

LETTER TO THE EDITOR

Calibration of the photometric G passband for *Gaia* Data Release 1[★]

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ABSTRACT

Context. On September 2016 the first data from *Gaia* were released (DR1). The first release included photometry for over 10^9 sources in the very broad G system.

Aims. The aims here are to test the correspondence between G magnitudes in DR1 and the synthetic equivalents derived using spectral energy distributions from observed and model spectrophotometry; to correct the G passband curve; and to measure the zero point in the Vega system.

Methods. I have computed the synthetic G and *Tycho-2* $B_T V_T$ photometry for a sample of stars using the Next Generation Spectral Library (NGSL) and the *Hubble* Space Telescope (HST) CALSPEC spectroscopic standards.

Results. I have found that the nominal G passband curve is too blue for the DR1 photometry, as shown by the presence of a color term in the comparison between observed and synthetic magnitudes. A correction to the passband applying a power law in λ with an exponent of 0.783 eliminates the color term. The corrected passband has a Vega zero point of 0.070 ± 0.004 mag.

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

1. Introduction

The first *Gaia* data release (DR1) was published in September 2016 and included positions and G magnitudes for over 10^9 sources to $G = 21$ (Brown et al. 2016). The G passband is very broad, covering from the U to the y bands, although the sensitivity at both extremes is rather low (Jordi et al. 2010 and Fig. 1). The complex photometric calibration of such a large number of sources is presented by Carrasco et al. (2016) and involves both internal and external processes.

Carrasco et al. (2016) described the existence of a color term in the external calibration of the G magnitude scale in the sense that, for a fixed observed value, a blue source was actually brighter than a red one. The difference between two unextinguished O and M stars amounts to about 0.2 mag (see Fig. 14 in Carrasco et al. 2016) and it arises because the nominal G passband of Jordi et al. (2010) differs from the true one. It is not uncommon to have small differences (sometimes of unknown origin) between a lab-measured passband and one measured once the instrument is operating. In this case there was a known contamination effect caused by water freezing in some optical elements, a problem that affected the mission in its early observing stages (Prusti et al. 2016). Carrasco et al. (2016) indicated that the effect would be solved in future data releases by publishing a modified G passband and suggested that, in the meantime, a color correction be applied to the observed G magnitudes when

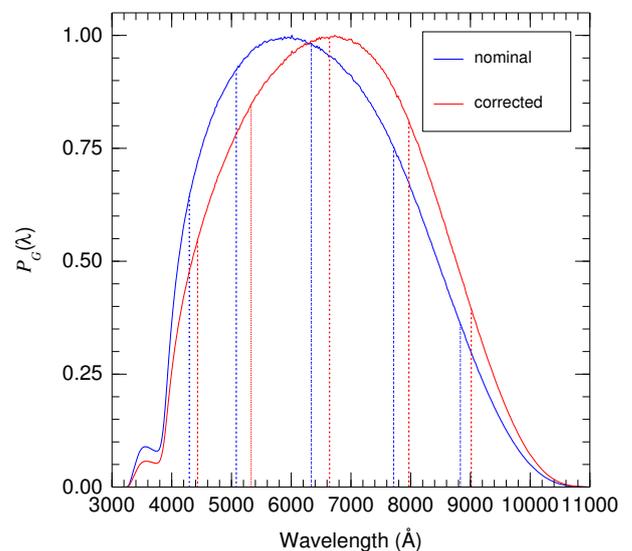


Fig. 1. Nominal and corrected G passbands $P_G(\lambda)$. The dotted vertical lines mark the median and the $\pm\sigma$ and $\pm 2\sigma$ Gaussian percentile equivalents for both passbands.

comparing them with synthetic photometry. That strategy has two problems:

- The color correction is a function of $G_{BP} - G_{RP}$, magnitudes that are not currently accessible as they will not be available until at least the second *Gaia* data release (DR2). Furthermore, the correction itself is not explicitly listed as it only appears in a plot.

[★] Tables 1 and 2 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/608/L8>

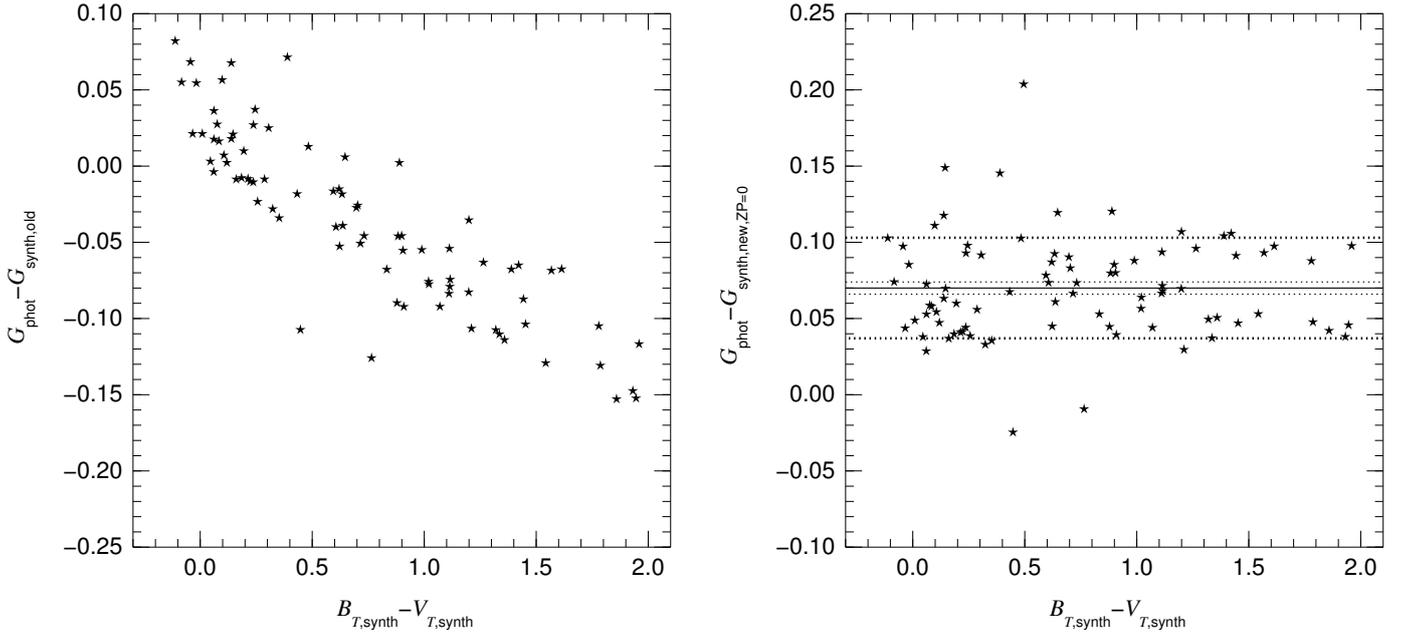


Fig. 2. Difference between the photometric DR1 and the synthetic G magnitudes for the main NGSL+CALSPEC sample in this paper as a function of the synthetic $B_T - V_T$ color. The *left panel* uses the nominal G passband curve and Vega zero point (0.030 mag) while the *right panel* uses the corrected G passband curve and a Vega zero point of 0. The horizontal lines in the right panel show the mean value (solid line, the new zero point) and the range spanned by the standard deviation of the data (thick dashed line, the typical uncertainty of an unsaturated star) and by the standard deviation of the mean (thin dashed line, the uncertainty of the zero point).

- Such color terms may be useful in some cases (van Leeuwen et al. 2017) but they cannot be applied in a general-purpose code for comparing observed and synthetic photometry such as CHORIZOS (Maíz Apellániz 2004), which uses arbitrary filter sets and treats extinction in a detailed manner (extinguishing the SEDs and integrating over the band a posteriori).

For these reasons I decided to attempt a different approach: using existing information to generate a correction to the G passband, a technique I used successfully in Maíz Apellániz (2006) for Johnson U and Strömrgren u . In that way, it should be possible to compare DR1 and synthetic photometry at this time without using color corrections and without having to wait for a future *Gaia* data release. That is the purpose of this Letter.

2. Results

I define the G synthetic magnitude (Maíz Apellániz 2005, 2006, 2007) as:

$$G_{\text{synth}} = -2.5 \log_{10} \left(\frac{\int P_G(\lambda) f_\lambda(\lambda) \lambda d\lambda}{\int P_G(\lambda) f_{\lambda,\text{Vega}}(\lambda) \lambda d\lambda} \right) + ZP_G, \quad (1)$$

where $P_G(\lambda)$ is the total-system passband or efficiency, $f_\lambda(\lambda)$ is the spectral energy distribution (SED) to be measured, $f_{\lambda,\text{Vega}}(\lambda)$ is the Vega (reference) SED, and ZP_G is the zero point in the Vega system. I highlight the fact that our $P_G(\lambda)$ includes three terms in the equivalent definition of Jordi et al. (2010): T , P , and Q , but not λ , that is, it is a photon-counting passband, not an energy-counting one (Maíz Apellániz 2006). The Vega SED is that of the CALSPEC file `alpha_lyr_stis_003.fits` (Bohlin 2007). The nominal passband is that of Jordi et al. (2010), also listed in Table 1, with $ZP_G = 0.030$ mag. Table 1 contains three columns: wavelength (in nm), the nominal total-system passband

from Jordi et al. (2010), and the corrected one from this Letter. It is available at the CDS.

To test the validity of the nominal passband for *Gaia* DR1 magnitudes, I collected Space Telescope Imaging Spectrograph (STIS) spectrophotometry from two sources: the Next Generation Spectral Library (NGSL, Heap & Lindler 2007) and the CALSPEC spectroscopic standards (Bohlin et al. 2017). From those two sources I selected the stars with (a) accurate *Tycho-2* $B_T V_T$ and *Gaia* G photometry, eliminating objects with *Tycho-2* variability flags and objects brighter than $G = 6$, where saturation starts taking place (see below for additional information on G saturation) and (b) coverage of at least the 3000–10 200 Å range. The CALSPEC data were observed with a wide slit and require no further additional flux calibration. The NGSL data were reduced with the same techniques used in Maíz Apellániz (2005) but with the additional step of recalibrating in flux using the V_T magnitude and the zero point of Maíz Apellániz (2007). As the G band has some sensitivity beyond 10 200 Å, the flux was extended until 11 000 Å using both a simple power law extension and 2MASS J photometry (both alternatives yielded very small differences in G_{synth} , at the level of 0.001 mag or less which, as is shown below, is significantly smaller than the effect that is being measured). A total of 84 stars satisfied the requirements and they are given in Table 2. It contains five columns: star name, *Gaia* DR1 ID, J2000 right ascension, J2000 declination, and a flag indicating the SED source (N for NGSL, C for CALSPEC). It is available at the CDS.

The left panel of Fig. 2 shows the difference between the observed G magnitudes (G_{phot}) and G_{synth} for the 84 stars in our sample as a function of the synthetic $B_T - V_T$ color using the nominal passband and zero point. There is a clear linear color term in the vertical scale that amounts to ~ 0.2 magnitudes in the 2 mag range spanned by the $B_T - V_T$ color and that corresponds approximately to the difference between unextinguished

O and M stars. The effect is consistent in sign and amplitude with the one found by Carrasco et al. (2016) discussed above, even though the samples and data used to measure it are different. Therefore, I confirm that the nominal G passband does not accurately describe the *Gaia* DR1 photometry and needs to be corrected, as already indicated by Carrasco et al. (2016).

The likely source of the observed discrepancy (the presence of frozen water in some optical elements during the early stages of the mission) suggests that the passband should be modified not by one or more discrete absorption bands but rather by multiplying it by a continuous smooth function. I chose as such a function a power law in λ , that is, a correction of the type λ^α , and I iteratively tested different values of the exponent α to see the effect on $G_{\text{phot}} - G_{\text{synth}}$ in order to eliminate the color term in the left panel of Fig. 2. After several attempts, the algorithm converged onto $\alpha = 0.783$, with lower values yielding color terms with a negative slope and larger ones overcorrecting to produce a positive slope. The result is shown in the right panel of Fig. 2: the linear color term in $B_T - V_T$ has disappeared (a linear fit yields a slope that is essentially zero) and there are no obvious second- or third-order terms. Therefore, I conclude that modifying the nominal G passband by multiplying it by a power law with an exponent of 0.783 provides a much improved characterization of the photometry when comparing it to observed spectrophotometry. The corrected G passband is shown in Fig. 1 and listed in Table 1.

The right panel of Fig. 2 assumes ZP_G of 0, as that value is a priori unknown. However, it can be easily calculated as the mean value of the data in the plot, which is 0.070. The plot also shows the standard deviation of the data, which is 0.033 mag. Some of that scatter is caused by the photometric uncertainties of the CALSPEC+NGSL data and once I remove that effect we are left with a dispersion of 0.030 mag. That should be the value used to estimate the photometric uncertainty when comparing *Gaia* DR1 photometry with spectrophotometric models. I note that uncertainty is significantly greater than the published flux uncertainties in DR1; I suspect that this is a consequence of the time-variable nature of the contamination, with different stars being observed at different points during the early stages of the mission. If that is the case, the *Gaia* DR2 should be more precise, as more epochs would have been included and the contamination effect would have a lower weight. The uncertainty on the zero point itself can be estimated from the standard deviation of the mean and is 0.004 mag.

As a test of the validity of our calibration, I show in Fig. 3 the observed and synthetic $G - V_T$ colors for the sample of 84 stars as a function of the synthetic $B_T - V_T$ colors, along with the cubic polynomial fit of van Leeuwen et al. (2017). Both the observed and synthetic colors show a good correspondence with the fit (other than the existence of possible higher-order fluctuations). The standard deviation of $(G - V_T)_{\text{phot}} - (G - V_T)_{\text{synth}}$ is 0.032, that is, nearly identical to that of $G_{\text{phot}} - G_{\text{synth}}$. I also show the synthetic photometry for those colors computed from the Maíz Apellániz (2013) grid with solar metallicity. The photometry is reproduced using a wide range of T_{eff} and luminosities and requires a small degree of extinction in some of the stars, as expected from the NGSL+CALSPEC sample.

An application of the new passband is the possibility of correcting saturated DR1 G magnitudes, which are expected to start at $G = 6$. I have selected an extended sample by relaxing the selection criteria to include NGSL stars brighter than that value, which yields an additional 33 stars in the range $G = 3.5-6.0$. The difference between the observed and synthetic magnitudes as a function of the observed G is plotted in Fig. 4, where the

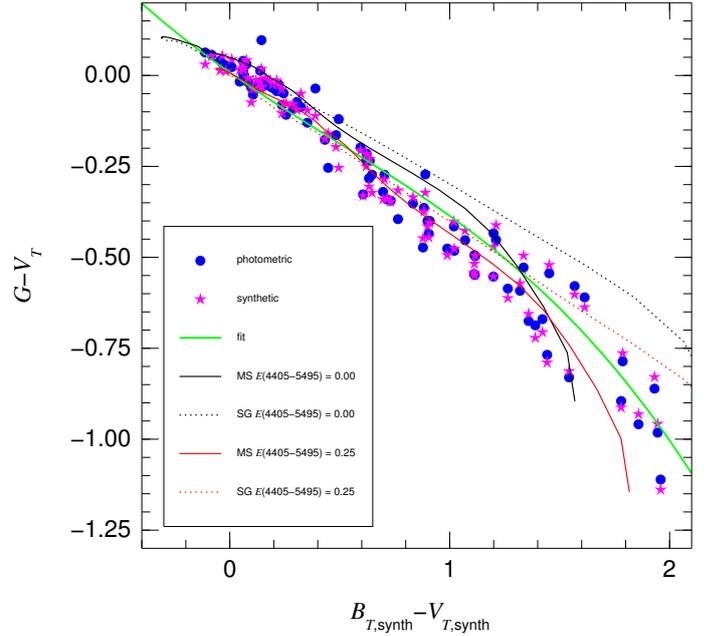


Fig. 3. $G - V_T$ colors as a function of the synthetic $B_T - V_T$ color. Both the observed (or photometric) and the synthetic (using the corrected G passband and the new zero point) values are shown for the vertical axis. The green line is the cubic polynomial fit of van Leeuwen et al. (2017). The other four lines show synthetic photometry for main sequence (MS) and supergiant (SG) solar-metallicity 4000–40 000 K models with no extinction and with $E(4405 - 5495) = 0.25$ and $R_{5495} = 3.1$ from Maíz Apellániz (2013) and Maíz Apellániz et al. (2014).

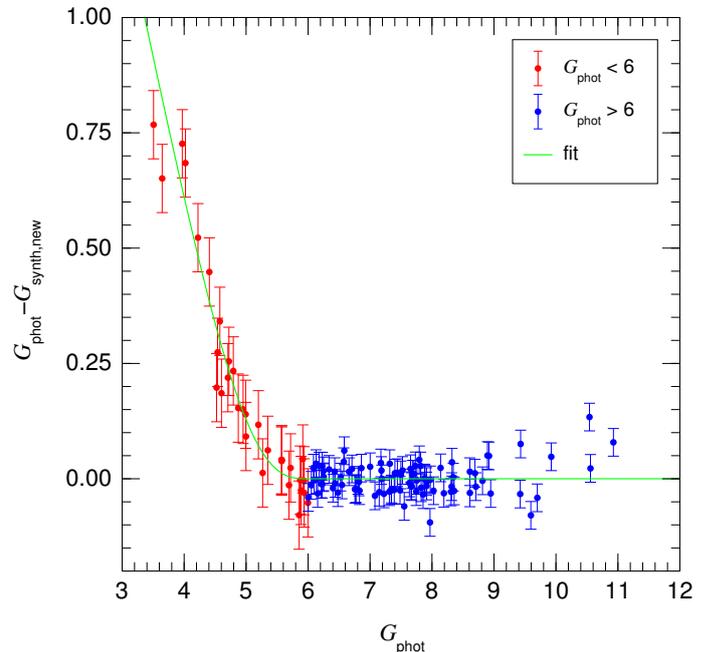


Fig. 4. Difference between the observed DR1 and the synthetic magnitudes for the extended NGSL+CALSPEC sample in this paper as a function of the observed G using the corrected G passband curve and the new zero point of 0.070 mag. Blue points are used for unsaturated objects ($G > 6$) and red for saturated/near-saturated ones ($G < 6$). The green line shows the fit that can be used to correct for saturation in DR1 G magnitudes. The size of the blue error bars corresponds to the typical uncertainty of an unsaturated star (0.030 mag, Fig. 2) while the red error bars correspond to the typical uncertainty of a saturated star, as determined from the standard deviation of the difference between the red points and the green fit (0.074 mag).

onset of saturation is indeed shown to be close to $G = 6$ mag. I note, however, that the scatter in the brighter stars is small. This led me to fit a saturation correction of the form:

$$\Delta = \frac{a(G - 6)^3}{b + (G - 6)^2}, \quad (2)$$

for $G < 6$ and 0 for $G \geq 6$, where a and b are two parameters to be fitted. The best fit yields $a = -0.56$ and $b = 3.39$ and the standard deviation between the data and the fit is 0.074 mag. Therefore, if one uses Eq. 2 with those parameters to correct for G saturation, 0.074 mag should be the photometric uncertainty of the resulting value. I note that the correction has not been tested for objects brighter than $G_{\text{phot}} = 3.5$. Another application of the new passband is the combination of G magnitudes with other sources of photometry to calculate the extinction towards Galactic O stars (Maíz Apellániz & Barbá 2017).

3. Conclusions

I have verified that the nominal G passband curve requires a correction for *Gaia* DR1 data, obtained such a correction, successfully tested it, and applied it to correct saturated magnitudes.

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