is significantly smaller than 1% at all the wavelengths, and hence it is not included in our analysis. The monochromator measurements presented in this paper include the attenuation due to the secondary corrector.

The thin solid curves indicate the response function that has been taken as the standard from the beginning of the survey as described in F96. It was obtained by the synthesis of the measured transmission and the quantum efficiency of the relevant filters and CCD. These specific filters and CCD have
Table 2
Filter Characteristics

| System         | $\lambda_{\text{eff}}(u)$ | $\lambda_{\text{blue}}(u)$ | $\lambda_{\text{red}}(u)$ | $\lambda_{\text{eff}}(g)$ | $\lambda_{\text{blue}}(g)$ | $\lambda_{\text{red}}(g)$ | $\lambda_{\text{eff}}(r)$ | $\lambda_{\text{blue}}(r)$ | $\lambda_{\text{red}}(r)$ | $\lambda_{\text{eff}}(i)$ | $\lambda_{\text{blue}}(i)$ | $\lambda_{\text{red}}(i)$ | $\lambda_{\text{eff}}(z)$ | $\lambda_{\text{blue}}(z)$ | $\lambda_{\text{red}}(z)$ |
|----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| F96 standard   | 3499                        | 3216                        | 3849                        | 4728                        | 4076                        | 5485                        | 6200                        | 5548                        | 6934                        | 7615                        | 6939                        | 8474                        | 9054                        | 8334                        | 9741                        |
| PT-new         | 3496                        | 3207                        | 3838                        | 4714                        | 4035                        | 5506                        | 6180                        | 5559                        | 6879                        | 7593                        | 6971                        | 8346                        | 9054                        | 8334                        | 9741                        |
| USNO           | 3500                        | 3211                        | 3847                        | 4704                        | 4057                        | 5476                        | 6201                        | 5551                        | 6930                        | 7606                        | 6931                        | 8461                        | 9051                        | 8329                        | 9739                        |
| 2.5m reference | 3531                        | 3259                        | 3852                        | 4627                        | 4019                        | 5330                        | 6140                        | 5589                        | 6748                        | 7467                        | 6902                        | 8178                        | 8887                        | 8257                        | 9347                        |
| SDSS “public”  | 3498                        | 3203                        | 3844                        | 4627                        | 4022                        | 5330                        | 6139                        | 5593                        | 6748                        | 7467                        | 6903                        | 8171                        | 8927                        | 8271                        | 9449                        |

Notes. $^a$ $\lambda_{\text{eff}}$ is defined in Equation (2) in the text, $\lambda_{\text{blue}}$ and $\lambda_{\text{red}}$ are defined as the wavelengths that give 50% of the peak response function. PT-new is the PT system after the filter replacement. The system before the filter replacement is the same as F96 standard. SDSS “public” means the response function that is made public through the World Wide Web (2001). All characteristics are without atmosphere transmissions.

Figure 5. Same as Figure 2, but for the $r$ band.
(A color version of this figure is available in the online journal.)

Figure 6. Same as Figure 2, but for the $i$ band.
(A color version of this figure is available in the online journal.)

Figure 7. Same as Figure 2, but for the $z$ band.
(A color version of this figure is available in the online journal.)

been used at PT before the filter replacement. The curves also include reflection of two aluminum surfaces. This represents the response functions for PT with the original filter set, allowing, however, for variations caused by environmental effects.

There are two more curves drawn. The thin dashed curves are synthesized response functions expected for the USNO 1 m telescope system. Since the actual quantum efficiency was not measured for the CCD used in the USNO system, the quantum efficiency of the PT CCD was used, for the USNO system uses a CCD with surface treatment identical to that used at PT. The

other curves, drawn dotted, are the response functions for the PT with the new set of filters.

For the $u$ band (Figure 3), a large departure of the reference response function for the 2.5 m telescope imager from the others is apparent at shorter wavelengths $\lambda < 3650 \, \text{Å}$. This is ascribed to the aging effect that we will discuss below.

Another conspicuous set of deviations of the 2.5 m reference response curves is seen around the red edges with the $g$, $r$, and $i$ bands. We see that the red edges of the 2.5 m reference response curves are significantly blueward of the other curves. This shift is caused by coating films placed in the vacuum environment, as mentioned earlier. The shifts amount to 120 Å ($g$), 160 Å ($r$), and 175 Å ($i$), which are also confirmed in laboratory experiments (FS10). Some variations up to (40–50) Å are also seen at the blue edges, which are mostly due to fluctuations of characteristics of color glass, and to a minor extent to the temperature effect which we shall discuss below. Similar differences visible at red edges between the F96 standard and USNO are fluctuations in coatings. The temperature effect is absent for the red edge. The curves for the PT (with newer filters) fall between the F96 standard and the 2.5 m reference curves (except for the $g$ band which lies somewhat outside the F96 standard, as a result of fluctuations in the coating process): this is as designed when we made the new set of filters for PT.

Interference coatings from different coating batches lead to some fluctuations in the cutoff wavelengths up to 30–40 Å, which are within our specifications given to the vendor. Interference films even in the same batch of coating may also vary to the extent up to 15 Å due to inhomogeneity in the coating
vessel. The transmission of colored glass also shows fluctuations of the same order from piece to piece. We did not reject the filters unless the effective wavelengths differ substantially more than by 30 Å from the specification.

For the z band (Figure 7), the large difference between the 2.5 m reference response curve and the others is due to the lower quantum efficiency of the front-illuminated thick CCDs in the main imager, compared with thinned CCD used for the other curves. This causes an appreciable difference in the effective wavelengths.

As a quantitative measure for the variation of response functions we use the effective wavelength or the effective
frequency defined by

\[
\lambda_{\text{eff}} = \frac{c}{v_{\text{eff}}},
\]

\[
v_{\text{eff}} = \frac{\int v R(v) dv / h \nu}{\int R(v) dv / h \nu},
\]

(2)

where \( R(v) \) is the response function and the integrand is weighted to give the photon number.\(^{13}\) Note that this definition of effective frequency \( v_{\text{eff}} \) differs from the one used in Table 2 of F96, where \( 1/h \nu \) is not included. This definition is the average with respect to the photon number, not energy.

\(^{13}\) There are several definitions for effective wavelengths. The traditionally used is \( \int \lambda d\lambda / \int d\lambda \) for photomultiplier measurements. For other definitions, see F96.

Figure 9. Response functions at various epochs of measurements for the imager in the main camera: (a) \( u \) band, Camcol 1, (b) \( g \) band, Camcol 1, (c) \( r \) band Camcol 1, (d) \( i \) band, Camcol 1, (e) \( z \) band, Camcol 1, and (f) red leak for the \( u \) band, Camcol 1.

(A color version of this figure is available in the online journal.)
Figure 10. Time variations of the response functions and their effects on photometry. From the top to the bottom: (i) the effective wavelength, $\lambda_{\text{eff}}$, (ii) 50% response wavelengths of the blue edges, (iii) 50% response wavelengths of the red edges, (iv) the detector sensitivity, i.e., the quantity proportional to $-2.5 \log N_{\text{pe}}$ (arbitrary unit) where $N_{\text{pe}}$ is the number of photoelectrons in the detector, or brightness defined by Equation (3) but with the denominator set equal to unity. The star is BD+17°4708; (v) brightness of BD+17°4708 from Equation (3). The response function includes the effect of atmosphere at 1.3 air mass. The symbols are the same as in Figure 8 (circle, cross, triangle, star, square, and plus present Columns 1–6, respectively). The horizontal line in each panel is for the reference response. In the panels (i), (ii), and (iii), the error bars show 10 Å, and in (iv) and (v), they show 0.05 mag and 0.01 mag, respectively.

(A color version of this figure is available in the online journal.)
which is the relevant quantity for nearly all modern detectors and CCDs included. Table 2 also gives the effective wavelengths \( \lambda_{\text{eff}} \) and the wavelengths at the 50% yield of the maximum at both blue and red edges for four response functions (without atmospheric transmission) shown in Figures 3–7. The PT system before the replacement of filters is the F96 standard, ignoring temperature effects. Note that the shape of the response function is modified by atmospheric extinction in actual observations, while we work with the intrinsic response function without atmospheric extinction in laboratories, and hence in this paper up to some exceptions when we refer to the observation, for which we include the effect due to atmospheric extinction.

The response curves should vary from column to column even within the main imager, although the interference film transmission varies less, because all film coatings used for the main imager are made in one single batch for each color. Figures 8 (a)–(e) show the response curve for each column of the imager for the five color bands to show the column-to-column variation. These data are taken from the measurement in 2004 October/November. The difference of \( \lambda_{\text{eff}} \) relative to the 2.5 m reference measured at three epochs is presented in Table 3, the dispersions being 8.9 Å for \( u \), 5.8 Å for \( g \), 6.5 Å for \( r \), 4.1 Å for \( i \), and 27.5 Å for \( z \), respectively. The larger variations for the \( z \) band are due to different CCD sensitivities near the red cutoff. We saw a very small variation (0.8 Å) in the transmission curve of \( z \) filters used for the main imager in the measurement when the filters are produced. For other colors, the dispersions of the difference are consistent with those of the filters we measured at the time of procurement, except for the \( u \) band for which in situ measurements in combination with CCD give a larger dispersion if only by a factor of 2. Observed in the measurement is approximately what is anticipated for \( g \), \( r \), and \( i \). The maximum deviation of \( \lambda_{\text{eff}} \) against the reference is (+9, −16) Å for \( u \), (+6, −15) Å for \( g \), (+4, −16) Å for \( r \), (+6, −6) Å for \( i \), and (+46, −31) Å for \( z \).

Figures 9(a)–(e) show the results of our measurements for the \( u − z \) bands at specified columns and Figure 9(f) is for red leak of the \( u \) filter at Camcol 1 on 2000 April, 2000 December, 2001 September, 2004 July, 2004 October/November, and 2006 December. The 2.5 m reference is also drawn for comparison. Measurements for other columns give similar results. The most conspicuous variation at different epochs is visible for the \( u \) band as we have already noted above (Figure 9(a)). The response functions, notably at shorter wavelengths, diminish as time passes till 2004 July: the sensitivity diminished by \( \sim 30\% \) between the years 2000 and 2004. The characteristics has gradually stabilized, so that such a large variation was not visible after 2004 July. We confirmed that no appreciable aging effects are visible with the \( u \) filters at the PT and the spare \( u \) filters retained at the laboratory. We also noted that the illumination pattern visible on the CCD chip in our measurement in 2004 differs from the one in earlier measurements for the \( u \) band. No such conspicuous aging effects are visible in other color bands. These observations lead us to suspect that aging is basically due to that of the sensitivity of the ultraviolet-sensitive CCD itself, probably the deterioration of the ultraviolet-enhancing coating and/or the associated manipulation of the surface potential profiles on the devices.

The time variations of the response curves in other passbands are small. We have shown in Figure 10 the time dependence of the effective wavelengths and the cutoff wavelengths as a function of the epoch of the measurement. Except for the \( u \) filters the time variation of \( \lambda_{\text{eff}} \) is of the order of \( \lesssim 10 \) Å, which is mostly seasonal. For instance, we observe the average difference \( 4.2 \pm 2.5 \) Å between 2004 July and November for the \( g \) band. We made careful wavelength calibration work in the operations of 2004 July and November. So we focus on the
two measurements. This seasonal variation is largely ascribed to the temperature effect of GG400 color glass used to cut off the blue side. The air temperature decreases by 17° between the two epochs. The measured shift of the blue edge 6.8 ± 1.3 Å is consistent with 7.2 Å expected from the laboratory experiment for the temperature effect on GG400. The red-side cutoff varies little, 1.8 ± 1.6 Å, which is consistent with null within the error. The red-side cutoff wavelengths of interference coating films such as those on the new PT filters made with ion-assisted deposition are stable against temperature, which we have confirmed in laboratory experiments (FS10).

Similarly, we find a shift of 14.7±0.5 Å in the blue edge of the r passband as compared with 12.8 Å expected from the temperature-dependence measurement for color glass pieces. The same trend also applies to the i filter. The shift in the blue edge is measured to be 21.0±0.8 Å for the i filter, as compared with 9.2 Å (35 Å if the Schott catalog value is used) expected from our laboratory experiments. The measured shifts of the red edge cutoff are 2.0 ± 0.8 Å, −2.0 ± 0.8 Å for the r and i passbands, respectively, which are again consistent with null shifts when the systematic error of 3 Å in the wavelength calibration is taken into account. The temperature dependence is not clearly identified for the u passband in our measurements. For the z filter the measured blue edge shift 51 ± 21 Å appears larger than those expected from the temperature dependence of a laboratory measurement 19 Å, but is consistent with the Schott value 40 Å. In summary, the effective wavelength shift of the

14 The Schott document gives the temperature coefficient 0.7 Å deg⁻¹ for GG400 between 10°C and 90°C, but our measurement in the laboratory (FS10) for this glass piece gives 0.43 deg⁻¹ at −10°C to 20°C, the temperature variation being smaller than the Schott value by a factor of 2. We noted that the temperature dependence is not quite linear. We found that the temperature dependence is mild at low temperatures and it becomes sharper at higher temperatures. The observed wavelength shift is consistent with our laboratory measurement. Similarly, we get 0.75 Å deg⁻¹ for OG530 compared with the Schott value of 1.3 Å deg⁻¹, and 0.55 Å deg⁻¹ for RG605 compared with the Schott value of 1.8 Å deg⁻¹. For RG830, our 1.1 Å deg⁻¹ is compared with 2.3 Å deg⁻¹ by Schott. The u filters are cut by color glasses for both sides: BG38 (and UG11) for the blue side and UG11 for the red side. The temperature dependence is 0.5 Å deg⁻¹ at the laboratory, while the numbers are not given in the Schott catalog. Unlike the coating surface, this does not depend on whether the environment is air or vacuum (FS10).
| \( \lambda \) | \( u \) | \( g \) | \( r \) | \( i \) | \( z \) | \( T_{\text{1.5 air mass}} \) |
|---|---|---|---|---|---|---|
| 4240 | ... | 0.3773 | ... | ... | ... | 0.7378 |
| 4260 | ... | 0.3830 | ... | ... | ... | 0.7416 |
| 4280 | ... | 0.3886 | ... | ... | ... | 0.7455 |
| 4300 | ... | 0.3943 | ... | ... | ... | 0.7493 |
| 4320 | ... | 0.3999 | ... | ... | ... | 0.7529 |
| 4340 | ... | 0.4043 | ... | ... | ... | 0.7564 |
| 4360 | ... | 0.4083 | ... | ... | ... | 0.7600 |
| 4380 | ... | 0.4122 | ... | ... | ... | 0.7635 |
| 4400 | ... | 0.4161 | ... | ... | ... | 0.7671 |
| 4420 | ... | 0.4200 | ... | ... | ... | 0.7705 |
| 4440 | ... | 0.4240 | ... | ... | ... | 0.7739 |
| 4460 | ... | 0.4279 | ... | ... | ... | 0.7773 |
| 4480 | ... | 0.4314 | ... | ... | ... | 0.7808 |
| 4500 | ... | 0.4337 | ... | ... | ... | 0.7824 |
| 4520 | ... | 0.4359 | ... | ... | ... | 0.7842 |
| 4540 | ... | 0.4381 | ... | ... | ... | 0.7869 |
| 4560 | ... | 0.4404 | ... | ... | ... | 0.7904 |
| 4580 | ... | 0.4426 | ... | ... | ... | 0.7939 |
| 4600 | ... | 0.4448 | ... | ... | ... | 0.7965 |
| 4620 | ... | 0.4470 | ... | ... | ... | 0.7996 |
| 4640 | ... | 0.4488 | ... | ... | ... | 0.8021 |
| 4660 | ... | 0.4504 | ... | ... | ... | 0.8047 |
| 4680 | ... | 0.4521 | ... | ... | ... | 0.8072 |
| 4700 | ... | 0.4537 | ... | ... | ... | 0.8097 |
| 4720 | ... | 0.4553 | ... | ... | ... | 0.8122 |
| 4740 | ... | 0.4569 | ... | ... | ... | 0.8141 |
| 4760 | ... | 0.4586 | ... | ... | ... | 0.8160 |
| 4780 | ... | 0.4601 | ... | ... | ... | 0.8179 |
| 4800 | ... | 0.4611 | ... | ... | ... | 0.8199 |
| 4820 | ... | 0.4622 | ... | ... | ... | 0.8218 |
| 4840 | ... | 0.4633 | ... | ... | ... | 0.8237 |
| 4860 | ... | 0.4644 | ... | ... | ... | 0.8256 |
| 4880 | ... | 0.4655 | ... | ... | ... | 0.8276 |
| 4900 | ... | 0.4666 | ... | ... | ... | 0.8295 |
| 4920 | ... | 0.4677 | ... | ... | ... | 0.8314 |
| 4940 | ... | 0.4687 | ... | ... | ... | 0.8327 |
| 4960 | ... | 0.4698 | ... | ... | ... | 0.8340 |
| 4980 | ... | 0.4709 | ... | ... | ... | 0.8353 |
| 5000 | ... | 0.4719 | ... | ... | ... | 0.8366 |
| 5020 | ... | 0.4730 | ... | ... | ... | 0.8379 |
| 5040 | ... | 0.4741 | ... | ... | ... | 0.8388 |
| 5060 | ... | 0.4752 | ... | ... | ... | 0.8397 |
| 5080 | ... | 0.4762 | ... | ... | ... | 0.8406 |
| 5100 | ... | 0.4770 | ... | ... | ... | 0.8415 |
| 5120 | ... | 0.4775 | ... | ... | ... | 0.8423 |
| 5140 | ... | 0.4784 | ... | ... | ... | 0.8432 |
| 5160 | ... | 0.4791 | ... | ... | ... | 0.8441 |
| 5180 | ... | 0.4794 | ... | ... | ... | 0.8450 |
| 5200 | ... | 0.4800 | ... | ... | ... | 0.8458 |
| 5220 | ... | 0.4807 | ... | ... | ... | 0.8467 |
| 5240 | ... | 0.4812 | ... | ... | ... | 0.8477 |
| 5260 | ... | 0.4826 | ... | ... | ... | 0.8487 |
| 5280 | ... | 0.4836 | ... | ... | ... | 0.8497 |
| 5300 | ... | 0.4846 | ... | ... | ... | 0.8507 |
| 5320 | ... | 0.4856 | ... | ... | ... | 0.8517 |
| 5340 | ... | 0.4863 | ... | ... | ... | 0.8527 |
| 5360 | ... | 0.4871 | ... | ... | ... | 0.8537 |
| 5380 | ... | 0.4878 | ... | ... | ... | 0.8547 |
| 5400 | ... | 0.4885 | ... | ... | ... | 0.8557 |
| 5420 | ... | 0.4893 | ... | ... | ... | 0.8567 |
| 5440 | ... | 0.4900 | ... | ... | ... | 0.8571 |
| 5460 | ... | 0.4908 | ... | ... | ... | 0.8576 |
| 5480 | ... | 0.4916 | ... | ... | ... | 0.8580 |
| 5500 | ... | 0.4923 | ... | ... | ... | 0.8585 |
| 5520 | ... | 0.4930 | ... | ... | ... | 0.8589 |
| 5540 | ... | 0.4937 | ... | ... | ... | 0.8594 |
| 5560 | ... | 0.4944 | ... | ... | ... | 0.8598 |
| \(\lambda\) | \(u\) | \(g\) | \(r\) | \(i\) | \(z\) | \(T_{1.5\ air\ mass}\) |
|---|---|---|---|---|---|---|
| 6880 | ... | ... | 0.0273 | 0.1952 | ... | 0.8581 |
| 6900 | ... | ... | 0.0201 | 0.2377 | ... | 0.8722 |
| 6920 | ... | ... | 0.0185 | 0.2839 | ... | 0.8686 |
| 6940 | ... | ... | 0.0097 | 0.3222 | ... | 0.9004 |
| 6960 | ... | ... | 0.0076 | 0.3565 | ... | 0.9145 |
| 6980 | ... | ... | 0.0054 | 0.3869 | ... | 0.9286 |
| 7000 | ... | ... | 0.0036 | 0.4104 | ... | 0.9298 |
| 7020 | ... | ... | 0.0019 | 0.4301 | ... | 0.9301 |
| 7040 | ... | ... | 0.0003 | 0.4458 | ... | 0.9305 |
| 7060 | ... | ... | 0.4565 | ... | ... | 0.9308 |
| 7080 | ... | ... | 0.4648 | ... | ... | 0.9312 |
| 7100 | ... | ... | 0.4706 | ... | ... | 0.9315 |
| 7120 | ... | ... | 0.4764 | ... | ... | 0.9319 |
| 7140 | ... | ... | 0.4791 | ... | ... | 0.9322 |
| 7160 | ... | ... | 0.4814 | ... | ... | 0.8928 |
| 7180 | ... | ... | 0.4823 | ... | ... | 0.8553 |
| 7200 | ... | ... | 0.4815 | ... | ... | 0.8703 |
| 7220 | ... | ... | 0.4806 | ... | ... | 0.8873 |
| 7240 | ... | ... | 0.4771 | ... | ... | 0.8896 |
| 7260 | ... | ... | 0.4732 | ... | ... | 0.8919 |
| 7280 | ... | ... | 0.4694 | ... | ... | 0.8942 |
| 7300 | ... | ... | 0.4655 | ... | ... | 0.8966 |
| 7320 | ... | ... | 0.4617 | ... | ... | 0.9156 |
| 7340 | ... | ... | 0.4578 | ... | ... | 0.9346 |
| 7360 | ... | ... | 0.4539 | ... | ... | 0.9358 |
| 7380 | ... | ... | 0.4505 | ... | ... | 0.9365 |
| 7400 | ... | ... | 0.4477 | ... | ... | 0.9371 |
| 7420 | ... | ... | 0.4449 | ... | ... | 0.9371 |
| 7440 | ... | ... | 0.4421 | ... | ... | 0.9371 |
| 7460 | ... | ... | 0.4393 | ... | ... | 0.9371 |
| 7480 | ... | ... | 0.4364 | ... | ... | 0.9371 |
| 7500 | ... | ... | 0.4335 | ... | ... | 0.9371 |
| 7520 | ... | ... | 0.4306 | ... | ... | 0.9371 |
| 7540 | ... | ... | 0.4264 | ... | ... | 0.9371 |
| 7560 | ... | ... | 0.4220 | ... | ... | 0.9371 |
| 7580 | ... | ... | 0.4176 | ... | ... | 0.9209 |
| 7600 | ... | ... | 0.4132 | ... | ... | 0.5647 |
| 7620 | 0.000003 | ... | 0.4088 | ... | ... | 0.6334 |
| 7640 | 0.000044 | ... | 0.4042 | ... | ... | 0.6037 |
| 7660 | 0.000149 | ... | 0.3996 | ... | ... | 0.7830 |
| 7680 | 0.000258 | ... | 0.3951 | 0.0000 | ... | 0.9396 |
| 7700 | 0.000397 | ... | 0.3905 | 0.0000 | ... | 0.9407 |
| 7720 | 0.000553 | ... | 0.3860 | 0.0001 | ... | 0.9410 |
| 7740 | 0.000676 | ... | 0.3815 | 0.0001 | ... | 0.9412 |
| 7760 | 0.000675 | ... | 0.3770 | 0.0001 | ... | 0.9415 |
| 7780 | 0.000551 | ... | 0.3725 | 0.0001 | ... | 0.9417 |
| 7800 | 0.000403 | ... | 0.3680 | 0.0002 | ... | 0.9420 |
| 7820 | 0.000276 | ... | 0.3636 | 0.0002 | ... | 0.9422 |
| 7840 | 0.000179 | ... | 0.3610 | 0.0002 | ... | 0.9424 |
| 7860 | 0.000093 | ... | 0.3586 | 0.0003 | ... | 0.9427 |
| 7880 | 0.000044 | ... | 0.3562 | 0.0004 | ... | 0.9429 |
| 7900 | 0.000026 | ... | 0.3539 | 0.0006 | ... | 0.9432 |
| 7920 | 0.000011 | ... | 0.3515 | 0.0008 | ... | 0.9433 |
| 7940 | 0.000007 | ... | 0.3492 | 0.0010 | ... | 0.9434 |
| 7960 | ... | ... | 0.3469 | 0.0012 | ... | 0.9435 |
| 7980 | ... | ... | 0.3449 | 0.0016 | ... | 0.9437 |
| 8000 | ... | ... | 0.3432 | 0.0023 | ... | 0.9438 |
| 8020 | ... | ... | 0.3411 | 0.0030 | ... | 0.9439 |
| 8040 | ... | ... | 0.3388 | 0.0044 | ... | 0.9440 |
| 8060 | ... | ... | 0.3362 | 0.0059 | ... | 0.9442 |
| 8080 | ... | ... | 0.3328 | 0.0078 | ... | 0.9443 |
| 8100 | ... | ... | 0.3279 | 0.0105 | ... | 0.9444 |
| 8120 | ... | ... | 0.3215 | 0.0132 | ... | 0.9420 |
| 8140 | ... | ... | 0.3043 | 0.0171 | ... | 0.8966 |
| 8160 | ... | ... | 0.2763 | 0.0212 | ... | 0.8966 |
| 8180 | ... | ... | 0.2379 | 0.0257 | ... | 0.8966 |
filter is grossly consistent with the temperature dependence of the color glass cutoff. This change is smaller than \( \sim 20 \) Å for the \( u-i \) bands, small enough to cause any significant effects on photometry at a 1\% level, as we will see in the following section. This is also true with the \( z \) band, although the shift itself is larger.

The \( z \)-band response function curves appear to show the time variation in their shapes. We infer that the variation is due to the variation of the operational temperature of the CCD, which may have not been controlled well. We know that the quantum efficiency is sensitive to the temperature in reddest wavelengths.

We remark that the accuracy of our earlier measurements was somewhat lower: the sampling pitch in early measurements is too coarse for an accurate characterization of the response function; a careful wavelength calibration is made only after 2004 July; positional control of the illumination system could not be done very accurately in the beginning, etc. The measurements were significantly better controlled in the 2004 and later runs. We show in Table 5 the summary of various uncertainties in the effective wavelength.

Figure 9(f) presents the red leak measurement for the \( u \) response function for Camcol 1. The \( u \) filter composed of UG11 (1 mm) and BG38 (1 mm) color glass causes red leak between 6600 Å and 8000 Å, which is suppressed by interference coating. Our best design of coating still produces a small red leak at 6600 Å and 8000 Å, which is suppressed by interference coating. This is also true with the \( u \) filter, although the shift itself is larger.

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We have not seen the aging and light. The thick line shows the average of all six columns.

The numbers in the bottom row are the fluxes that would be obtained in various detection systems (while the atmospheric attenuation of the flux is removed). The flux of F subdwarf BD+17°4708 calculated with the various response functions is given in magnitude in Table 6. Note that the photometric system used in F96 (and also in the present paper) is AB95, which differs slightly from the AB79 system used by Oke & Gunn (1983). The numbers in the bottom row are the fluxes that would be obtained with the use of the response functions presented in the SDSS public Web site (SDSS public Web site 2001). We note that the survey adopts the system normalized to the response function expected at 1.3 air masses of atmospheric extinction, so that the atmospheric effect that modifies the response function must be included in $R(v)$ when one discusses the actual observation (while the atmospheric attenuation of the flux is removed). The fluxes (in magnitude) that would be obtained in various detection systems with 1.3 air mass response functions for BD+17°4708 are presented in Table 7. They differ from the numbers in Table 6 by smaller than 0.01 mag except for the $u$ passband for which

4. EFFECTS ON PHOTOMETRY

We discuss the effects expected on photometry due to the small differences in response functions from column to column and from their variations with the epoch during the survey. We also consider the difference in photometry due to the use of different response functions among the 2.5 m telescope main imager, PT, and the USNO detector system. Comparisons with the original F96 standard are also made. The SDSS primary standard stars (Smith et al. 2002) were observed using the USNO system, and then those observations are tied to the 2.5 m system with the PT. Our results confirm that the color effects between two systems are sufficiently small.

Let us consider brightness of the fundamental standard star, F subdwarf BD+17°4708 (Oke 1990), by a synthetic analysis. The AB magnitude is defined by

$$m = -2.5 \log \frac{\int d(\log v) f(v) R(v)}{\int d(\log v) R(v)} - 48.60,$$

(3)

with $f(v)$ being the object flux. The flux of F subdwarf BD+17°4708 calculated with the various response functions is given in magnitude in Table 6. Note that the photometric system used in F96 (and also in the present paper) is AB95, which differs slightly from the AB79 system used by Oke & Gunn (1983). The numbers in the bottom row are the fluxes that would be obtained with the use of the response functions presented in the SDSS public Web site (SDSS public Web site 2001). We note that the survey adopts the system normalized to the response function expected at 1.3 air masses of atmospheric extinction, so that the atmospheric effect that modifies the response function must be included in $R(v)$ when one discusses the actual observation (while the atmospheric attenuation of the flux is removed). The fluxes (in magnitude) that would be obtained in various detection systems with 1.3 air mass response functions for BD+17°4708 are presented in Table 7. They differ from the numbers in Table 6 by smaller than 0.01 mag except for the $u$ passband for which

If one uses the AB79 Vega spectrum, the brightness of BD+17°4708 for the F96 responses will be $u = 10.498$, $g = 9.631$, $r = 9.329$, $i = 9.219$, and $z = 9.194$. These differ from the numbers given in Table 6 (AB95) which are about 0.030-0.038 mag fainter. If one adopts the spectrum by Bohlin & Gilliland (2004), the brightness of BD+17°4708 for the F96 responses will be $u = 10.563$, $g = 9.616$, $r = 9.343$, $i = 9.254$, and $z = 9.247$.

**Table 5**

Summary of the Uncertainties in the Effective Wavelength

| Source | Uncertainty (Å) | Band | Comments |
|--------|-----------------|------|----------|
| Monochromator repeatability | ±3 | All | rms |
| Incident angle | ±2–±3 | $g, r, i$ | Half of red cutoff shifts |
| Filter temperature | 7, 15, 21, 51 | $g, r, i, z$ | Peak-to-peak, color glass temperature effect |
| Aging | $\approx -30$ | $u$ | CCD coating? |
| CCD sensitivity? | $\approx ±30$ | $z$ | Temperature effect? |

**Figure 11.** $u$-band red leak response after subtraction of the possible scattered light. The thick line shows the average of all six columns. (A color version of this figure is available in the online journal.)

**Table 6**

Brightness of BD+17°4708 in AB95 Without Atmospheric Extinction

| System | $u$ | $g$ | $r$ | $i$ | $z$ |
|--------|-----|-----|-----|-----|-----|
| F96 standard | 10.559 | 9.636 | 9.353 | 9.251 | 9.230 |
| USNO 1 m | 10.558 | 9.644 | 9.353 | 9.252 | 9.230 |
| PT-new | 10.565 | 9.640 | 9.356 | 9.252 | 9.230 |
| 2.5 m reference | 10.525 | 9.670 | 9.361 | 9.257 | 9.228 |
| SDSS public Web site (2001) | 10.560 | 9.671 | 9.361 | 9.257 | 9.229 |

15 Tables for each column are available from http://www.ioa.s.u-tokyo.ac.jp/~doi/sdss/SDSSresponse.html.
Figure 12. Column-to-column color variations expected in the \textit{u} band as a function of \(g - r\) color of stars. The response function involves atmospheric extinction at 1.3 air mass. (b) The same as Figure 11(a) but in the \textit{g} band. (c) The same as Figure 11(a) but in the \textit{r} band. (d) The same as Figure 11(a) but in the \textit{i} band. (e) The same as Figure 11(a) but in the \textit{z} band.

The difference amounts to about 0.036–0.039 mag due to a large atmospheric effect. The effective wavelengths for this case are also given in upper rows of this table.

In practice, in application to SDSS photometry all measured fluxes are adjusted to fit the standard scale adopted from F96, and the variations seen in this table are absorbed into the calibration. In Table 7, we see that the difference among the different systems is at most 0.038 mag (\textit{u} band). In \textit{g} and \textit{r}, it is 0.034 mag and 0.007 mag, respectively, and even smaller for redder color bands. This change would cause constant shifts in photometry, so that relative magnitudes will be unchanged. These variations, however, are flattened by the calibration process when the fluxes are presented in the catalog. We emphasize that the fluxes in Table 7 are not yet intended to give accurate AB magnitudes taken as the standard, but are referred to here for the purpose of comparisons among different systems.
Figure 13. Expected offset of $u - g$ color between the USNO photometric system and the original F96 standard, $\Delta(u - g)_{AB} = (u - g)_{96} - (u - g)_{USNO}$ plotted as a function of $u - g$. The response function involves atmospheric extinction. (b) The same as Figure 12(a) but for $g - r$. (c) The same as Figure 12(a) but for $r - i$.

Table 7

| System                           | $u$  | $g$  | $r$  | $i$  | $z$  |
|---------------------------------|------|------|------|------|------|
| F96 standard $\lambda_{\text{eff}}$ | 3537 | 4753 | 6209 | 7619 | 9032 |
| USNO 1 m $\lambda_{\text{eff}}$   | 3539 | 4731 | 6210 | 7609 | 9030 |
| PT-new $\lambda_{\text{eff}}$    | 3534 | 4742 | 6189 | 7595 | 9032 |
| 2.5 m reference $\lambda_{\text{eff}}$ | 3568 | 4653 | 6148 | 7468 | 8865 |

| System                           | $u$  | $g$  | $r$  | $i$  | $z$  |
|---------------------------------|------|------|------|------|------|
| BD+17$^\circ$ 4708 with F96 standard (1.3 air mass) | 10.520 | 9.628 | 9.353 | 9.251 | 9.231 |
| BD+17$^\circ$ 4708 with USNO 1 m (1.3 air mass) | 10.519 | 9.635 | 9.353 | 9.252 | 9.231 |
| BD+17$^\circ$ 4708 with PT-new (1.3 air mass) | 10.527 | 9.632 | 9.355 | 9.252 | 9.231 |
| BD+17$^\circ$ 4708 with 2.5 m reference (1.3 air mass) | 10.489 | 9.662 | 9.360 | 9.257 | 9.228 |
| BD+17$^\circ$ 4708 with SDSS “public” Web (1.3 air mass) | 10.518 | 9.662 | 9.360 | 9.257 | 9.229 |

**Note.** Atmospheric extinction in flux itself is removed in brightness.

The flux defined by Equation (3) depends primarily on $\lambda_{\text{eff}}$, and the change of the sensitivity tends to cancel between the numerator and the denominator. We find that the $\lambda_{\text{eff}}$ dependence is roughly $\delta m_u \simeq -0.105\Delta\lambda_{\text{eff}}/(100 \ \text{Å})$, $\delta m_g \simeq -0.077\Delta\lambda_{\text{eff}}/(100 \ \text{Å})$, $\delta m_r \simeq -0.044\Delta\lambda_{\text{eff}}/(100 \ \text{Å})$, $\delta m_i \simeq -0.032\Delta\lambda_{\text{eff}}/(100 \ \text{Å})$, $\delta m_z \simeq -0.024\Delta\lambda_{\text{eff}}/(100 \ \text{Å})$, where $\Delta\lambda_{\text{eff}}$ is the change in the effective wavelength between the two systems considered, for the BD+17$^\circ$ 4708 spectrum. For stars with $g - r < 0.6$ it is smaller than $-0.01 \ \text{mag}$, but increases to $-0.05 \ \text{mag}$ for $g - r \approx 1$, and it can be as large as $-0.5 \ \text{mag}$ for very red stars such as $g - r \approx 1.6$. Therefore, caution is necessary when one deals with red stars. The time variations of the main imager are shown in the lowest two panels of Figure 10 (they are shown column by column). Panels (v) represent brightness of BD+17$^\circ$ 4708 with 1.3 air mass atmosphere. In order to show the time-dependent variation of the sensitivity, we also show in panel (iv) the CCD output, ~ $-2.5 \ \log N_{p.e.}$, i.e., Equation (3) where the denominator is
replaced by unity, so that it represents the variation of the number of photoelectrons in CCD (using the response function without atmosphere). With the brightness definition this variation is largely canceled by the denominator in Equation (3): brightness of objects (magnitude) is sensitive solely to the shift of the effective wavelength. The decline of the CCD sensitivity in the $u$ band seen in Figure 10 (iv) is as much as $30\%$ (or $≈0.3$ mag; somewhat smaller if $1.3$ air mass atmosphere is excised), which agrees with the size we expect from the change of the response function seen in Figure 9(a). This is reduced to a $−0.03$ mag (in the opposite sign) change in magnitude if the brightness definition is used (Figure 10(v)), and such a variation should further be reduced by calibration procedures. For other color bands, the change of the sensitivity is $0.01$ mag for $g$ and $r$, and $0.03$ mag for $i$ and $z$. These variations are also largely canceled by the denominator in Equation (3), and the variation in brightness is smaller than $0.01$ mag, which could in principle be further reduced by calibration procedures. Note that the numbers given here are color dependent and apply only to BD$+17^\circ 4708$. The calibration would reduce these variations by enforcing measured brightness to the SDSS reference magnitudes obtained at USNO. When one is interested in sub-percent accuracy photometry, separate treatments of Camcols are desired (Ivezić et al. 2007).

Similar considerations apply to colors. Each detector has a slightly different response function, which causes some tilts in color space. We estimate the magnitude difference at column $A$ of the camera relative to the $2.5$ m reference $Δm_A = m_A − m_{\text{ref}}$ as a function of color in Figure 12 for the five colors, where the stars used are taken from the spectrophotometric atlas by Gunn & Stryker (1983). The variation is largest in the $u$ and $z$ bands. It can be as much as $0.02$ mag, especially for red stars. The variation is also fairly large for $g$ and $r$. For others, it is mostly smaller than $0.01$ mag. We see that $Δm$ nearly vanishes for $g − r ≃ −0.5$ for $g$, and for $g − r ∼ 0$ for $r$ and $i$. These variations are without calibration and are reduced by photometric calibrations.

We then consider the difference of colors that depends on associated telescope systems used. Figures 13–15 show the color–color plot written in the form $Δ(j−k)_{\text{AB}} = (j−k)_{\text{systemA}}−(j−k)_{\text{systemB}}$ as a function of $(j−k)_{\text{USNO}}$ to enhance the scale of the difference which is tiny. Here, $j$ and $k$ stand for $u$, $g$, $r$, and $i$, and $A$ and $B$ are two different systems. Again, Gunn–Stryker’s spectrophotometric atlas is used for the sample. This represents the bare system–dependent color term of each system. Figure 13 is the color term of the USNO system against the F96 original standard, Figure 14 is that of PT against USNO, and Figure 15 is the $2.5$ m telescope imager (reference) against the USNO. Note that color measured with PT, and hence with the $2.5$ m telescope imager, is adjusted to that with the USNO system for some set of standard stars in the calibration procedure (Smith et al. 2002; Tucker et al. 2006). The output of the $2.5$ m telescope...
Figure 15. Expected offset of $u - g$ color between the 2.5 m reference and the USNO photometric system, $\Delta(u - g)_{AB} = (u - g)_{2.5\text{mreference}} - (u - g)_{USNO}$ plotted as a function of $u - g$. (b) The same as Figure 14(a) but for $g - r$. (c) The same as Figure 14(a) but for $r - i$.

is calibrated with stars measured by PT in secondary patches which are calibrated with some sets of the standard stars, which are given fixed values throughout all observations, and therefore variations are, in principle, largely canceled by this reset. The SDSS photometry is published after these calibrations against secondary standard stars.

To verify that the variations we have seen here have not directly propagated into the final SDSS output photometry catalogs, we show in Figures 16(a) and (b) the time variation of $r$ and $u$ magnitudes of stars in the SDSS catalog in a patch of 2.5 deg$^2$ (R.A. = 5°, decl. = 0°) taken from stripe 82 from the epoch 1999 July to 2004 January. The difference from the mean is calculated for 600 stars with $r < 18$ for $r$ and 200 stars with $u < 18.5$ for $u$ by tracing photometry in time taken from Data Release 6 Supplement. The error bars indicate the variance in the sample. We see that both $r$ and $u$ magnitudes are very stable, the variation being less than 0.01 mag. In particular, the large variation expected for the $u$ band sensitivity ($\Delta u \simeq 0.3$ mag) between years 2000 and 2004 does not appear in Figure 16(b).

We confirmed that this is also true with brightness in other color bands.

To differentiate the aging effect possibly seen in the $u$ band, we consider the variation of $u - g$ color, as a function of $g - i$ color. Most of the variation in the $u$ band is absorbed into a time-varying constant adjusted in the calibration, but the color effect is suspected to remain in the final catalog, since the photometric calibrations do not take account of the color term. The time variation in $u - g$ colors seen in photometry of stars at stripe 82 (Ivezić et al. 2007) is plotted in Figure 17. The figure shows the mean differences of $u - g$ measured in the first four years of the survey (1998–2002) and the later four years (2004–2007) as a function of $g - i$ color. We note that it is so adjusted in the calibration that $\Delta(u - g)$ is zero as a matter of principle for stars of normal color, which are used to determine the zero points in $u$ and $g$. $\Delta(u - g)$ is about $-0.01$ mag for blue stars ($g - i \sim -0.2$) and is about $-0.01$ mag for red stars ($g - i \sim 2$). This difference can be larger, as much as $-0.02$ mag, for extremely red stars (we note that $g - r \approx (g - i)/1.2$). This is compared with the plot (shown by crosses) that shows the expected variation using spectral synthesis of Gunn–Stryker stars between 2001 and 2004. We conclude that photometry is consistent with what is expected from the secular variation of the response function, although the variation is small, of the order of 0.01 mag except for extreme colors. We expect a larger change for very blue stars, but we have no appropriate sample of such stars in our database. We confirmed that the variation was no more than 0.005 mag for $g - r$, $r - i$, and $i - z$.

Another way to find the instrumental variation in observational data, e.g., such as variations due to aging of the $u$-band detectors, may be to look at the nightly calibration monitor data.
for the so-called a-term, the difference in the nightly zero point between the atmospheric extinction corrected instrumental magnitude and the magnitude taken as the standard (Tucker et al. 2006). This may directly measure the sensitivity of the system. Figures 18(a) and (b) show this term as a function of the epoch of observations. In the $u$ band (Figure 18(b)), we observe a rapid change as much as 0.4 mag from MJD 51000 (1998 July 5) to MJD 52200 (2001 November 6), and a gradual decline then to MJD 53200 (2004 July 13). The trend and size are consistent with what is anticipated from the aging effect. We also observe some change in the $r$ band (Figure 18(a)), to at most 0.1 mag, the reason of which is not clearly identified.

5. SUMMARY

We have described the in situ measurement of the response functions of the SDSS 2.5 m telescope imager, which has been used to produce the SDSS astronomical catalogs during the period from 2000 to 2007. We then discussed the effect of

Figure 17. Time variation of $u-g$ colors in repeated photometry at stripe 82 (Ivezić et al. 2007) is shown by filled circles. All the non-variable stars with $u < 21$ were used. Crosses show color variation $\Delta (u-g)$ expected for Gunn–Stryker stars between the 2001 (taken as the zero point) and the 2004 measurements as a function of $g-i$. The error bar is the mean and variance of the data in each color bin.

Figure 18. Nightly variation of the instrumental photometric zero points of 2.5 m photometry in the $r$ band. (b) The same as panel (a) but in the $u$ band.
variations of the response function on photometry. We also presented the outline of the monochromatic illumination system constructed for this purpose.

We studied the variation of the response functions from column to column and also in time over the duration of the survey, both secularly (aging) and with environmental temperature. We presented the reference response function of the 2.5 m telescope imager as a mean over the six columns of the imager. We showed the detection of a significant aging effect for the $u$ band, especially in the short wavelength side, which amounts to about a 30% decrease in the sensitivity over the period of the survey.

We confirmed, however, that brightness appears to be invariable to 0.01 mag over the years, and the SDSS catalogs are likely to be accurate to this level: we confirmed that the error caused by variations of the response function is not a dominant component of the error in photometry. Time variability was also detected for the response function for other color bands, but it is small and well within our tolerable errors. The variation other than that for the $u$ passband is ascribed mostly to the temperature dependence of transmission properties of the color glass that composes the filters.

We have studied the seasonal, secular, and column-to-column variations of the response function and their effects on photometry. We also studied the effect of the use of the associated systems that have slightly different response functions in the SDSS photometric calibration procedure. We have verified that the effect of the variation of the response function, which may amount to 0.01 mag in $g$, $r$, $i$, and $z$ bands and, and variations among six different devices of the imager, which also amount to 0.01–0.02 mag, are canceled very well by calibration procedures, and do not appear in the final SDSS catalogs; the residual effects are not larger than 0.01 mag for all passbands. We have expected sizable aging effects in the response function for the $u$ band, but photometric calibrations absorb most of variations, and the variation visible in the SDSS catalog is small. The variation of $u - g$ colors is of the order of $\Delta(u - g) \sim 0.01$ mag except for stars with extreme colors for which it can be 0.02 mag.

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