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Faint $UBVRI$ CCD sequences for wide-field surveys – II. $UBVR$ sequences at $\delta = -30^\circ$

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ABSTRACT

We present results from a continuing campaign to secure deep multi-colour CCD sequences for photometric calibration in UK Schmidt fields with galactic latitudes $|b| > 50^\circ$. In this paper we present $UBVR$ photometry in 12 fields and BR photometry in a further 14 fields observed within UK Schmidt survey fields centred at $\delta = -30^\circ$. Our observations were carried out with the 0.9m Telescope at the Cerro-Tololo Inter-American Observatory. The data are available electronically at `http://star-www.dur.ac.uk/~scroom/phot/photom.html`.

Key words: Techniques: photometric – catalogues

1 INTRODUCTION

Many large astronomical survey projects are currently being carried out, or planned over the next few years. Wide-field instruments such as the 2-degree Field (2dF) multi-fibre spectrographic system on the Anglo-Australian Telescope (AAT) are now allowing astronomers to observe many hundreds of objects at the same time. Thus, surveys of many thousands of objects are now possible, covering very large areas on the sky. Indeed, major programs are already underway to obtain redshifts for $\sim 250,000$ galaxies and $\sim 30,000$ QSOs. The candidate selection procedures for these and many other projects are based on machine measurements of photographic plates (for example, using APM or SuperCOSMOS), as this is currently the only method that can deal with sufficiently large areas.

These large surveys are either solely magnitude limited (as in the case of the 2dF Galaxy Survey, Maddox 1998), or also include colour selection (for example, in the case of the 2dF QSO Redshift Survey, Smith et al. 1997). It is imperative that both magnitudes and colours are well known in order to have an effective selection of target objects. This is particularly the case when the survey area covers a large number of photographic plates, in order that the survey be consistent over its entire area.

In Boyle, Shanks & Croom (1995) (Paper I) we began an observational program to obtain deep ($B < 21$) CCD sequences in a large number of high galactic latitude fields ($|b| > 50^\circ$). Paper I and also Smith & Boyle (1998) (Paper III) are concerned with fields at $\delta = 0^\circ$. In this paper we extend this program to a strip of UK Schmidt Telescope (UKST) survey fields at $\delta = -30^\circ$, near the South Galactic Pole. These extend from 21^h51 to 03^h04 in Right Ascension, covering UKST survey fields 466-471 and 409-417. Here we present the first of the observations in our Southern fields, which consists of 12 fields with $UBVR$ photometry and a further 14 fields with BR photometry. We have endeavoured to make this data available to the astronomical community as soon as possible after observation. Therefore, computer readable data files are available via the WWW at `http://star-www.dur.ac.uk/~scroom/phot/photom.html`.

2 OBSERVATIONS

Observations of the sequence fields were carried out using the Tek#3 CCD mounted at Cassegrain focus on the 0.9m telescope at Cerro Tololo Inter-American Observatory (CTIO). Data was obtained in three separate observing runs, from 23 – 27 August 1995 (observers: A. Ratcliffe and Q.A. Parker), 15 – 20 September 1996 (observer: S.M. Croom) and 25 September – 2 October 1997 (observer: S.M. Croom). The Tek#3 CCD is a 2048×2048, thinned, AR coated device with low read noise and good quantum efficiency in the U band. Readout is controlled by the ARCON system which has four separate amplifiers, allowing quad readout, which allows a quick readout time of ~ 40s. The pixel scale is 0.396 arcsec pixel^{-1} giving a large $13.5' \times 13.5'$ field of

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Table 1. Data on all CCD sequence fields. Exposure times in each band are listed, along with the aperture corrections used to correct the photometric zero-points from 10 pixel to 25 pixel apertures ($\Delta m_{\rm ap}$). $B_{\rm lim}$ is a limiting magnitude in the B band for each field, defined as the magnitude at which photometric errors are 0.05mag. Fields marked $*$ were calibrated using shorter exposures on different nights.

Field Name	R.A. (J2000)	Dec. (J2000)	Date Obs.	u	$\Delta u_{\rm ap}$	b	$\Delta b_{\rm ap}$	v	$\Delta v_{\rm ap}$	r	$\Delta r_{\rm ap}$	$B_{\rm lim}$
f409-1	00 01 12.78	−27 33 48.6	25/08/95	–	–	1×1200	0.039	–	–	1×600	0.038	21.1
f409-2	00 02 56.49	−29 22 16.6	15/09/96	3×1200	0.042	2×600	0.051	2×300	0.036	2×300	0.041	20.8
f410-2	00 21 52.31	−29 48 21.6	30/09/97	3×1200	0.028	3×400	0.027	2×300	0.029	2×300	0.031	20.9
f410-1	00 36 43.89	−29 31 34.5	26/08/95	–	–	1×1200	0.068	–	–	1×600	0.059	21.0
f411-2	00 49 47.87	−29 09 40.0	28/09/97	3×1200	0.022	3×400	0.024	2×300	0.021	2×300	0.027	20.9
f411-1	00 51 19.84	−28 30 20.4	26/08/95	–	–	1×1200	0.035	–	–	1×600	0.035	21.2
f412-1	01 16 48.89	−28 35 06.6	26/08/95	–	–	1×600	0.038	–	–	1×300	0.049	20.8
f413-1	01 34 23.38	−31 38 30.4	26/08/95	–	–	1×600	0.053	–	–	1×300	0.056	20.8
f413-2	01 34 41.60	−29 36 39.9	28/09/97	3×1200	0.023	3×400	0.026	2×300	0.027	2×300	0.028	20.9
f414-2	02 01 38.73	−30 42 33.0	30/09/97	3×1200	0.029	3×400	0.036	2×300	0.028	2×300	0.033	20.9
f414-1	02 06 33.93	−28 18 41.0	25/08/95	–	–	1×1200	0.027	–	–	1×600	0.030	21.2
f415-1	02 20 47.83	−31 54 15.1	24/08/95	–	–	1×1200	0.027	–	–	1×600	0.040	21.2
f416-2	02 47 31.70	−30 18 30.5	15/09/96	3×1200	0.040	2×600	0.042	2×300	0.036	2×300	0.038	20.9
f417-2*	03 06 29.09	−29 40 28.1	28/09/97	3×1200	0.020	3×400	0.022	2×300	0.025	2×300	0.028	20.7
f417-1	03 12 31.47	−27 50 46.5	26/08/95	–	–	1×1200	0.043	–	–	1×600	0.052	21.2
f466-2	21 54 17.07	−29 50 48.0	15/09/96	3×1200	0.041	2×600	0.033	2×300	0.035	2×300	0.037	20.8
f466-1	21 56 02.40	−29 19 29.9	24/08/95	–	–	1×1200	0.084	–	–	1×600	0.068	21.1
f467-1	22 09 07.17	−27 24 38.5	26/08/95	–	–	1×600	0.047	–	–	1×300	0.083	20.7
f467-2	22 13 13.45	−30 03 07.2	27/09/97	3×1200	0.024	2×600	0.023	2×300	0.038	2×300	0.035	20.9
f468-1	22 32 26.17	−31 12 12.1	25/08/95	–	–	1×600	0.027	–	–	1×300	0.031	20.9
f468-2	22 44 16.60	−30 02 13.8	28/09/97	3×1200	0.036	3×400	0.022	2×300	0.034	2×300	0.029	20.8
f469-1	23 05 43.34	−30 39 01.0	25/08/95	–	–	1×1200	0.031	–	–	1×600	0.032	21.2
f470-1	23 19 39.65	−29 31 26.1	25/08/95	–	–	1×600	0.036	–	–	1×300	0.048	20.8
f470-2*	23 26 02.57	−29 22 29.4	29/09/97	3×1200	0.022	3×400	0.020	2×300	0.022	2×300	0.028	21.0
f471-1	23 47 38.91	−28 08 28.3	25/08/95	–	–	1×1200	0.028	–	–	1×600	0.035	21.2
f471-2	23 48 58.85	−30 01 19.0	30/09/97	3×1200	0.030	3×400	0.032	2×300	0.033	2×300	0.037	21.0

view, allowing us to obtain magnitudes for a large number of stars in each frame (~ 100 with $B<21$). The first observing run produced sequences in B and R in 14 independent UKST survey areas. These fields were centred on areas with bright ($B<17$) galaxies in order to verify the calibration of the Durham/UKST FLAIR Galaxy Redshift Survey (Ratcliffe et al. 1996). However, the majority of area in each field could also be used to obtain stellar sequences. The second and third observing runs produced a total of 12 CCD sequences in $UBVR$. For these runs the fields were chosen to contain a broad and even range of stellar magnitudes. All the fields observed in the three runs are listed in Table 1. The filters used for these observations were the standard CTIO $UBVR$ 3×3 inch filters, BVR being similar to the Harris BVR set, while the U filter uses a Copper Sulphate solution blocker. Magnitude zero-points, extinction and colour terms relating the instrumental magnitudes to the standard Johnson-Kron-Cousins system were obtained from frequent observations of standard stars from the E-field standards at $\delta=-45°$ (Graham 1982). These standards were also used to monitor the quality of photometric conditions during each observing run. All data observed in the first run was taken in photometric conditions. Only one night of the second run was photometric, so only data from this night is included in this paper. During the third observing run, the beginning of the night of the 26/9 was photometric, as was most of the 28/9. The night of the 30/9 was completely photometric, and shorter exposures were taken on this night to validate the calibration in fields f417-2 and f470-2. 1×600s, 1×300s, 1×150s and 1×150s exposures were taken in these fields in $UBVR$ respectively. All observations of the sequence fields were made at low airmass, $\sec(z)\leq1.34$, with most of the fields being observed at $\sec(z)\leq1.1$.

3 DATA REDUCTION

Removal of the instrumental signature of the CCD from the images was carried out using the ARED.QUAD.QUADPROC and IMRED.CCDRED.CCDPROC tasks in the IRAF package. QUADPROC is a variant of CCDPROC specifically designed to reduce data from the multi-readout ARCON system. This software removes the instrumental bias and also corrects bad columns and pixels (of which there are a number in the Tek#3 CCD), as well as flat fielding each frame. In each passband we obtained both dome flats (taken during the day) and sky flats (taken at twilight). It was found that both dome and sky flats adequately corrected small scale variations in pixel sensitivity. However, division by dome flats generally left a residual large scale gradient across the image. This gradient was at the 5% level in many cases.

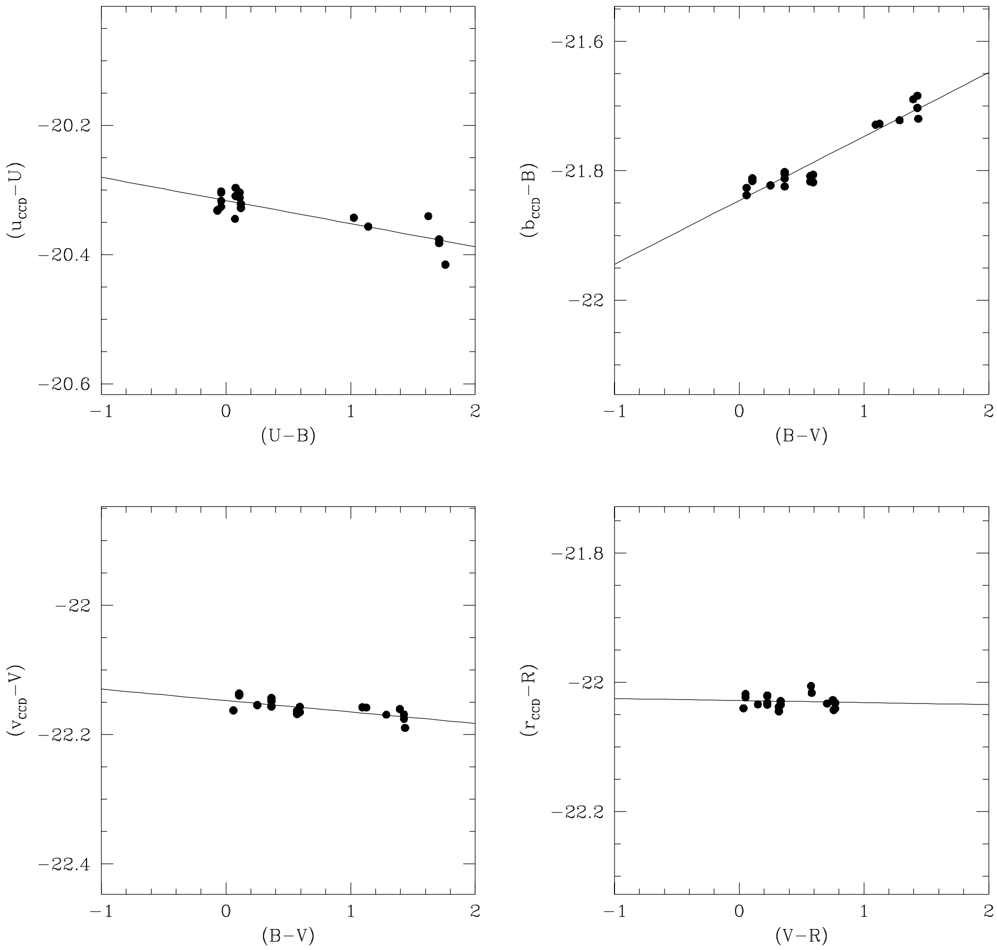

Figure 1. Colour-magnitude relations in the $UBVR$ passbands derived from observations of E-field photometric standards (Graham 1982) during the 1997 observing run. We plot $m_{\rm CCD} - M$ (the extinction corrected instrumental magnitude minus the known standard magnitude) against the known colour of the stars. The solid lines denote the best fit.

Therefore, we used the sky flats, which flattened the images at the 1% level. At least 5 separate exposures were used to generate each flat-field. These were median combined using 3σ clipping to remove cosmic ray events (CREs).

We used the IRAF task DIGIPHOT.DAOPHOT.PHOT to obtain photometry of all the E-field standard stars observed. We used 25-pixel ($10''$) radius apertures centred on each standard star to obtain their instrumental magnitudes, which we denote by u, b, v and r; the instrumental magnitude is simply given by

$$m = -2.5\log(f) + 2.5\log(t), \qquad (1)$$

where f is the flux and t the exposure time. The sky background value was obtained from the mode of an annulus between 35 and 50 pixels in radius. The IRAF task DIGIPHOT.PHOTCAL.FITPARAMS – an inter-active multi-parameter fitting routine – was used to obtain the magnitude zero-points, colour and extinction terms. For the first set of data (BR sequences) we assumed standard extinction values for Cerro-Tololo: $A_{\rm B} = 0.209$ mag airmass^{-1}, $A_{\rm R} = 0.108$ mag airmass^{-1}. For these data the maximum airmass reached was 1.341 in r and 1.292 in b, with over 50% of the observations obtained at airmasses of less than 1.1. Even in the most extreme cases this assumption would only cause a zero-point error of less than 0.01 mag. For the second and third sets of observations ($UBVR$ sequences) the extinction term was fitted as well as the zero-point and colour terms. We fitted inverse colour equations of the form

$$b = B - X + Y(B - V) + A_{\rm B}\sec(z), \qquad (2)$$

where X is the zero-point, Y is the colour term, A_λ is the extinction value and $UBVR$ denote the standard magnitude system. The parameters from these fits are given in Table 2, and example colour-magnitude relations from the 1997 observing run are shown in Fig. 1. The colour terms are with respect to $(B - R)$ for both B and R in the 1995 observing run, while for the 1996 and 1997 runs they are with respect to $(U - B)$, $(B - V)$, $(B - V)$ and $(V - R)$ for U, B, V and R respectively.

The sequence fields were combined using IRAF's IM-

Table 2. Photometric solutions (found using the IRAF routine FITPARAMS) for standard stars observed in each of the three observing runs.

Obs. Run	Band	Extinction mag airmass^{-1}	Zero Point	Colour Term	Fit r.m.s.
1995	B	0.209	22.442	0.095	0.003
1995	R	0.108	22.566	0.006	0.004
1996	U	0.453	20.240	−0.035	0.014
1996	B	0.232	21.800	0.110	0.014
1996	V	0.131	22.030	−0.019	0.007
1996	R	0.113	21.992	−0.002	0.005
1997	U	0.459	20.316	−0.036	0.017
1997	B	0.202	21.846	0.099	0.016
1997	V	0.138	22.147	−0.018	0.009
1997	R	0.066	22.028	−0.003	0.010

COMBINE task, with the CRREJECT algorithm used to reject CREs. In the case of single exposures on a field (as was the case for data from the first run), we used the image detection routines, and the matching of images in different bands to reject CREs. All images with peak counts higher than a 5σ threshold above the sky background were selected using DAOFIND. Aperture photometry was obtained for these objects using PHOT within 10 and 25 pixel apertures. The larger aperture, corresponding to $10''$ radius, is the same as that used for our standard observations and defines the zero-point for our magnitude system. The median seeing during the observations was $1.5''$ and was rarely above $2.0''$. At faint fluxes the sky counts add considerable noise within an aperture of this size. For this reason we use the magnitude obtained within a 10 pixel aperture and then corrected it to the 25 pixel magnitude scale using the brightest unsaturated stars (at least 8 per field) with no close companions in each field to define the aperture correction. This corrections was typically ~ 0.03 mag (see Table 1), with an r.m.s. error of ~ 0.002 mag. We also obtained aperture photometry within a 6 pixel aperture. The difference between this and the 10 pixel aperture magnitude was used to give an approximate star–galaxy separation criterion. Fig. 2 shows this plotted as a function of B magnitude.

The aperture corrected instrumental magnitudes were then converted to the standard $UBVR$ system using the INVERTFIT task and the colour equations derived above. The Poisson photometric errors were plotted as a function of magnitude (an example of which is shown in Fig. 3) in order to estimate the effective limiting magnitude of the standard observations in each field. We define this limit to be the magnitude at which the photometric errors reach 0.05 mag. These limiting B band magnitudes are shown in Table 1.

Two fields, f417-2 and f470-2, were observed in non-photometric conditions. We obtained shorter exposures in these fields in an attempt to measure an accurate zero-point. Fig. 4 shows the offsets between the photometric data (e.g. rc) and non-photometric data (e.g. r). We fit a constant to any observed offset, rejecting points that are $> 3\sigma$ from the fit in an iterative process. We find that there is no significant

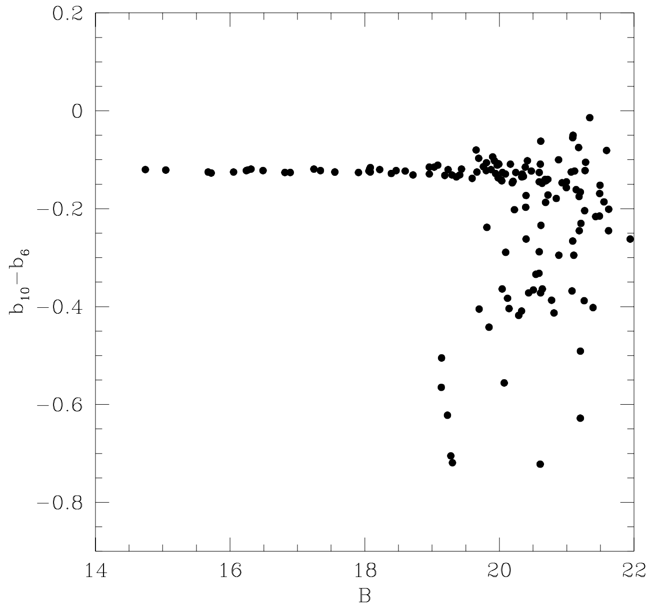

Figure 2. The star-galaxy separation parameter, $b_{10}-b_6$, plotted as a function of B for field f471-2. Objects with large negative values are galaxies, with the divide between stellar and non-stellar sources being at $b_{10}-b_6 \sim -0.2$.

Table 3. Zero-point offsets for non-photometric fields.

Field	Band	Offset	σ
f417-2	r	0.5223	0.0067
f417-2	v	0.1822	0.0050
f417-2	b	0.1789	0.0068
f417-2	u	0.0030	0.0136
f470-2	r	0.0186	0.0074
f470-2	v	0.0050	0.0041
f470-2	b	0.0073	0.0060
f470-2	u	0.4388	0.0108

offset in the u data in f417-2, while the bvr data does show a significant offset. For f470-2, the u photometry shows the only large offset, of $\simeq 0.4$ mag. The offsets and errors on the offsets are listed in Table 3. While these data can in principle be used in a similar manner to the other sequences, any potential users should note that the error in the zero-point offset will increase significantly the total photometric errors. For example, the U photometry in field f417-2 would then have a minimum error of 0.022 mag.

The brightest 10 unsaturated stars in each field were matched to their positions on APM scans of UKST IIIaJ survey plates which in turn have been matched to the PPM (B1950) (Bastian & Roeser 1993) astrometric catalogue. These stars were then used to derive a transform from CCD (x, y) positions to (α, δ) using the Starlink ASTROM software.

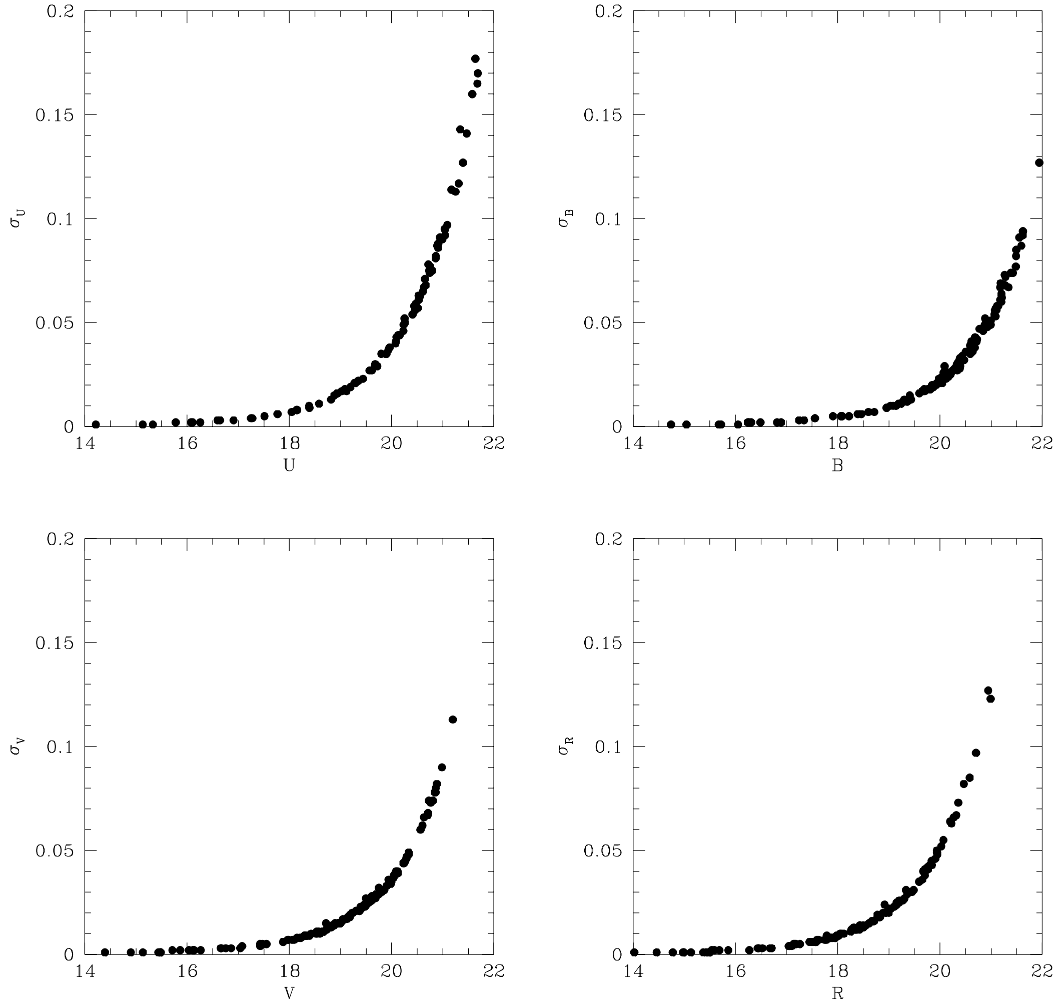

Figure 3. Photometric errors as a function of magnitude for the fully reduced and calibrated data in field f471-2.

4 RESULTS

In Tables 4–29 we list the positions, $UBVR$ magnitudes and Poisson errors for all our sequence stars. We note that the errors listed in these tables are purely Poisson errors and do not account for systematic uncertainties. Also listed are the 25 pixel aperture magnitudes, which give good estimates of total galaxy magnitudes for galaxies with isophotal diameters less than $20''$. The star galaxy separation parameter, $b_{10} - b_6$, is given and generally objects with $b_{10} - b_6 < -0.2$ will be galaxies, although this does vary somewhat from field to field, depending on the seeing in each observation. The Poisson errors on the aperture corrected 10 pixel aperture magnitudes is ~ 0.05 mag at $B = 21$ (see Table 1), while the 0.05 mag error limit for the other bands is typically 20.2, 20.5, 20.0 for U, V and R respectively (Fig. 3). It is clear that at bright magnitudes the Poisson error estimate breaks down and the errors are dominated by systematic effects such as the accuracy of the determination of zero-points, colour terms and aperture corrections. The photometric fits are clearly the main source of error, as the typical aperture correction errors were ~ 0.001 mags and were rarely above ~ 0.003 mags. Therefore, the r.m.s. errors from the fits listed in Table 2 should be taken as lower limits to the total photometric errors.

The photometric sequences presented in this paper are intended primarily for the calibration of photographic plates. In this case, it is expected that the sequences be used as a whole to obtain a calibration curve, rather than to provide accurate magnitudes for individual stars. As we have not repeated our observations over a sufficient time scale we are unable to remove variable objects from our catalogues. Also, as discussed in Paper I, the most extreme sequence stars have colours outside of the range of the standards used (namely, $-0.068 < U - B < 1.760$, $0.060 < B - V < 1.436$ and $0.035 < V - R < 0.770$). As the colour terms are small (see Table 2) extrapolation outside of the range of the standards, which is at most 0.5 mag, is unlikely to produce errors as large as the overall r.m.s. error in the fits. Of course, it is clearly possible to construct sequences of a large number of stars which do have colours within the range of the standard observations. The three observing runs also give us independent measurements of the colour terms which should not have changed from run to run. We have three measure-

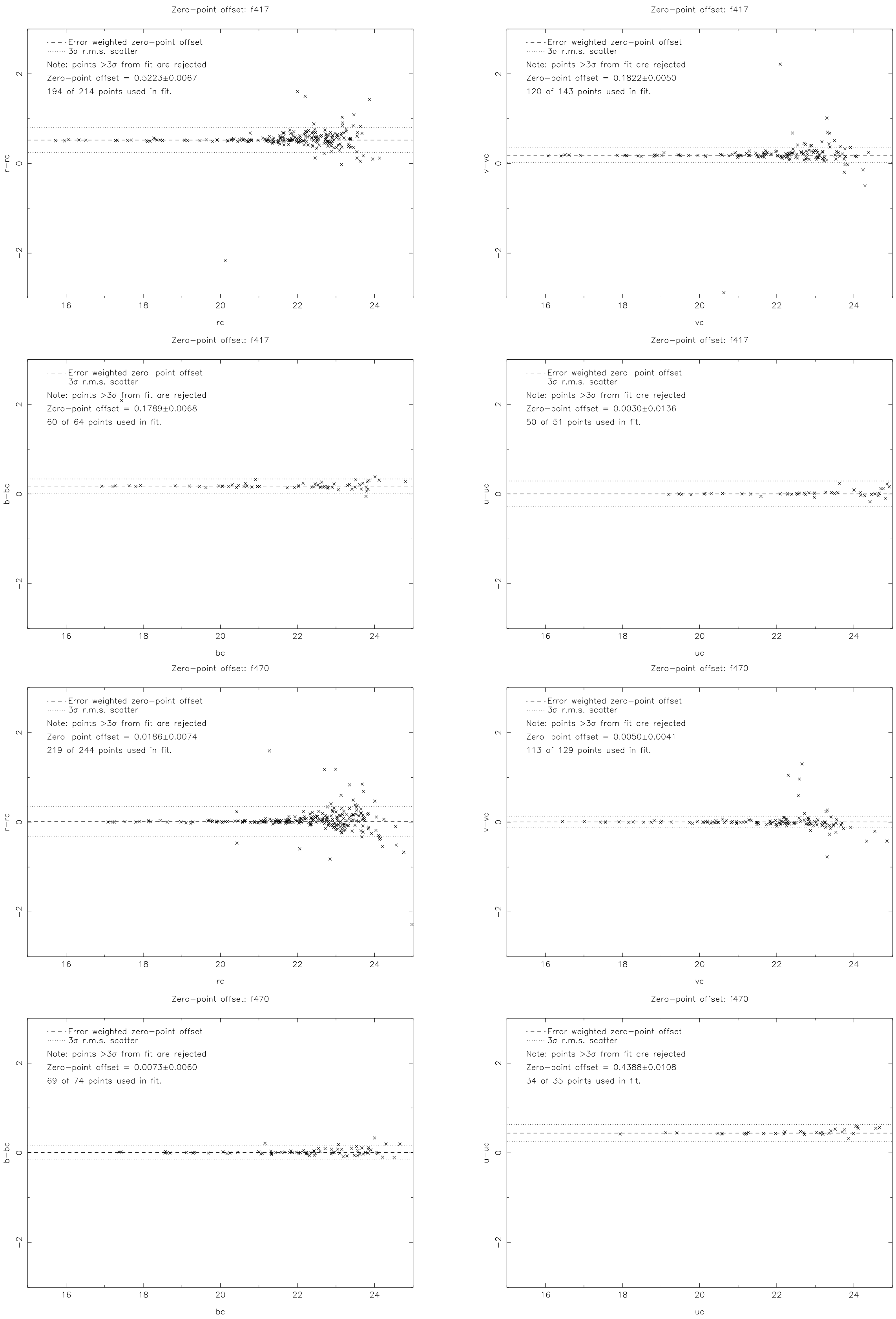

Figure 4. Zero-point corrections for data observed in non-photometric conditions (f417-2 and f470-2). We plot the difference between the photometric (e.g. rc) and non-photometric (e.g. r) instrumental magnitudes in each band. The measured offset is shown, along with the 3σ upper and lower bounds.

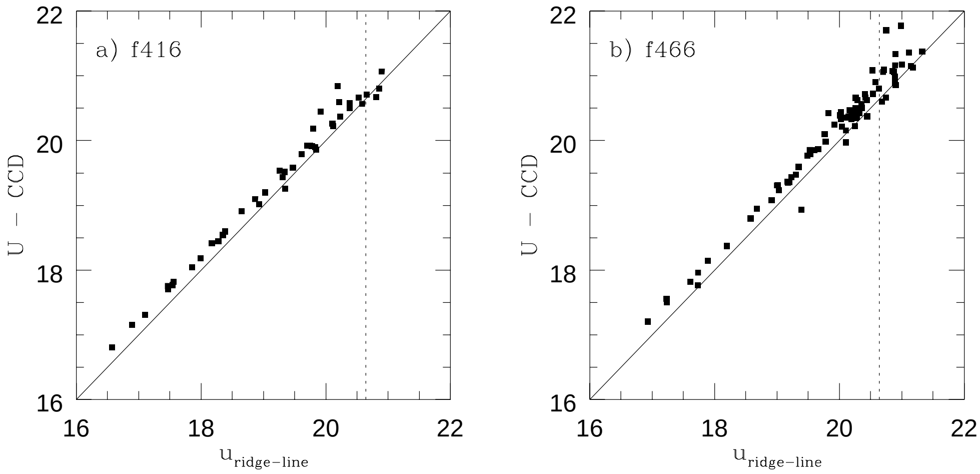

Figure 5. An example of the U photometry from this paper used to check the calibration in the 2dF QSO Redshift Survey for fields a) f416 and b) f466. We plot U CCD photometry against photographic u photometry from UKST plates calibrated by boot-strapping to the $u - b_J$ colours of main sequence stars. The dotted vertical line shows the effective magnitude limit of the survey in the U band.

ments of the colour terms for B and R, with the scatter between them being 0.008 and 0.005 respectively. We have only two measurements of the U and V colour terms, but in both cases the difference between the 1996 and 1997 measurements was only 0.001. This consistency between runs gives us great confidence in the reliability of our measurements.

These sequences and the others from this project have already been used in several wide area surveys, including the 2dF QSO Redshift Survey (Smith et al. 1997) and the 2dF Galaxy Redshift Survey (Maddox 1998) amongst others. In Fig. 5 we demonstrate possible uses of this data set by way of a photometric calibration example taken from Croom 1997. The 2dF QSO Redshift Survey candidate catalogue is constructed from u, b_J and r UKST plates. The photographic u photometry was calibrated by boot-strapping from available B CCD photometry via the colour of the main-sequence stellar ridge-line. In practice, this is done by straightening the stellar locus in the $u-b_J$ vs. u plane. In Fig. 5 we compare the "ridge-line" photometry to data from our CCD sequences f416-2 and f466-2. This figure shows that the boot-strapping has indeed linearized the photographic magnitudes. However, the process leaves a ~ 0.2 mag offset with respect to the CCD photometry. Of course, this has no practical effect on the QSO selection as the candidate selection criteria are determined relative to the stellar locus.

We hope that by making this data available to the general community it will help in the photometric calibration of many other wide-field projects.

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