Photometric calibration of Megacam data

S.Prunet, with help from P.Fouqué and S. Gwyn

I. 2013 ELIXIR STATE OF THE ART

Traditionally, the elixir pipeline (Magnier and Cuillandre 2004) has been using the standard stars observed by Smith et al. (2002)to establish an absolute photometric calibration scale for Megacam data. This set of standard stars is the basis of the absolute calibration of the SDSS photometric survey, and is used by Smith et al. (2002) to establish the correspondance between the (now standard) *u'g'r'i'z'* Sloan photometric system first introduced by Fukugita et al. (1996), and the more traditional Johnson-Morgan-Cousins photometric system (see e.g. Mermilliod et al. 1997).

This choice of standard stars to establish a reference photometric system for Megacam data presents however several difficulties:

1. for a typical Megacam run dominated by scattered pointings (P.I. data), the chance to find some of the standard stars in the observed fields is very small, so that specific "calibration" observations must be done in all bands during the run. The spatially scattered nature of the standard stars chosen by Smith et al. (2002), while adpated to a large survey like the SDSS, implies that any such calibration observation contains at most a few standard stars. This in turn implies that zero point estimates based on these stars are bound to have large statistical errors.

2. This set of standard stars were chosen in particular for their known spectroscopic properties, and were thus relatively bright (typical magnitude of $r' \sim 10$). This in turn implied to take some of the calibration observations out of focus, possibly introducing systematic errors in the photometry.

3. Finally, the filters, CCDs and optical elements of the USNO telescope at Flagstaff, used in Smith et al. (2002), were close but **not precisely equivalent to** their counterparts on the 2.5m SDSS telescope at Apache Point Observatory. This lead in particular the SDSS team to re-label the 2.5m telescope photometric bands as *ugriz* (without quotes) to make the distinction between these two photometric system that were designed to be equivalent.

Since then, the SNLS team, to fully exploit their deep photometric survey using Megacam data, have investigated in much detail the different photometric systems (Megacam, 2.5m and USNO) and their relationships (Betoule et al. 2013, Regnault et al. 2009). They have in particular compiled the measured transmissions of all optical elements of the Megacam/Megaprime instrument (including the primary mirror, the wide field corrector optics, the filters themselves, and the CCD QEs). On the other hand, precise measurements of the atmospheric absorption properties above Maunakea have been done with the SNIFS spectrograph on the UH 88" telescope by Buton et al. (2013), allowing a complete characterisation of the Megacam photometric system. Together with the precise, absolutely calibrated, faint spectro-photometric standards observed with the HST in the context of the CALSPEC spectral library (Bohlin et al. 2014), they give the possibility of computing synthetic AB magnitudes of the CALSPEC standards.

In order to investigate the quality of the original "Megacam-SDSS" photometric equations used originally in elixir to establish zero point estimates, based on the Smith et al. (2002) measurements, I did some observations with Megacam on two well-studied CALSPEC stars, P177D and P330E, for which I could compute synthetic magnitudes from their CALSPEC spectra. This allowed me to make **two independent zero point estimates** for the same run, one using elixir on the Smith et al. (2002)standards observed during the run and the elixir photometric equations, and the second by directly comparing the synthetic and observed magnitudes of the two CALSPEC stars. **Comparing these two zero-point estimates showed a reasonable agreement in the *griz* bands, but a $\simeq 0.15$ mag discrepency in the *u* band.**

Using the BD17 Star (both observed bySmith et al. (2002) and part of the CALSPEC spectral library), we could compare directly the (predicted) BD17 Megacam magnitudes using the Smith et al. (2002)measurement and the elixir photometric equations, and the synthetic magnitudes using the CALSPEC spectrum and the measured Megacam spectral transmissions. This lead us to **predict** that zero-point estimates of elixir based on BD17 would be systematically high by 0.13 mag in the *u* band (see annex A for details).

Although we were not able to trace exactly the origin of the color equations in elixir, we believe that the source of the discrepency could be linked to the confusion between the primed (USNO) and unprimed (APO 2.5m) photometric systems, which were designed to be equivalent but showed significant differences in practice (comparison of the elixir original color terms with `http://www.astro.uvic.ca/~pritchet/SN/Calib/ColourTerms-2006Jun19/index.html#Sec04` let us think that they are equal to the Megacam to unprimed magnitudes, while the Smith et al. (2002)

standard magnitudes used in the zero point estimates are in the primed photometric system).

All these problems led us to change the set of "standard" stars used to calibrate the Megacam images: we are now using as absolute calibrators the set of tertiary Megacam standards measured in the SNLS deep fields over many epochs by the SNLS team. This catalog gives absolutely calibrated natural Megacam magnitudes of more than 10000 stars in a single Megacam pointing, which solves also the problem of the poor statistical quality of the zero point estimates using the Smith et al. (2002)standards. We used the version 3.2 of the catalog, that can be downloaded `http://supernovae.in2p3.fr/snls_sdss/`. The zero point estimates based on these tertiary standards **are in good agreement with those obtained from the comparison of synthetic and observed magnitudes of CALSPEC spectro-photometric standard stars** for the old filters, and in reasonable agreement for the new filters. The estimates based on the tertiary standards are shown in the sixth column of table I below, and the corresponding estimates based on synthetic CALSPEC magnitudes are shown in the seventh column. Estimates for the old filters are based on the January 2015 run (14Bm06), while estimates for the new filters are based on the May 2015 run (15Am04).

II. NEW MEGACAM BROAD-BAND FILTERS

In 2014 new ugriz broad-band filters were acquired for Megacam, with transmission properties (both spectrally and spatially) superior to those of the former generation. These filters have also slightly different central wavelengths, and therefore must be related to the SNLS photometric system that relied on the old ugriz filters. These filters are also spatially larger, allowing to use four additional CCDs, thus bringing the total number of chips in the focal plane to 40.

For all these reasons (different spectral properties, additional chips) these filters needed a complete photometric characterisation, expressed in terms of AB magnitude zero points, photometric grid (aka "superflat") corrections to the twilight flats, and color corrections to relate them to the SNLS photometric system.

A. Photometric grid solutions

Until now, photometric grid (superflat) solutions were computed by the SNLS team for all broad-band filters (including the u-band that they did not use), based on dense stellar fields observations and specific horizontal and vertical, log-spaced, dithering patterns that allow a stable photometric solution on all scales. Details of the model and the algorithm can be found in Regnault et al. (2009). In practice, although specific observations had been made every semester, the last photometric grid solution in production was done in 2008. For all these reasons, and the need to obtain rapidly new grid solutions for the new filters, it was decided to bring the photometric grid analysis software from the SNLS team to CFHT.

Following Regnault et al. (2009) for a little while, the idea is to relate the observed magnitude of a star i at position $\mathbf{x}$ to the magnitude it would have at a reference position $\mathbf{x_o}$in the focal plane (chosen near the center of the mosaic, but can be arbitrary), with a color-independent, space-dependent mapping of zero point fluctuations $\delta z(\mathbf{x})$, and a color-dependent, space-dependent term $\delta k(\mathbf{x})$, via a linear model:

$$m_b(\mathbf{x}) = m_b(\mathbf{x_0}) + \delta z(\mathbf{x}) + \delta k(\mathbf{x}) \times (\mathrm{col} - \langle \mathrm{col} \rangle)(\mathbf{x_0}) \quad (1)$$

for each broad band b, and where the color term is chosen to be $\mathrm{col} = m_g - m_i$, and the average is taken over the SNLS deep field values of the color term. The average color term is chosen so that for a star of average color, a simple (grey) flat field correction is enough to homogeneize its magnitude over the focal plane. Of course, for stars with very unusual colors, one should in principle use its color through equation 1 to make its magnitude independent of focal plane position. In practice, $\delta k \sim 0.01$, so that we chose, as was done previously in elixir, to compute the grid solutions according to the full equation 1, but to only apply $\delta z(\mathbf{x})$, as a systematic correction to the twilight flat fields of each run, or more precisely:

$$f(\mathbf{x}) = f_{\mathrm{twilight}}(\mathbf{x}) \times 10^{-0.4\delta z(\boldsymbol{x})}$$

where f_{twilight} is the master twilight flat of each camera run. This grid correction, defined on large super pixels (4x9 per ccd for δz, 2x3 per ccd for δk), corrects for plate scale variations, as well as scattered light within the camera optics that results in a non-uniform illumination of the detector mosaic. It consists therefore mostly in a smooth, radial pattern, but also has chip-to-chip variations due to spectral variations in quantum efficiency of the ccds (most important in u band). These chip-to-chip variations are mostly a color-dependent effect, induced by the fact that the mean color of the deep field stars is noticeably different from the twilight illumination color.

The original code was shown to reproduce the existing grid solutions, and was then adapted to take into account the four additional ccds. The photometric grid solutions for all new wide band filters are shown in figure 1. The grid solutions of the new filters look quite similar to their old-filter counterparts, with a few grid pixel outliers, differing at most by 0.02 mag from their neighbours. We expect that these outliers will disappear when we refine (and robustify) the reference catalog over multiple semesters.

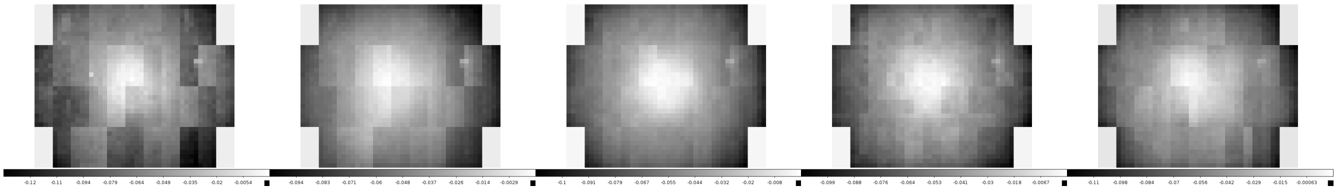

Figure 1. Photometric grid corrections in ugriz, from left to right, with the new Megacam filters

B. Color corrections with respect to the SNLS photometric system

The specifications, as well as the manufacturing process of the new broad-band filters are sufficiently different from their older counterparts that color corrections are needed to relate AB magnitudes taken with these new filters and the SNLS reference. To be specific, we will in the following design the broad band filters by their "generation", so that e.g. $u_3$correspond to the u band filter of the third generation (2014-2015), $i_2$corresponds to the i band filter of second generation (replacing its first generation counterpart that was broken in jukebox accident in 2007), etc.

Using the Pickles library of stellar spectra, the knowledge of the instrument (including the mirror, wide field corrector, megacam optics and ccd quantum efficiency as compiled by the SNLS team, see Betoule et al. 2013), as well as the mean transmission above Maunakea at an average airmass of 1.25 (Buton et al. 2013) , as well as transmission measures from the filter manufacturers (Asahi for the u band, Materion for all others), we were able to compute synthetic magnitudes in the third generation filters and compare them to their older counterparts as a function of neighboring colors.

On the other hand, S. Gwyn computed empirical color corrections using SNLS deep field observations in the new and old filters, that can be compared to the synthetic estimates. All these results are summarized in figure 3.

The following table (I) relates the full Megacam filter nomenclature to their short name based on their generation, and compares the zero point estimates obtained by using the elixir pipeline based on the SNLS catalog, as well as the empirical color corrections shown in figure 3 (column Elixir ZP) to zero point estimates obtained on a few spectrophotometric (CALSPEC) standards (column Spectroscopic ZP). Note that the agreement is correct but not excellent for the new bands; we hope that the agreement between the two estimates will improve as our knowledge of the magnitude equations relating the photometric systems defined by the old and new filters improves. Some of the discrepancy might also come from contamination by slightly non-photometric exposures.

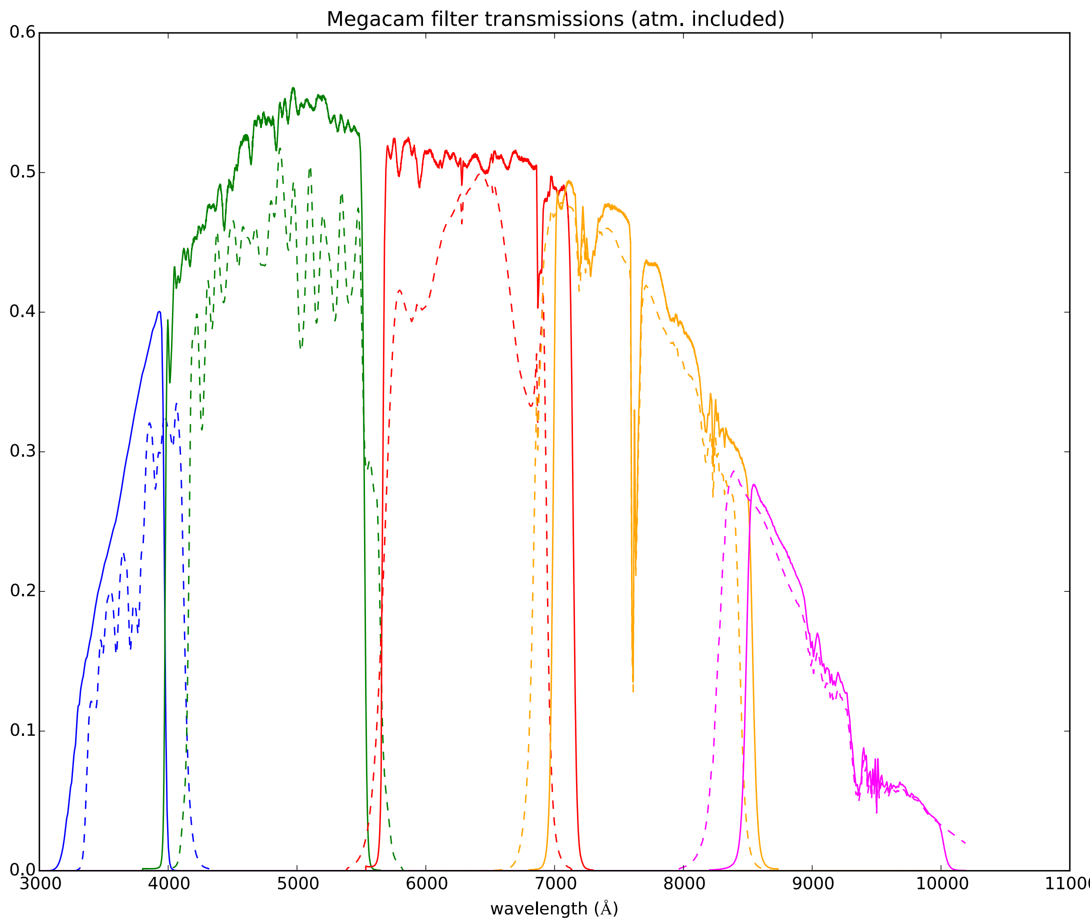

Figure 2. Full transmission spectra in the old (dashed lines) and new (solid lines) broad Megacam bands, including the filter transmission themselves, as well as the transmission of the different parts of the Megacam optics (wide field corrector, lenses), the telescope primary mirror, and an average atmospheric transmission above Maunakea at an airmass of 1.25 (see Betoule et al. 2013, Buton et al. 2013).

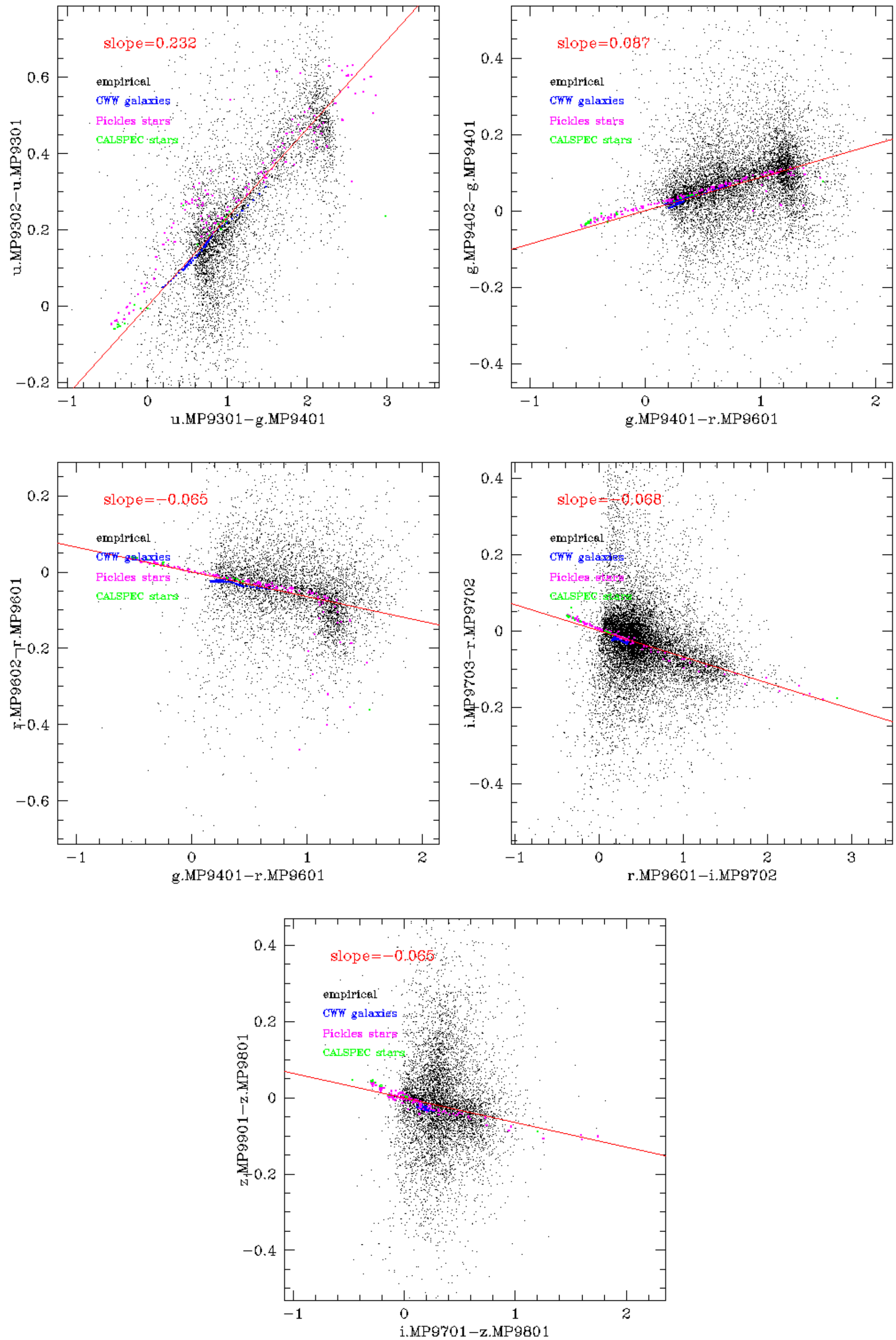

Figure 3. Empirical and synthetic color corrections, relating the third generation filter magnitudes to their older counterparts. Note that the y axis label of figure 4 has a typo, it should read i.MP9703 - i.MP9702. Figure courtesy of S. Gwyn

Full name	name	Available	$\bar{\lambda}$ (nm)	$\Delta\lambda$ (nm)	Elixir ZP (SNLS)	Spectroscopic ZP	Pred. ZP
u.MP9301	u_1	yes	375	74	25.22	25.21 ± 0.02	25.38
g.MP9401	g_1	yes	487	143	26.48	26.50 ± 0.02	26.45
r.MP9601	r_1	yes	630	124	25.98	26.00 ± 0.02	26.01
i.MP9701	i_1	no			NA	NA	NA
z.MP9801	z_1	yes	NA	NA	24.82	24.89 ± 0.02	24.85
i.MP9702	i_2	yes	770	159	25.86	25.89 ± 0.02	25.98
u.MP9302	u_3	yes	355	86	25.26	25.28 ± 0.02	25.52
g.MP9402	g_3	yes	475	154	26.59	26.62 ± 0.02	26.70
r.MP9602	r_3	yes	640	148	26.22	26.26 ± 0.02	26.32
i.MP9703	i_3	yes	776	155	25.70	25.76 ± 0.02	25.94
z.MP9901	z_3	yes	925	153	24.50	24.52 ± 0.02	24.61

Table I. Megacam filters, old and new, with some of their quantitative properties. The Elixir ZP column refers to estimates based on thousands of stars from the SNLS deep fields, using the SNLS catalog of tertiary standards (Betoule et al. 2013). The Spectroscopic ZP column refers to (manual) estimates based on spectroscopic standard stars from the CALSPEC library (Bohlin et al. 2014) for which synthetic AB magnitudes are computed using the known transmission properties of the instrument and the atmosphere. Note that these estimates *do not* depend on our knowledge of the overall normalization of the transmissions. Finally, the last column gives a (completely theoretical) estimate of the zero points, based this time on our knowledge of the full transmission (spectrum *and* overall amplitude), the gain of the first CCD of the mosaic (the reference of the flat fields), and the telescope aperture. We therefore expect the "Elixir ZP" and "Spectroscopic ZP" columns to be in rather good agreement, while we do expect some scattern in the theoretical predictions. Values in red have suffered from non-photometric conditions.

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III. ANNEX: U BAND OFFSET WITH OLD ELIXIR SDSS COLOR CORRECTIONS

The original color transformation matrix used by elixir to compare "SDSS" magnitudes (in practice the USNO magnitudes of the Smith et al. (2002)standards, to Megacam magnitudes in the (old) uS,gS,rS,iS,zS filters read:

$$\begin{pmatrix} u_S \\ g_S \\ r_S \\ i_S \\ z_S \end{pmatrix} = \begin{pmatrix} 1 & -0.241 & 0.241 & 0 & 0 \\ 0 & 1-0.148 & 0.148 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -0.083 & 1+0.083 & 0 \\ 0 & -0.05 & 0 & 0 & 1+0.05 \end{pmatrix} \cdot \begin{pmatrix} u_{USNO} \\ g_{USNO} \\ r_{USNO} \\ i_{USNO} \\ z_{USNO} \end{pmatrix} \tag{2}$$

It happens that the star BD17 is part of the Smith et al. (2002) measured standards, **and** part of the CALSPEC spectrophotometric standards. We can therefore predict its magnitude in the Megacam bands in two ways: using the color transformation above (equation 2), or using our knowledge of the bandpass transmissions to compute synthetic Megacam magnitudes from its calibrated CALSPEC spectrum. Let us denote the first predictions with and "elx" superscript, and the latter with a "CAL" superscript. Starting from BD17 measurement by Smith et al. (2002) we have:

$$(u, g, r, i, z)_{USNO}(BD17) = (10.56, 9.64, 9.35, 9.25, 9.23)$$

Applying the color transformation of equation 2, we get:

$$(u, g, r, i, z)_S^{elx} = (10.34, 9.60, 9.35, 9.24, 9.21)$$

while the synthetic magnitudes from the CALSPEC spectrum read:

$$(u, g, r, i, z)_S^{CAL} = (10.21, 9.59, 9.34, 9.25, 9.24)$$

and their difference (elixir-CAL) reads:

$$\delta(u, g, r, i, z)_S^{elx-CAL} = (0.13, 0.01, 0.01, -0.01, -0.03) \tag{3}$$

which is probably precise at the centimag level. We see a large discrepency in the u band, and a mild one in the z band, all others being insignificant at this level of precision.

This test relies however on the accuracy of the CALSPEC spectrum, as well as our knowledge of the combined spectral transmission of the atmosphere, the optical chain, as well as the quantum efficiency of the detector (but is insensitive to an overall normalization factor in front of the transmission as we always use calibrated magnitudes, i.e differences between the magnitude of the star and the magnitude of an artificial reference source of constant f_ν for AB magnitudes).

It is therefore interesting to use real measurements of some CALSPEC standard stars of known, calibrated spectra, together with their synthetic magnitudes, to have another estimate of the zero points in a camera run for each star measurement, and to compare it to the Elixir zero points estimated during the same run using the Smith et al. (2002) standard star magnitudes, as well as their corresponding Megacam magnitudes (from observations in the same camera run), and the equation 2 to relate them. While the individual star measurements are bound to be noisy, this is an interesting test to assess wether the difference seen in equation 3 is seen in the same way in the difference between these zero point estimates. Indeed, we expect that if our knowledge of the instrumental transmission is correct (up to a multiplicative constant to which the zero point estimate will be insensitive), the difference seen in equation 3 should be reproduced in the zero point differences.

We therefore selected some observations of the CALSPEC white dwarves P177D and P330E, conducted during camera run 14Am01 for which an elixir zero point was obtained in all bands. These stars are faint enough to be observed directly with Megacam without any defocusing Results are presented in table II.

Finally, the absolute calibration of the CALSPEC spectra (upon which rely the estimates of the individual star zero points), have been shown to be quite accurate. For example, synthetic V magnitudes based on these two stars, compared to real observations in the V band, have been shown to agree at the centimag level or better, see Bohlin and Landolt 2015.

CALSPEC star	u_S	g_S	r_S	i_S	z_S
P177D (obs)	-10.18	-12.57	-12.57	-12.56	-11.56
P177D (cal)	14.71	13.69	13.30	13.19	13.15
P177D ZP	24.89	26.26	25.87	25.75	24.71
P330E (obs)	-10.73	-13.04	NA	NA	-12.02
P330E (cal)	14.16	13.22	NA	NA	12.69
P330E ZP	24.89	26.26	NA	NA	24.71
Elixir ZP	25.06	26.28	25.87	25.74	24.69
Elixir-CAL	0.17	0.02	0.00	-0.01	-0.02
Equation 3	0.13	0.01	0.01	-0.01	-0.03

Table II. Elixir zero point estimates, based on Smith et al. (2002) standard star magnitudes in the USNO photometric system, and observations of these standard stars in the Megacam bands, are established using the color transformations of equation 2. These zero point estimates are compared with individual estimates using observations, during the same run, of the CALSPEC standard stars P177D and P330E, as well as their synthetic magnitudes derived from their CALSPEC calibrated spectra and a model of the complete instrumental transmission (including the atmosphere). The magnitudes with an "obs" subscript are per second, and expressed at unit airmass.. The last rows show respectively the measured zero point differences between the Elixir estimates and the CALSPEC estimates, and the predicted differences using synthetic Megacam magnitudes and observed USNO magnitudes of BD17 (see equation 3). Despite a slight discrepency in the u band, both show that the Elixir zero points are overestimated in the u band by ~ 0.15 mag.