



# HYPERCALIBRATION: A PAN-STARRS1-BASED RECALIBRATION OF THE SLOAN DIGITAL SKY SURVEY PHOTOMETRY

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## ABSTRACT

We present a recalibration of the Sloan Digital Sky Survey (SDSS) photometry with new flat fields and zero points derived from Pan-STARRS1. Using point-spread function (PSF) photometry of 60 million stars with  $16 < r < 20$ , we derive a model of amplifier gain and flat-field corrections with per-run rms residuals of 3 millimagnitudes (mmag) in *griz* bands and 15 mmag in *u* band. The new photometric zero points are adjusted to leave the median in the Galactic north unchanged for compatibility with previous SDSS work. We also identify transient non-photometric periods in SDSS (“contrails”) based on photometric deviations co-temporal in SDSS bands. The recalibrated stellar PSF photometry of SDSS and PS1 has an rms difference of {9, 7, 7, 8} mmag in *griz*, respectively, when averaged over 15′ regions.

*Key words:* methods: data analysis – surveys – techniques: photometric

## 1. INTRODUCTION

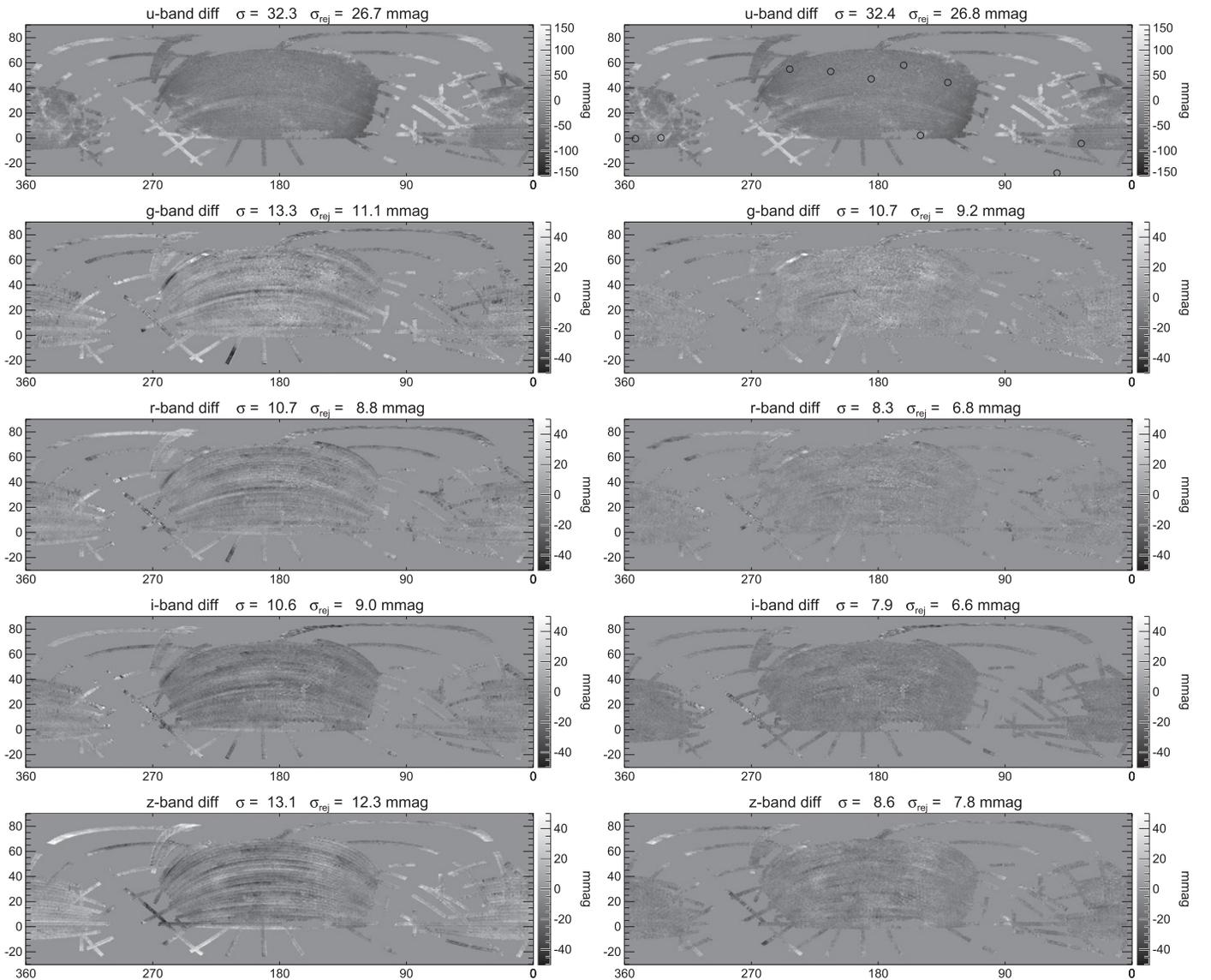
One of the challenges of wide-field surveys is ensuring the uniformity of photometric calibration over the survey area. The traditional approach of calibrating to networks of standard stars requires a transfer of calibrations between systems that would require perfect knowledge of both the bandpasses and the stellar spectral energy distributions (SEDs) to avoid introducing systematic errors. Furthermore, standard stars are typically too bright to be observed accurately under survey conditions, introducing additional steps in the calibration process.

The Sloan Digital Sky Survey (SDSS; York et al. 2000) took a different approach to the calibration problem, now generally referred to as “ubercalibration” (Padmanabhan et al. 2008). The underlying idea is simple: the flux from a star is assumed to be constant,<sup>10</sup> and therefore comparisons of instrumental flux in repeat observations can be used to infer calibration parameters. By construction, such comparisons are all done on a consistent photometric system and using comparable observations, obviating the need for bandpass transformations between the standard system and the survey system. Indeed, nearly every multiply observed star in the survey plays the role of a “standard” star without detailed knowledge of its SED. Such an algorithm is based on differences in magnitude and can only determine relative calibrations up to an overall offset, cleanly separating the problem of relative calibration from that of absolute calibration to, e.g., AB magnitudes (Oke & Gunn 1983) or physical units.

This calibration scheme requires a network of overlapping observations that connect the entire survey area. The SDSS camera is found to have a nearly stable photometric zero-point during a night, with small drifts in the atmospheric extinction parameterized by a time derivative term ( $k$ ). This stability allows widely separated regions of sky to be connected by a single hours-long drift scan. This spatial and temporal structure of overlapping observations ultimately determines the complexity of the calibration model and therefore the photometric accuracy available. Padmanabhan et al. (2008) present a detailed discussion of the various degeneracies possible due to insufficient overlaps. Since the SDSS was not designed with ubercalibration in mind, imaging overlaps are limited to overlaps of interleaved “strips,” and the survey poles where the imaging great circles converge. A set of fast scans with the SDSS camera, binned  $4 \times 4$ , were obtained from 2002 May to 2004 April that cross the main survey scans nearly perpendicularly, but the bulk of these photometric data span only  $23 \text{ hr} < \text{R.A.} < 8 \text{ hr}$ . The addition of 3000 square degrees of imaging in the south Galactic cap, released as part of SDSS-III Data Release 8 (Aihara et al. 2011), is only weakly connected to the main SDSS-I/II observations in the north Galactic cap. The low number of drift scans connecting the Galactic south with the Galactic north results in uncertainty in their relative calibration.

At the time the SDSS ubercalibration was released, it was not possible to directly determine the achieved spatial uniformity of the calibration. Using simulations, Padmanabhan et al. (2008) estimated the lower bound on these errors to be  $\sim 8$  millimagnitudes (hereafter mmag) in the *g*, *r*, *i*, and *z* bands and  $\sim 13$  mmag in the *u* band. Consistent estimates of the

<sup>10</sup> We ignore variability, which can be mitigated by averaging multiple stars in a given region with appropriate outlier rejection.



**Figure 1.** Left panels: the mean difference (PS1 minus SDSS) in 15 arcmin pixels using the color transformations defined in Section 2.4. In dark regions, SDSS underestimates the stellar fluxes. Stripes corresponding to the SDSS scan pattern are readily apparent, as well as offsets between Galactic north and south. The  $u$ -band difference map involves an extrapolation from  $g_{\text{p1}}$  and is far more sensitive to metallicity and extinction than the other bands. The rms of the difference per 15' pixel is given, with and without  $3\sigma$  outlier rejection. Note the increased grayscale range in  $u$ -band. Right panels: same as left panels, but after the recalibration described in Section 3. Striping is reduced, and the north-south offsets removed. The calibration is adjusted to preserve the median magnitude at  $b > 20^\circ$  so as to minimally perturb SDSS results in the northern Galactic cap (see Section 3). Dust cirrus is visible in the top panels, as it affects the extrapolation from PS1 bands to  $u$  band more than the other bands. Because of this, and possible gradients due to metallicity variations, we do not apply zero-point corrections to  $u$  band. Positions of the 10 Medium-Deep Fields are indicated by black circles in the upper right panel.

calibration errors have been obtained by Schlafly et al. (2010) using the blue tip of the stellar locus, but the direct interpretation of these results as calibration errors is complicated by spatial variations in the properties of stellar populations, e.g., metallicity. This paper presents an astrophysics-free estimate of the spatial uniformity of the SDSS calibration by direct comparison with data from the Pan-STARRS1  $3\pi$  survey. Pan-STARRS1 has the great advantage that it observed the survey footprint 6–8 times in each filter, providing high redundancy. Furthermore, ten “Medium-Deep” fields (MD01–MD10 in Tonry et al. 2012a) were observed hundreds of times per filter with longer exposures, resulting in a photometric solution far more rigid than that of SDSS. See upper-right panel of Figure 1 for MD field locations.

We find that the SDSS achieves the claimed photometric stability of (20, 10, 10, 10, 20) mmag in ( $ugriz$ ) in the north Galactic cap, but contains spatially coherent offsets on the scale of fields, runs, and even hemispheres (Figure 1), as well as a small fraction of significant non-Gaussian outliers. In the following, we present a new determination of flat fields and per-run offsets based on the comparison to PS1. We emphasize that it is the rigidity of the PS1 solution on large angular scales, *not* a superior per-exposure stability, that makes it an excellent foundation upon which to build an improved calibration of SDSS. Indeed, neither the statistical uncertainties nor systematic errors on small scales in PS1 are very much better than SDSS, but they are *different*.

The SDSS calibration also fails to capture short periods of non-photometricity caused by small clouds or contrails. We

identify sudden (in SDSS observation time) deviations in the PS1-SDSS difference and record them in two new CALIB\_STATUS mask bits.

In Section 2 we present the SDSS and PS1 data, the sample of stars, and color transformations between the systems. The new calibration is presented in Section 3, and detection of unphotometric periods of time is described in Section 4.

## 2. DATA

### 2.1. SDSS

The SDSS has been in operation since 1998, and is now in its third phase (SDSS-III). It uses a dedicated 2.5 m telescope (Gunn et al. 2006) at Apache Point Observatory in New Mexico to perform a variety of surveys. In this work, we use photometry from a 30 CCD camera with 1.5 deg<sup>2</sup> effective field of view (Gunn et al. 1998) that imaged 14,555 deg<sup>2</sup> (about 35%) of the sky in 5 broad bands (*ugriz*) (Fukugita et al. 1996) between 1998 September and 2009 November, after which the camera was retired from operation. The CCDs are arranged with one chip per band in each of 6 *camera columns*, and operate in a drift-scan mode such that objects pass over the 5 filters in a period of 5.4 minutes. A contiguous period of drift scan is a *run* and may last for up to 10 hr. The region imaged by the 6 camera columns is a *strip* with 6 regions 13'.5 wide separated by gaps of 12'.5. A subsequent strip fills in these gaps, and together the two strips constitute a *stripe* 2°.5 wide. Objects are detected and characterized by a photometric pipeline (Lupton et al. 2001) and astrometric and photometric calibrations are applied (Pier et al. 2003; Ivezić et al. 2004; Tucker et al. 2006; Padmanabhan et al. 2008). As of Data Release 8 (DR8; Aihara et al. 2011), the imaging survey was completed. We use DR9 photometry (Ahn et al. 2012), which is identical to DR8 except for its astrometric calibration tying the full survey to UCAC 2.0 (Zacharias et al. 2004; details at <http://www.sdss3.org/dr9>). To emphasize that the photometry is identical for the two data releases, we refer to them hereafter as DR8/DR9. We use the `calibObj` files,<sup>11</sup> trimmed versions of the `photoObj` files containing the most commonly used parameters, and separated into star and galaxy files. There is one stellar `calibObj` file for each run+camcol. DR8/DR9 contains 764 runs.

We reject objects with flag bits 2, 11, 18, 22, and 43 set, corresponding to `EDGE`, `DEBLEND_TOO_MANY_PEAKS`, `SATUR`, `BADSKY`, and `SATUR_CENTER`, respectively. Because of many levels of outlier rejection, our results are not sensitive to these choices.

### 2.2. Pan-STARRS1

The Pan-STARRS1 (Pan-STARRS1)  $3\pi$  survey (Kaiser et al. 2010) and (K.C. Chambers et al. 2016, in preparation) is a systematic imaging survey of 3/4 of the sky north of  $\delta = -30^\circ$  in five optical and near-infrared photometric bands ( $g_{P1}r_{P1}i_{P1}z_{P1}y_{P1}$ ; Tonry et al. 2012b). The survey is conducted with a 1.4 billion pixel, 3°.3 field of view camera (Onaka et al. 2008; Tonry & Onaka 2009) on a dedicated 1.8 m telescope (Hodapp et al. 2004) located on Haleakala, Hawaii. Any location in the survey is observed repeatedly for a planned four times per year per filter, conditions permitting, with exposure times of 43/40/45/30/30 s in the

$g_{P1}/r_{P1}/i_{P1}/z_{P1}/y_{P1}$ -bands, respectively (Metcalf et al. 2013). The median FWHM values in these bands are 1.27/1.16/1.11/1.06/1.01 arcsec. Images are automatically processed through the Image Processing Pipeline (Magnier 2006, 2007; Magnier et al. 2008) to produce the object catalog. The data set used for this work includes three consecutive seasons of observing, yielding up to twelve exposures per filter. Chip and cell gaps, variable observing conditions, and technical problems cause the survey depth to vary from place to place. For point sources,  $5\sigma$  limits for the  $3\pi$  survey (single exposure) are 22.2, 22.2, 22.0, 21.2, 20.1 in *grizy<sub>P1</sub>*, respectively. For comparison, SDSS has stellar  $5\sigma$  depth of 22.2, 23.1, 22.7, 22.2, 20.7 in *ugriz*.

The PS1 focal plane has 60 OTA *chips*, each of which is an  $8 \times 8$  grid of independently addressable *cells*. The Pan-STARRS1  $3\pi$  survey covers the entire SDSS footprint, to similar depth in similar filters (except *u*-band), allowing a straightforward comparison between the two surveys after modest color transformations Section 2.4.

The Pan-STARRS1 photometric calibration (Schlafly et al. 2012) minimizes the variance of repeat measurements of stars in much the same way as the SDSS ubercalibration. Schlafly et al. fit for a flat field (in  $2 \times 2$  cell regions), as well as a zero point and atmospheric extinction term per night. On nearly every night, PS1 observes a few of the 10 medium deep (MD) fields, which have been observed hundreds of times per filter on dozens of nights. These serve as *de facto* standard star fields in the calibration, providing a rigid foundation on which to build the photometric solution for the entire  $3\pi$  survey. Because of this, and the multiple coverings of the  $3\pi$  area, the PS1 solution is more rigid on large angular scales, tying the northern and southern Galactic hemispheres together much better than SDSS. As an estimate of the photometric stability of this solution, the zero points of repeat visits to the MD fields vary by less than 5 mmag in *griz<sub>P1</sub>* (Schlafly et al. 2012, Section 3.1). On small (sub-degree) scales, the PS1 photometry may not be more stable than SDSS, but the two surveys have uncorrelated systematic errors, allowing precise derivation of SDSS photometric parameters by comparison to PS1.

### 2.3. Matching Catalogs

We match PS1 objects to SDSS detections of point sources (`objc_type = 6`) with  $16 < r_{SDSS} < 20$ , using a match radius of 1". This is not a list of unique stars; stars observed multiple times by SDSS are multiply counted in the following. Of 118,582,000 matches, we select 111,980,000 that pass the cuts on flags described above. We discard stars within 15° of the Galactic plane because of difficulty with high stellar density and with color transformations in regions of high dust reddening, leaving 81,068,000 stars, or 72.4% of the selected stars.

Approximately 11% of the SDSS sample is marked unphotometric (by `CALIB_STATUS` bit 0, see Table 1 and the SDSS-III web site)<sup>12</sup>, and we exclude these stars from determination of the flat fields. In terms of sky area, the fraction of photometric fields containing stars with  $|b| > 15^\circ$  is 87.5% (813912/929827). This corresponds to 27451 deg<sup>2</sup> of 31360 deg<sup>2</sup>, much larger than the actual survey footprint because of run overlaps and repeated scans of the equatorial stripe.

When deriving new photometric offsets for runs, we require at least 3° of the scan to be photometric and at  $|b| > 15^\circ$ . If

<sup>11</sup> Schema at <http://data.sdss3.org/datamodel/files>.

<sup>12</sup> [http://www.sdss3.org/dr8/algorithms/bitmask\\_calib\\_status.php](http://www.sdss3.org/dr8/algorithms/bitmask_calib_status.php)

**Table 1**  
Calib\_Status Bits

CALIB_STATUS Bit Name	Bit	Description
PHOTOMETRIC	0	Photometric observations
UNPHOT_OVERLAP	1	Unphotometric observations, calibrated based on overlaps with clear, ubercalibrated data; done on a field-by-field basis. <i>Use with caution.</i>
UNPHOT_EXTRAP_CLEAR	2	Extrapolate the solution from the clear part of a night (that was ubercalibrated) to the cloudy part. <i>Not recommended for use.</i>
UNPHOT_EXTRAP_CLOUDY	3	Extrapolate the solution from a cloudy part of the night (where there is overlap) to a region of no overlap. <i>Not recommended for use.</i>
UNPHOT_DISJOINT	4	Data is disjoint from the rest of the survey. Even though conditions may be photometric, the calibration is suspect. <i>Not recommended for use.</i>
INCREMENT_CALIB	5	Incrementally calibrated by considering overlaps with ubercalibrated data
<b>PS1_UNPHOT</b>	<b>6</b>	<b>PS1 comparison reveals unphotometric conditions</b>
<b>PS1_CONTRAIL</b>	<b>7</b>	<b>PS1 comparison shows slightly unphotometric conditions</b>
PT_CLEAR	8	(INTERNAL, DR8 and later) PT calibration for clear data
PT_CLOUDY	9	(INTERNAL, DR8 and later) PT calibration for cloudy data
DEFAULT	10	(INTERNAL, DR8 and later) a default calibration used
NO_UBERCAL	11	(INTERNAL, DR8 and later) not uber-calibrated
INTERNAL	12	(INTERNAL USE)
<b>PS1_PCOMP_MODEL</b>	<b>13</b>	<b>PS1 Used PCA model for flats</b>
<b>PS1_LOW_RMS</b>	<b>14</b>	<b>PS1 comparison to SDSS has low noise</b>

**Note.** New ones are bold.

these criteria are not met, we use all stars in the run to determine the offset anyway, but flag the offset as unreliable. 675 of 764 runs (88%) satisfy these criteria.

A rejection algorithm is applied to remove variable objects such as variable stars and quasars that would degrade the calibration measurements. For each band, we reject objects with  $\sigma > 0.05$  mag in that band, and require at least one good measurement in at least 4 PS1 bands. For the  $u$ -band comparison we also require  $S/N > 10$  in  $u$ -band. After these cuts, the catalogs contain 24.7 M, 47.5 M, 60.0 M, 61.8 M, 59.3 M stars, respectively, in the  $ugriz$  fits.

#### 2.4. Color Transformations

The SDSS  $griz$  filters are similar to the  $g_{P1} r_{P1} i_{P1} z_{P1}$  filters, but not identical. We apply a correction to transform the PS1 magnitudes to the SDSS system, and then compare with SDSS magnitudes. This transformation is defined as a function of PS1 magnitudes so that it is stable as we alter the calibration of the SDSS magnitudes in each run. The transformation itself was determined from measurements in PS1 Medium Deep Fields 9 and 10, which overlap SDSS stripe 82. The high redundancy in these fields in both surveys provides a very low noise measurement of the color transformation parameters, with an rms per-star residual of 7 mmag. We find that the color transformation is stable from year to year and field to field at the 3 mmag level. These transformations are a function of  $g - i$  color, which behaves better than transformations based on  $g - r$  or  $r - i$ , as long as both  $g_{P1}$  and  $i_{P1}$  are well measured. For fainter stars,  $g - r$  is better for blue stars and  $r - i$  is better for red stars, which may have no  $g$ -band detection.

The transformations are third-order polynomials in  $x \equiv g_{P1} - i_{P1}$ , with coefficients given in Table 2.

$$m_{p1} - m_{sdss} = a_0 + a_1x + a_2x^2 + a_3x^3. \quad (1)$$

They are valid for main-sequence stars with  $0.4 < x < 2.7$ . Coefficients are provided for  $g_{P1} - u_{sdss}$  and  $y_{P1} - z_{sdss}$  for completeness, with the caveat that these extrapolations are

**Table 2**  
Color Transformation Coefficients for the `qx_noref` Ubercalibration of the PV1 Processing Used in This Work

Band	$a_0$	$a_1$	$a_2$	$a_3$
$u$	0.04438	-2.26095	-0.13387	0.27099
$g$	-0.01808	-0.13595	0.01941	-0.00183
$r$	-0.01836	-0.03577	0.02612	-0.00558
$i$	0.01170	-0.00400	0.00066	-0.00058
$z$	-0.01062	0.07529	-0.03592	0.00890
$y$	0.08924	-0.20878	0.10360	-0.02441

much less reliable than the  $griz$  transformations. In particular, the extrapolation from PS1 colors to  $u$  band is strongly metallicity dependent, and should be used with caution. The corrections are typically 0.01 mag in  $r$  and  $i$ , up to 0.1 mag in  $z$ , and up to 0.25 in  $g$ . These transformations, along with transformations as a function of other colors and their inverses are presented by ?.

### 3. A NEW CALIBRATION

#### 3.1. Run Zero Points

Using matched PS1 and SDSS detections of stars described in Section 2.3, and applying the color corrections described in Section 2.4, we compute the PS1 minus SDSS difference for each SDSS detection. A grayscale map of this difference exhibits obvious stripes along SDSS drift scans (Figure 1).

For each SDSS band, we obtain the zero-point offset for each run by computing the median difference. This provides a robust estimate if the atmospheric extinction is stable during the run. The airmass terms ( $k$ -terms) in the SDSS ubercal are generally well constrained, but on nights with a small range in airmass they may be nearly degenerate with that night's zero point. In these cases, poorly constrained  $k$ -terms can propagate to other areas of the SDSS footprint that have low redundancy, such as survey edges or disjoint regions. Such problems affect a small fraction of the data (Figure 1).

**Table 3**  
Median PS1 Minus SDSS Magnitudes in the North ( $b > 20^\circ$ ), South ( $b < -20^\circ$ ), and the Difference, Based on the Color Transformations Given in Section 2.4

Band	North (mmag)	South (mmag)	North–South (mmag)
<i>u</i>	−45.10	−18.81	−26.29
<i>g</i>	1.18	3.45	−2.27
<i>r</i>	−2.14	2.71	−4.85
<i>i</i>	−9.15	−1.29	−7.86
<i>z</i>	−5.24	7.41	−12.66

**Note.** These shifts are with respect to the median in the MD09 and MD10 reference fields, where the color transformations were originally determined. The *griz* north offsets are included in the color terms in Table 2 (see Section 3.1).

The SDSS ubercal was not able to fit a time variation in the airmass term ( $\dot{k}$ ) on a per-run basis. However, the Photometric Telescope (Hogg et al. 2001) adjacent to the survey telescope observed standard star fields continuously and obtained  $k$  and  $\dot{k}$  for every night. A systematic tendency for the atmosphere to become more transparent during the night was found, and a mean PT-derived  $k$  per band was included in the ubercal solution. The  $\dot{k}$  values of approximately  $1 \text{ mmag hr}^{-1} \text{ airmass}^{-1}$  from the earlier calibration (Table 3 of Padmanabhan et al. 2008) have been preserved.

In order to minimize discrepancy with previous SDSS research, we have adjusted the zero points derived above to preserve the median SDSS calibration in the Galactic north. In other words, if the color transformations in Table 2 are used, the median  $b > 20^\circ$  PS1 minus recalibrated SDSS difference is zero in *griz*. The difference between north and south offsets is a few mmag in *g* and increases in redder bands, reaching 13 mmag in *z* band (Table 3). Assuming the PS1 offsets are correct, this implies that SDSS magnitudes were too small (objects were too bright) in the Galactic south relative to the north.

The *u*-band shift is strongly metallicity dependent and is therefore not necessarily indicative of a photometric offset. It has *not* been applied and is uncertain by several hundredths of a magnitude.

### 3.2. Flat Fields

The updated zero points reduce the stripe residuals along SDSS scans (Figure 1), but significant smaller structure remains, motivating an examination of the SDSS flats. The SDSS drift scan technique averages over pixel rows on each CCD, making the flat a 1D function of pixel column. We understand the flat to include pixel sensitivity, filter response, and amplifier gains. Most SDSS chips have 2 amplifier readout, and they are usually stable to within  $\sim 1$  mmag but in some cases are observed to jump suddenly by  $\sim 5$  mmag with respect to each other.

For each run+chip, the differences are sorted into 64 bins in CCD pixel column (32 pixels per bin) to determine the *flat residual*,  $F_r$ .  $F_r$  is simply the median difference for “good” stars in each of the 64 bins. We distinguish between the observed flat residual and the *flat correction*, which is a model of it to be applied in the recalibration.

The flat residuals are generally stable in time, but with some sudden jumps. These jumps usually occur on the “season”

boundaries established previously (Padmanabhan et al. 2008), although we use a subset of these seasons: 8 seasons ending at MJD 51251, 51865, 52144, 52872, 53243, 53959, 55090, and 55153. These boundaries correspond to run numbers 725, 1869, 2504, 4069, 4792, 6245, 8032, and 8162. We compute a median flat correction  $F_s$  per season/chip, and use that as a basis for the flat model. In each season, the residuals  $F_r$  scatter about  $F_s$  with an rms of 2–3 mmag (Figure 2).

This does not remove all the structure in the flat residuals, so we model the remaining structure with a principal component expansion, one chip at a time (see Figure 3 for a comparison of the residuals before and after correction). We compute principal components of the residuals (after subtracting the season medians) for all runs with more than 10 good stars (according to CALIB\_STATUS bit 0) in each of the 64 camcol bins, a criterion that rejects runs without significant photometric data. For each run, we fit coefficients for the first 4 principal components and add these components to the per-season flat correction for that run. For short or unphotometric runs that do not have 10 good stars in each 32 pixel camcol bin, we simply apply the per-season flat correction and record this choice in CALIB\_STATUS bit 13. If the rms residual for a run is less than twice the median rms residual for all runs, the run is deemed to have low noise, and we set CALIB\_STATUS bit 14 (see Table 1). We repeated this entire procedure using 1–6 PC coefficients, and found by inspection that 4 PCs were adequate to remove the apparent structure in the flat residuals.

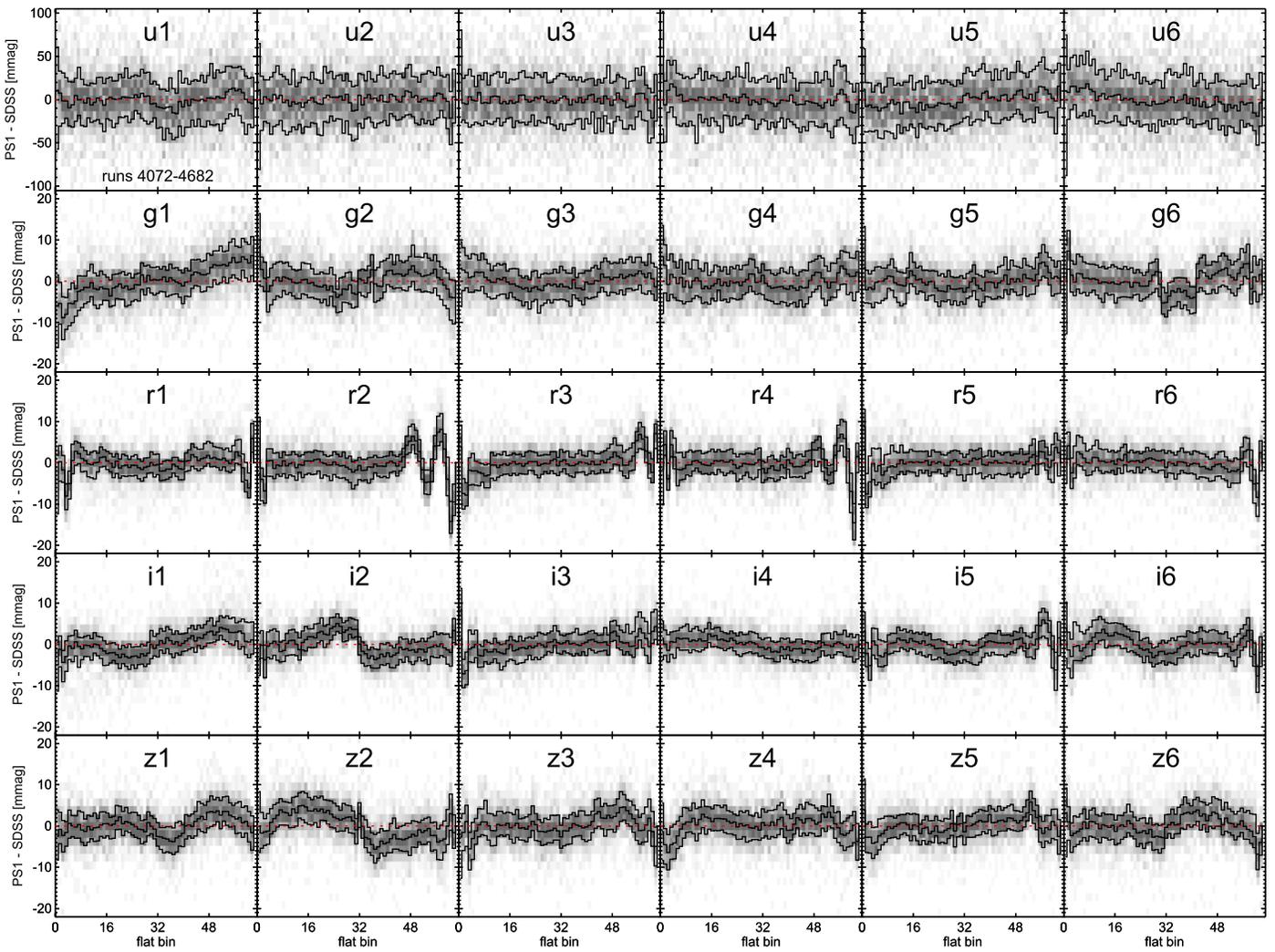
These models yield residuals  $\sigma_{\text{rej}}$  of 2–3 mmag in *griz* bands (Figure 4). The distribution has many-sigma outliers at the 1% level, but they are in all cases  $< 20$  mmag. Subject to the assumption that the flat is constant during a run, this implies that the flat is known at the  $\sim 3$  mmag level in *griz* and 15 mmag in *u*.

The extrapolation from  $g_{p1}$  to  $u_{\text{sdss}}$  is poorly defined, because of its dependence on stellar metallicity and dust extinction. Because metallicity gradients are on much larger scales than the features in the flat residuals and dust is uncorrelated with them, it is expected that we can get a good *u*-band flat anyway. We apply the updated *u*-band flat corrections, but do not alter the *u*-band zero points.

### 3.3. Validation

As an independent validation of our calibration, we use a spectroscopic sample of stars for which we have reddening estimates. The SDSS took spectra of over 1 million objects, including over 250,000 stars. The SDSS SEGUE Stellar Parameter Pipeline (SSPP; Lee et al. 2008) returns several estimates of the stellar type, including one based on the continuum-normalized spectrum, effectively using only line information and no information from the continuum or the *ugriz* photometry. This estimate is not affected by dust reddening or photometric calibration errors. Schlafly & Finkbeiner (2011) used these stellar types for 261,496 stars, along with appropriate spectral libraries, to estimate the true color of each star and subtract it from each broadband color to obtain a color excess. They interpreted the color excesses as dust reddening, and used them to argue that the Fitzpatrick (1999) reddening law is a good fit to the data, and to derive new calibrations for the Schlegel et al. (1998) map in 88 bands (Schlafly & Finkbeiner 2011, Table 6).

We use this same stellar sample to validate our current work. SDSS photometric calibration residuals also appear in



**Figure 2.** Distribution of per-run flat residuals (PS1 minus SDSS DR8/DR9 magnitudes) for the 2003–2004 observing season (runs 4072–4682) for each camera chip. The flat residuals are measured in 64 bins of 32 CCD pixels each, and represented as a grayscale image with (16, 50, 84) percentile lines. The oscillations in, e.g.,  $r_2$  and  $r_4$  are typical for these chips, and worsen as the survey progresses. Padmanabhan et al. (2008) approximated the flat with a 17-node B-spline, which could ring at this spatial scale. The 5 mmag dip in  $g_6$  is constant until it disappears suddenly in 2005. Jumps in the middle of two-amp chips often occur at the few mmag level (e.g.,  $i_2$ ,  $z_6$ ). The  $griz$  flats are stable to 2–3 mmag during a season, with  $u$ -band flats less well measured due to the extrapolation from  $g_{P1}$ . See supplemental materials for mean flats in every season.

the SSPP color residual, and we expect those residuals to be positively correlated with the correction we derive in Section 3. Because the per-star scatter is large, it is useful to bin in our correction (recalibrated magnitude minus DR8/DR9 magnitude) and plot the median and 16th, 84th percentiles (Figure 5). The median line in each panel has a slope of  $\sim 1/2$  in  $u-g$  and close to 1 in the other colors. Any noise in recalibrated color will spread the data points horizontally and cause the slope to be less than 1. It is not surprising that  $u-g$  is worse in this regard, since we did not apply zero-point corrections to  $u$  band. In the other bands, the PS1-based corrections are highly correlated with the correction implied by the SSPP sample.

#### 4. CONTRAILS

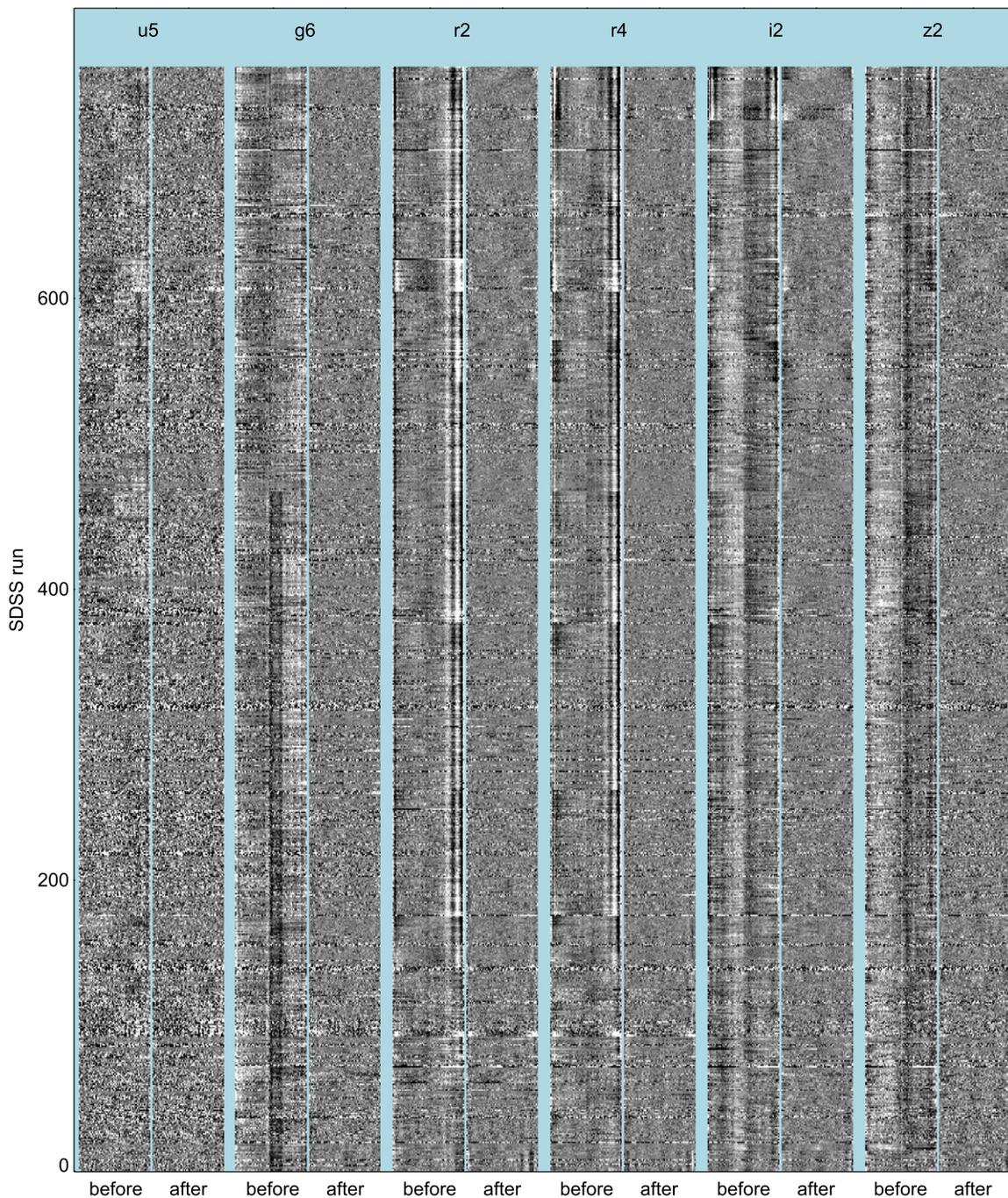
PS1 and SDSS attempt to censor unphotometric data, both during observations and later during calibration. Inevitably, some periods of non-photometricity persist in both data sets. Condensation trails from airplanes (“contrails”) are especially

pernicious, because they usually compromise photometry for only a single exposure (in PS1) or a frame or two of drift scan (in SDSS). In the following, we identify brief periods of unphotometric data in SDSS, and without loss of generality refer to them as contrails.

##### 4.1. SDSS Outliers

In Figure 6, dark patches are apparent, representing regions where SDSS stars are too faint relative to PS1. In most cases, these appear in groups of 5 or 6 in the cross-scan direction, with the same quarter-degree spacing as the SDSS camera columns. It is also clear from Figure 6 that similar features appear in multiple bands with slight offsets, consistent with the spacing between the  $griz$  chips in the SDSS camera. For example,  $i$  is observed 72 s after  $r$ , so a simultaneous deviation appears separated by  $18'$  on the sky. The bands are always observed in  $riuzg$  order.

For all 764 science runs in DR8/DR9, we compute the PS1 minus SDSS difference (including color terms) as a function of



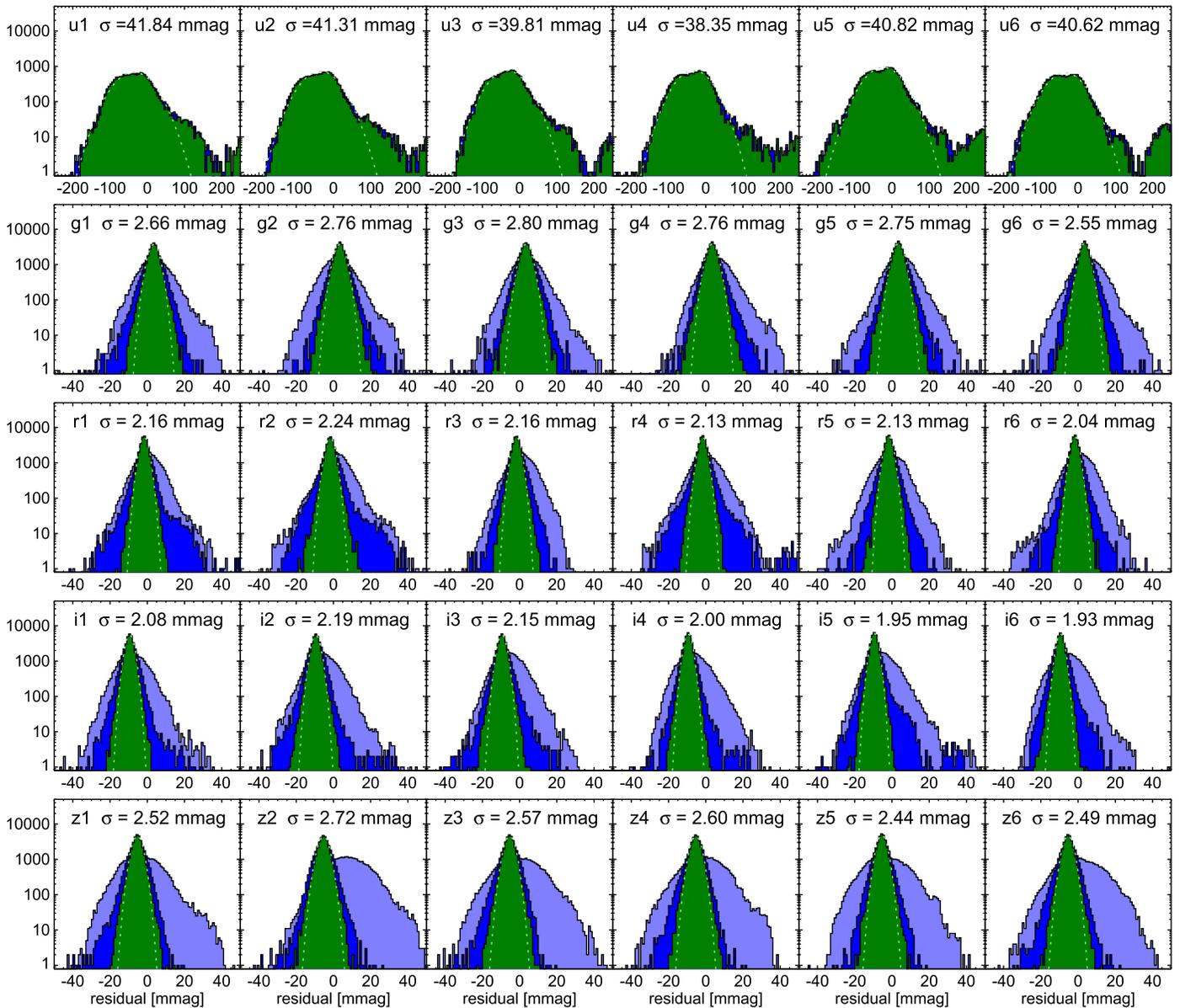
**Figure 3.** SDSS flat residuals for 764 runs, represented as a grayscale from  $-10$  to  $+10$  mmag ( $\pm 50$  mmag for  $u$ -band). Six of the 30 CCDs are shown. Each row of pixels corresponds to the median flat of an SDSS run, and each pixel column corresponds to 32 camera pixel columns, i.e., the 1D flat for a 2048 pixel wide chip is represented by 64 bins. In each case, the flat residuals “before” and “after” correction with the flat model of Section 3.2 are shown.

SDSS frame number for *griz* bands.<sup>13</sup> We flag deviations aligned in SDSS observation time as either “unphotometric” or “slightly unphotometric,” and set CABLIB\_STATUS bits 6 or 7, respectively. When all 4 bands are present (*griz*), we label a frame unphotometric if the median deviation in that frame is

<sup>13</sup> SDSS runs are split into *frames* according to observation time, and then offsets are applied to obtain *field* numbers corresponding to locations on the sky. In DR8/DR9, most runs begin with field 11, which is frame (15, 19, 11, 13, 17) in ( $u$ ,  $g$ ,  $r$ ,  $i$ ,  $z$ ) bands. Field 11 is generally the first field that has complete data in all five filters, and earlier fields (1–10) are discarded.

greater than 0.04 mag in at least two bands. If only 3 bands are present (e.g., near the beginning or end of a run), a single-band deviation of 0.04 mag is sufficient to be unphotometric. In either case, we pad the masked region by 1 frame. We recommend avoiding the masked frames for any work requiring accurate photometry.

For users desiring a more pristine sample, we define the “slightly unphotometric” mask bit. This bit is set when a frame has a deviation of at least 0.015 mag in 3 bands, or 0.025 in at least 2 bands. These criteria were chosen by



**Figure 4.** Flat residual histograms: the PS1-SDSS difference (light blue), difference after subtracting mean difference per run (dark blue), and difference after applying flat corrections (green), with outlier-rejected Gaussian fit (dotted line) with the rms given. The flat correction does little to tighten the core of the distribution, but dramatically suppresses outliers at  $5\sigma$ .

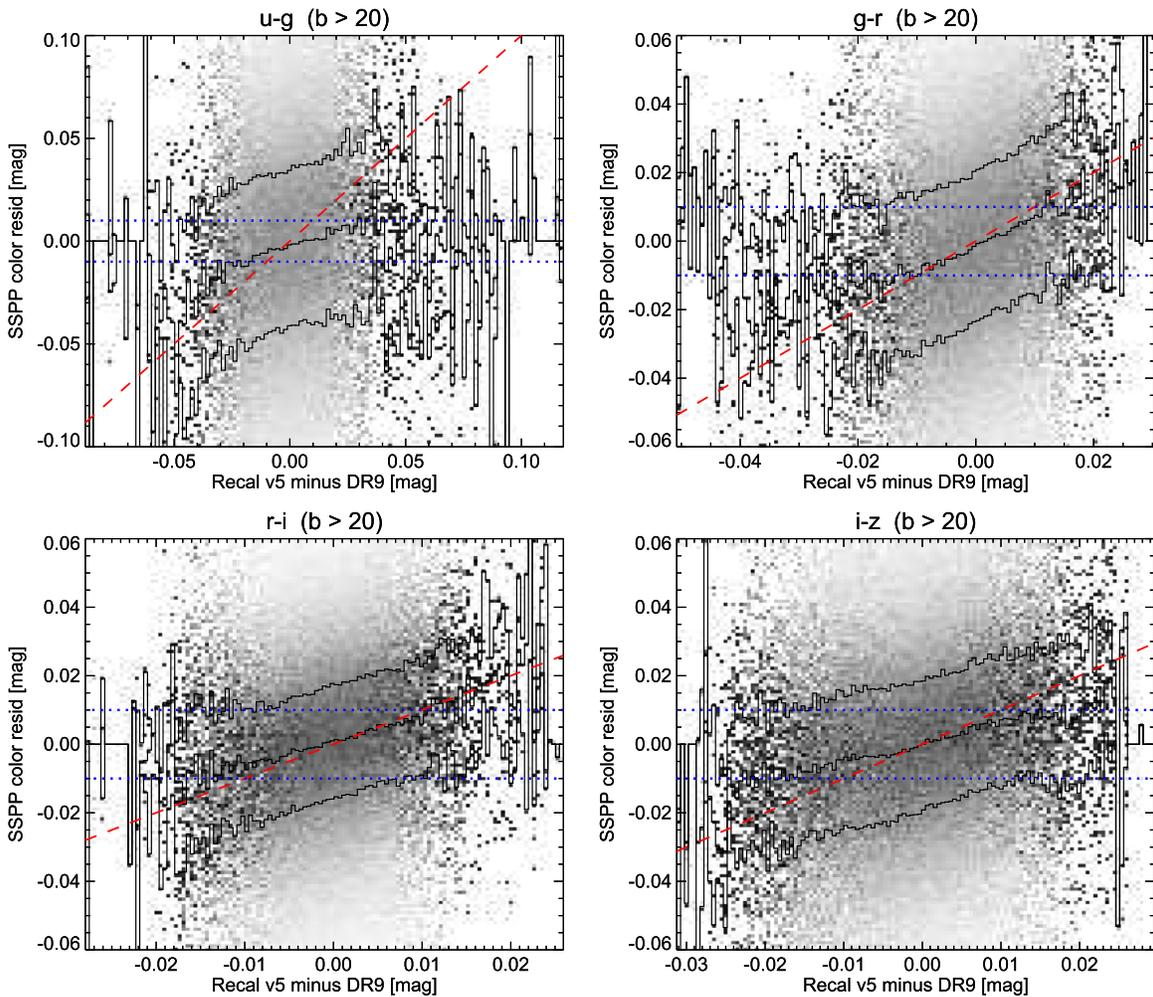
inspection, and strike a balance between catching most of the outliers and avoiding most false positives. As above, when only 3 bands are available, the criteria are loosened by one band. This loosening increases the chance of a false-positive at the beginning or end of a run, which is sensible given that a run might end because clouds rolled in. In either case, the “slightly unphotometric” region is then padded by 2 frames.

Figure 7 displays the PS1-SDSS residual versus time for four of the 764 runs. Most runs exhibit excellent agreement with PS1, with at most one or two contrails, and often none. In some cases (e.g., run 1895) several unphotometric periods do not coincide with the SDSS CALIB\_STATUS photometricity flag. In other cases (e.g., run 1863), SDSS has been too cautious, and has marked data unphotometric that appears to be fine in our comparison.

#### 4.2. PS1 Outliers

The difference maps also contain outliers in the opposite sense, but these light splotches are the size of a PS1 chip, suggesting PS1 stars on a chip are too faint. In previous iterations of this analysis, most such stars were on chips 14, 66, and to a lesser extent 27. Internal PS1 comparisons find these chips to be less reliable than the others.

In the latest iteration of PS1 ubercal (version `qx_noref`) we include some outlier rejection to discard an exposure of a chip if it disagreed with consensus by more than some threshold. This seems to have correctly rejected chips 27 and 66 in most cases, at least where we have enough coverage. However chip 14 still leaks through, because it is partly masked, and in some cases half of the chip is good, so it does not trigger the outlier rejection. This will be addressed in the final PS1 calibration, but is of no consequence for this work.



**Figure 5.** SSPP calibration test using stars from Schlafly & Finkbeiner (2011). SSPP color residual is the color determined from spectral lines, minus DR8/9 observed color, minus SFD dust reddening using SF11 coefficients. Grayscale shows the distribution of this residual in small bins of recalibrated SDSS magnitude minus DR8/9, while black lines show the (16, 50, 84)th percentile. The dashed line has slope unity and y-intercept zero—it is *not* a fit. Stars with  $b > 20^\circ$  are in good agreement except  $u-g$ , which is confused by metallicity gradients.

## 5. CONCLUSIONS

The SDSS photometry has been used in thousands of papers and is one of the most valuable astronomical data sets. It is the basis of target selection for all of the SDSS spectroscopy (including the e-BOSS survey), and it is a well studied data set for extended source photometry and colors. For many applications, precise calibration is increasingly important, and the recalibrated SDSS is more stable than either PS1 or SDSS alone.

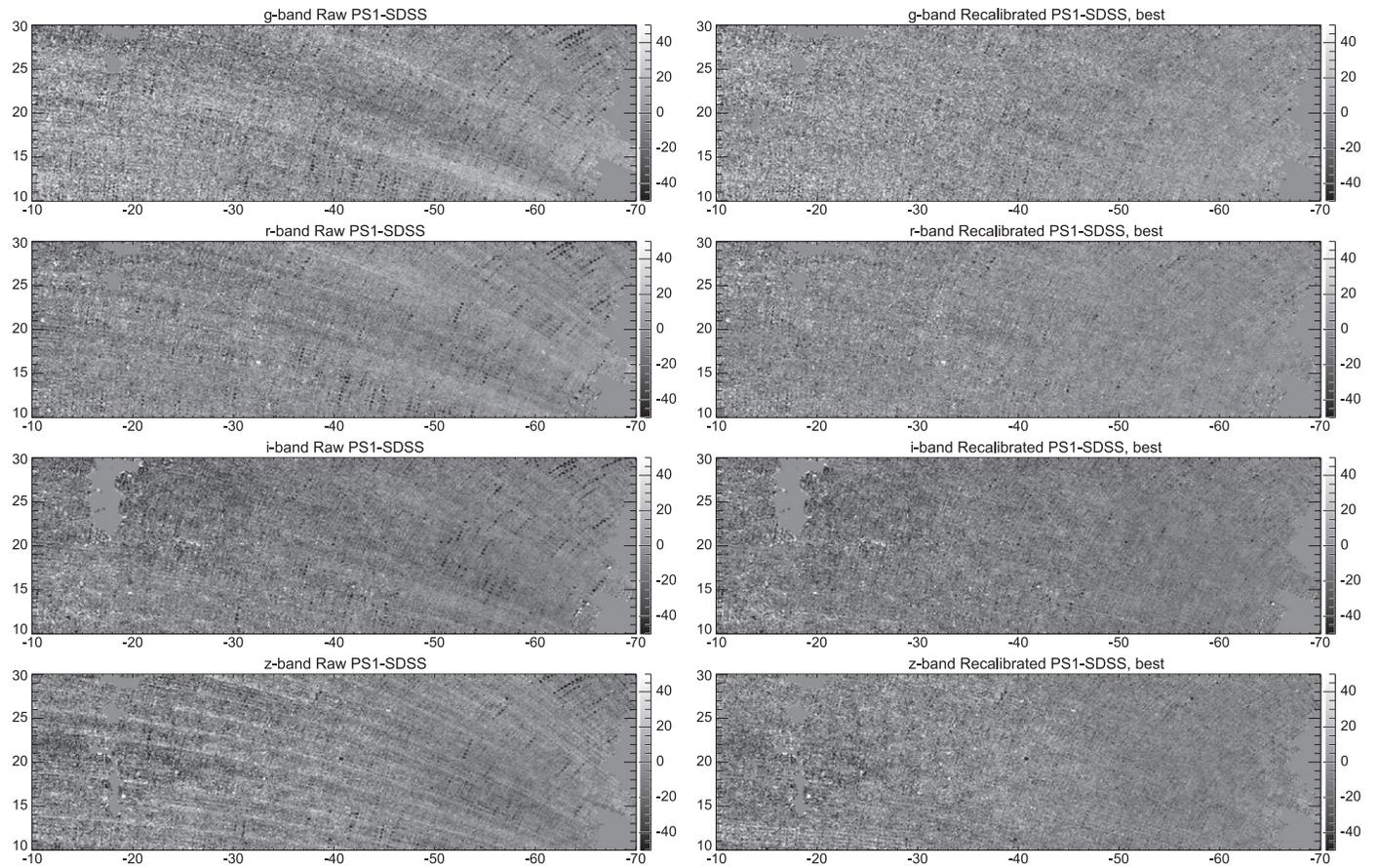
This work presents a new calibration, based on the first 3 years of Pan-STARRS1  $3\pi$  photometry. PS1 observes the sky with much higher redundancy than SDSS and frequent observations of the Medium Deep Fields add rigidity to the photometric solution. By comparing over 60 million SDSS detections with PS1, we derive new zero points for each *griz* chip in each SDSS run, and determine flat-field corrections at the 3 mmag level in *griz* and 15 mmag in *u*. We assess the stability of the new correction on the scale of an SDSS field ( $\sim 13'5$ ) by binning the SDSS minus PS1 difference in HEALPix  $N_{\text{side}} = 256$  pixels ( $\sim 13'7$ ). Using these new calibration parameters (and appropriate bandpass corrections) the difference has an rms of {9, 7, 7, 8} mmag in *griz*. In the limit of high stellar density ( $> 300$  stars per  $15'$  pixel) the rms

asymptotes to {7.5, 6.3, 6.1, 7.2} mmag in *griz*. However, these regions also have more overlap between SDSS runs, so we take {9, 7, 7, 8} mmag as representative. On much smaller scales  $N_{\text{side}} = 1024$  ( $3'4$ ), the rms asymptotes to {16, 12, 12, 14} mmag, but this likely includes a significant contribution from residuals in the PS1 focal plane.

In principle, a cross calibration of SDSS and PS1 could be performed, solving for the calibration parameters of both surveys simultaneously. We have resisted this temptation for two reasons:

The PS1 calibration, with a single atmospheric  $k$ -term and zero point per band per night, is already formally tightly constrained and including constraints from SDSS would add little. The PS1 model could be generalized to include more freedom and many more parameters. However, the PS1 zero points and flats are already so good that a substantial part of the photometric error in psf flux estimates comes from errors in the psf at each location in each exposure. We are reluctant to treat these errors as pure photometric offsets, as they depend on object size and shape.

Even with an expanded PS1 calibration model with enough freedom that SDSS helps constrain it, we would have a qualitatively different photometric stability inside the SDSS



**Figure 6.** Zoom on a patch of sky before (left) and after (right) calibration and contrail rejection. Stripes in the SDSS scan direction are mitigated by the recalibration. Dark patches oriented in the cross-scan direction are contrails (see Section 4). White spots are usually poor photometry in single PS1 chips (see Section 4.2). The  $\sim 5$  mmag flatfield instability in PS1 manifests itself as a faint honeycomb pattern corresponding to the pointings of the  $3^\circ$  diameter field of view.

footprint compared to the rest of the sky. It is more appealing to have PS1 be a monolithic survey with uniform properties across 3/4 of the sky. However, we anticipate a more general approach in future surveys, in which a simultaneous solution for calibration parameters of multiple large data sets might be computed. Such an approach is optimal, *if* a calibration model can be formulated that jointly describes the data sets to the required level of detail.

The new flats, per-run zero points, and a mask of short periods of non-photometricity (e.g., contrails) are encoded in the `calibPhotomGlobal` files and are publicly available.<sup>14</sup> They are expected to propagate into SDSS data release 13 (summer, 2016), but may be used immediately via the procedure `sdss_recalibrate`, available in the SDSS3 IDLUTILS repository.<sup>15</sup>

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<sup>14</sup> <http://faun.rc.fas.harvard.edu/ps1sdss/dr9/calib/v5b>

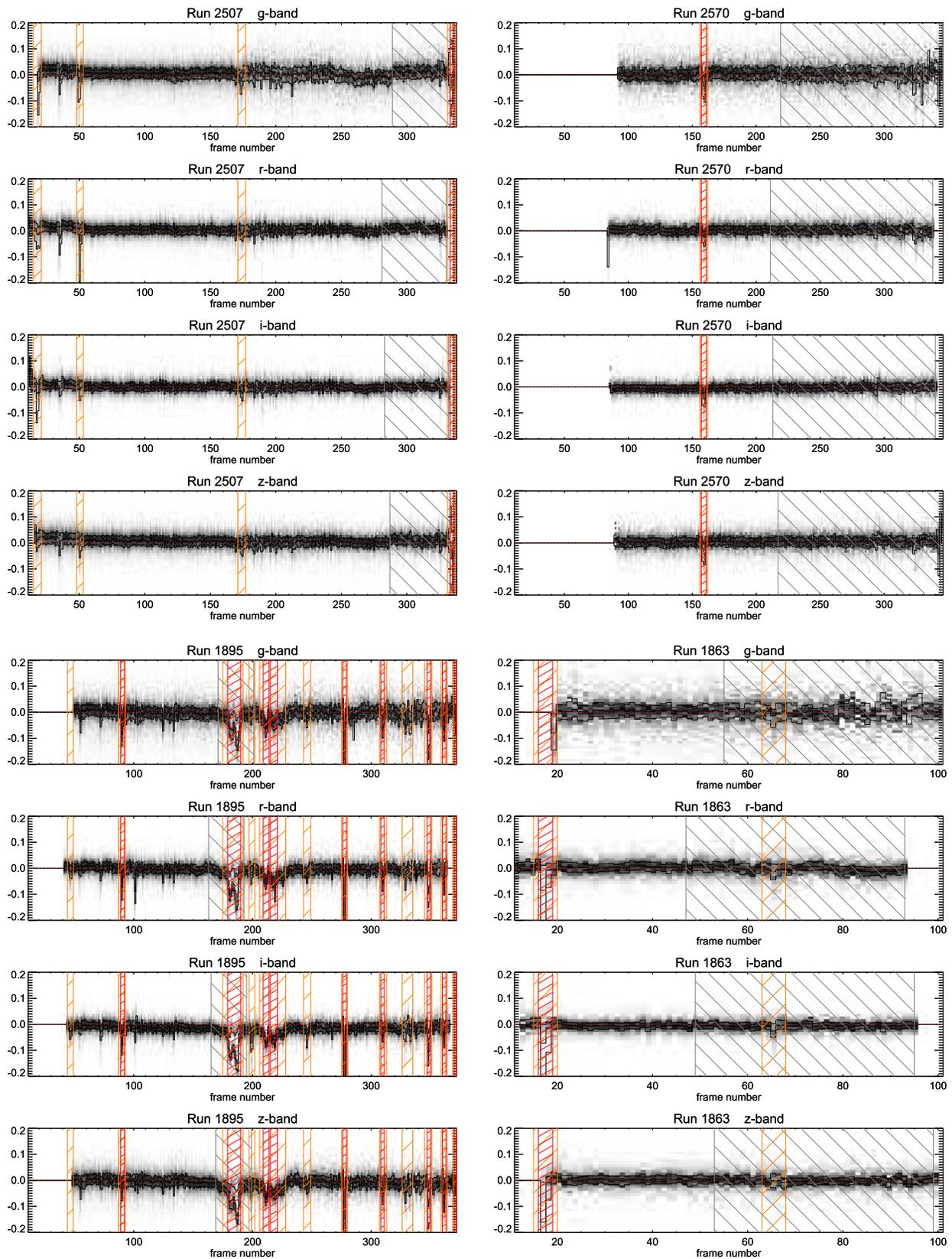
<sup>15</sup> <http://www.sdss3.org/dr8/software/idlutils.php>

<sup>16</sup> Available at <http://idlastro.gsfc.nasa.gov>.

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**Figure 7.** PS1 minus SDSS magnitudes as a function of SDSS frame number for 4 SDSS runs, as described in Section 4. We flag deviations aligned in SDSS observation time as contrails, padding 2 frames before and after. Periods that are unphotometric (red hatch) or “slightly unphotometric” (orange hatch) are indicated. Most runs exhibit excellent agreement with PS1, showing only occasional deviations (upper left panels). In some cases, a deviation is present in the first or last frame (upper right panels). In other cases, a run may show many deviations (lower left), only some of which are marked bad in the SDSS `CALIB_STATUS` flags (gray hatch). In run 1863 (lower right), unphotometric data were tied to overlapping runs starting at field 47, with good results.

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#### APPENDIX SUPPLEMENTAL MATERIAL

The QA plots generated by this study go far beyond the scope of this paper. We provide supplemental plots,<sup>17</sup> including the following:

1. flat30-all As in Figure 2, but for all seasons.
2. sdss\_contraails—*griz* conrail plots for 764 runs.
3. healdiff Full-sky maps at healpix nside = 256 (15 arcmin pixels).
4. healdiff and Nside = 1024 (3.5 arcmin pixels).
5. all\_pdfs.tar containing all of the above and more.

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<sup>17</sup> <http://faun.rc.fas.harvard.edu/ps1sdss/plots/v5b>