Basic assumptions for comparing and optimizing Gaia’s Photometric System

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Abstract. This note summarizes the assumptions and calculations needed to compare and optimize Gaia’s photometric system. Version 2 takes into account changes discussed at GST–10 and subsequently.

1 Introduction

The purpose of this note is to summarize the assumptions and data needed to compare possible variants of Gaia’s photometric system (PS) and to optimize such a system. Although all of this information is readily available elsewhere, it was felt useful to collect the data, or pointers to them, in a single document.

Up-to-date quantitative information about Gaia is available through the Gaia Parameter Database, which is a central, searchable repository of parameters pertaining to the mission and its different elements. It can be accessed from the main Gaia web page at URL www.rssd.esa.int/Gaia/ (Tools, data & software — Gaia parameter database). A password is required to use this tool.

Most of the information relevant for the photometric tasks is also available on the dedicated web site of the Photometry Working Group, gaia.am.ub.es/PWG, to which reference is frequently made in the following.

Briefly, the Gaia satellite will perform photometric measurements by means of two physically separate telescopes: the Astro instrument, which is primarily designed for astrometric observations, and the Spectro instrument, primarily used for photometry and radial-velocity measurements. The two instruments differ widely in spatial resolution, available integration time, and the number and type of filter bands that can be used. These differences are summarized below in Table 1 and Sect. 4. Schematic layouts of the Astro and Spectro focal planes are shown in Fig. 1.

The astrometric observations in the Astro instrument are always made without a filter in order to minimize photon noise. The mirror coatings and CCD quantum efficiency effectively define a very wide photometric band called $G$ (or $G_A$ to distinguish from $G_S$ in Spectro). However, the Astro field also contains the Broad Band Photometer (BBP), consisting of the four last strips of CCDs (BBP1–BBP4) arranged in 10 rows and equipped with interference filters. The Astro field is actually the superposition of two fields on the sky, separated by an angle of order 90°. The main implication of this for photometric measurements is that the apparent sky brightness is doubled [factor $n_{sup}$ in (4)].
The Spectro instrument contains the Medium Band Photometer (MBP), consisting of 20 strips of CCDs (MBP01–MBP20), arranged in 2 rows. The first 10 strips are of the red-enhanced type, the last 10 are blue-enhanced. Four of the red-enhanced strips (MBP01, 02, 06 and 07) are used as sky mappers (i.e., to detect the stars) and do not have filters. The remaining 16 strips (6 red and 10 blue enhanced) may be equipped with interference filters defining up to 16 different photometric bands. However, one of the red filter bands (called RVF) shall cover the same spectral region as the RVS (see below), around 860 nm. The sky mapper strips (without filter) define a very broad photometric band called $G_S$. It differs from $G_A$ in Astro because the mirror coatings, number of reflections, and CCD quantum efficiencies are different.

The Spectro instrument also contains the Radial Velocity Spectrometer (RVS) which observes a small spectral region around 860 nm at a resolution of $\sim 10^4$ in order to determine radial velocities. The measurements in the RVS itself are not used for photometry (at least that is not considered here).

All Gaia observations are made with CCDs operating in TDI (drift-scanning) mode, i.e. with the charge image transported in synchrony with the optical image moving across the field due to the rotation of the satellite. The rotation speed is fixed (60 arcsec s$^{-1}$) which gives a fixed integration time ($\tau$) per CCD crossing, depending on the angular size of the CCD on the sky. Each CCD may be equipped with an interference filter defining (together with the mirrors and the CCD) a certain photometric band ($j$).

Within each field of view (FOV) we define the along-scan direction (AL) to be that in
which the images are transported, and the across-scan direction (AC) as the perpendicular
direction. Thus, a star crosses the FOV in the AL direction at a roughly constant AC
coordinate. A star should preferably encounter the same set of photometric bands on each
FOV crossing, independent of the AC coordinate. (This means that the measurements in
the different bands are quasi-simultaneous, which is definitely an advantage for variable
stars.) Each photometric band thus covers the whole FOV in the AC direction, and is
assigned an integer number of CCD strips (or filter slots) in the AL direction. The total
number of strips or slots available, and thus the total integration time per FOV crossing,
is a given constraint.

The optimization of the Gaia photometric system should allow the best possible deter-
mination of the astrophysical parameters of given target objects, given the fixed set of
instrument characteristics and the constraints on the number of filter slots available and
on the design of filter curves. The meaning of ‘best possible determination’ needs to be
precisely specified, as well as the relative importance of the target objects; this is ad-
dressed in Sect. 5. Because the BBP and the MBP have very different spatial resolution,
and there are regions of the sky where the MBP cannot be used, it is of interest to consider
the optimization of BBP separately from that of the MBP.

2 Calculation of photometric precision

This section summarizes the steps needed to compute the photometric precision (stan-
dard error of the derived magnitude) for an arbitrary spectral energy distribution, filter
characteristics, etc.

It may not be necessary to code these steps, since the calculations can be performed by
means of the interactive web tool GAIA photometry simulator, available at gaia.am.ub.es
/PWG (Tools – Photometry simulator). The corresponding non-interactive code can be
made available on request.

2.1 Absolute stellar fluxes

The formulae below require stellar fluxes $N(\lambda)$ expressed in photons per unit area, time
and wavelength, e.g. in $[\text{ph s}^{-1} \text{ m}^{-2} \text{ nm}^{-1}]$. In addition, the fluxes must be normalized
so that they correspond to a star of magnitude $V = 0$. We propose to adopt the flux
normalization derived by J. de Bruijne in GAIA–JdB–005 (Rev. 1): for any $V = 0$ star,

$$\int_{470 \text{ nm}}^{700 \text{ nm}} N(\lambda)S_V(\lambda)d\lambda = 8.827 \times 10^9 \text{ ph s}^{-1} \text{ m}^{-2}$$

(1)

where $S_V(\lambda)$ is defined in Appendix D of GAIA–JdB–005 (table available at
gaia.am.ub.es/PWG/zero_mag2.html).
2.2 Photon counts

2.2.1 Star

For a star, the expected number of photons detected during a CCD crossing in photometric band \( j \) is:

\[
s_j = \text{dex}(-0.4V_0) \times F \tau \int_0^\infty N(\lambda)T_0(\lambda)T_j(\lambda)Q(\lambda)\text{dex}[-0.4A(\lambda)]d\lambda \quad [\text{e}^-]
\]  

(2)

where \( \lambda \) is wavelength, \( V_0 \) the intrinsic \( V \) magnitude of the star, \( N(\lambda) \) its photon flux in [ph s\(^{-1}\) m\(^{-2}\) n\(^{-1}\)] for \( V_0 = 0 \) (no extinction), and \( A(\lambda) \) the total monochromatic extinction in [mag]. Remaining quantities are defined in Table 1. The average extinction law derived by Cardelli, Clayton and Mathis (ApJ 345, 245, 1989) is used, viz.:

\[
A(\lambda) = A_V \times \left[ a(\lambda) + b(\lambda)/R_V \right]
\]  

(3)

where \( a \) and \( b \) are functions defined by their equations (2)–(4). The value \( R_V = 3.1 \) is assumed unless \( R_V \) is considered a parameter to be determined along with \( A_V \).

2.2.2 Sky background

For the present purpose the brightness of the sky background is assumed to be \( V_{\text{sky}} = 22.5 \) arcsec\(^{-2}\) with a spectral distribution similar to that of the Sun.

The background level \( b_j \) in photometric band \( j \), expressed in number of detected photons per sample, is:

\[
b_j = n_{\text{sup}} \times \text{dex}(-0.4V_{\text{sky}}) \times SF \tau \int_0^\infty N(\lambda)T_0(\lambda)T_j(\lambda)Q(\lambda)d\lambda \quad [\text{e}^- \text{ sample}^{-1}]
\]  

(4)

where \( n_{\text{sup}} \) is the number of superposed fields on the detector and \( S \) is the area of the sample in arcsec\(^2\) (see Table 1); \( N(\lambda) \) is for a solar-type star with \( V = 0 \). The spectrum \((f_\nu \text{ or } f_\lambda, \text{ in energy units})\) for a solar-type star is given in gaia.am.ub.es/PWG/sun.mod (note that \( N(\lambda) \propto f_\nu/\lambda \propto \lambda f_\lambda \)).

2.3 Photometric precision

The photometric precision \( \epsilon_j \) [mag] for a single crossing over a CCD (filter slot) in photometric band \( j \) is estimated via a simple ‘aperture photometry’ process, in which the star plus background is obtained from \( n_s \) samples (assumed to capture all the stellar counts) while the background level is estimated from \( n_b \) other samples, in which the contribution from the star is negligible. Then:

\[
\epsilon_j = 1.2 \times \frac{2.5 \left[ s_j + (b_j + r^2)n_s(1 + n_s/n_b) \right]^{1/2}}{\ln 10 \ s_j}
\]  

(5)

\(^1\)Note that \( A_V \) is not exactly the extinction in the \( V \) band, but the monochromatic extinction \( A(\lambda_{\text{ref}}) \) for \( \lambda_{\text{ref}}^{-1} = 1.82 \) \( \mu \text{m}^{-1} \).
Table 1: Characteristics of the BBP and MBP systems.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Astro</th>
<th>BBP</th>
<th>Spectro</th>
<th>MBP-Blue</th>
<th>MBP-Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$ telescope pupil area</td>
<td>0.70 m$^2$</td>
<td>0.25 m$^2$</td>
<td>0.25 m$^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau$ integration time per CCD</td>
<td>3.31 s</td>
<td>12.0 s</td>
<td>12.0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m$ number of filter slots available</td>
<td>4</td>
<td>10</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_0(\lambda)$ telescope (mirrors) transmittance</td>
<td>$T_{Ag}(\lambda)$$(1)$</td>
<td>$0.8 \times T_{Al}(\lambda)$$(2)$</td>
<td>$T_{Al}(\lambda)$$(2)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_j(\lambda)$ filter transmittance in band $j$</td>
<td>Sect. 4.2</td>
<td>Sect. 4.3</td>
<td>Sect. 4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q(\lambda)$ CCD quantum efficiency</td>
<td>CCD-AF$^{(3)}$</td>
<td>CCD-Blue$^{(4)}$</td>
<td>CCD-Red$^{(5)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S$ sample size on sky [arcsec$^2$]</td>
<td>0.07033</td>
<td>6.031</td>
<td>6.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_{sup}$ number of superposed fields</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r$ read-out noise per sample [e$^-$]</td>
<td>7.8</td>
<td>7.1</td>
<td>7.1$^{(6)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_s$ number of samples used for star</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_b$ number of samples for background</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_{obs}$ mean number of obs./slot (5 years)</td>
<td>82</td>
<td>92</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>corresponding no-filter magnitude</td>
<td>$G_A^{(7)}$</td>
<td>–</td>
<td>$G_s^{(8)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>angular resolution of double stars [arcsec]</td>
<td>0.05–0.1$^{(9)}$</td>
<td>0.5–1$^{(9)}$</td>
<td>0.5–1$^{(9)}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Remarks:

1. 6 reflections in Ag coated mirrors; 100$T_{Ag}(\lambda)$ in gaia.am.ub.es/PWG/instrum/reflectivity-Ag.txt
2. 3 reflections in Al coated mirrors; 100$T_{Al}(\lambda)$ in gaia.am.ub.es/PWG/instrum/reflectivity-Al.txt
   (the extra factor 0.8 in MBP-Blue comes from the dichroic mirror)
3. $Q(\lambda)$ in gaia.am.ub.es/PWG/instrum/qe-CCD-AF
4. $Q(\lambda)$ in gaia.am.ub.es/PWG/instrum/qe-CCD-Blue
5. $Q(\lambda)$ in gaia.am.ub.es/PWG/instrum/qe-CCD-Red
6. read-out noise in MBP08 (RVF) is $7.1 \times \sqrt{5} = 15.8$ e$^-$
7. measured in the Astrometric Field (AF)
8. measured in the Spectro Sky Mappers (SSM1 through SSM4)
9. according to GAIA–CUO–126

The factor 1.2 is an error margin (to include calibration errors etc). This is the precision per filter slot. If photometric band $j$ is assigned $k_j$ slots, then the photometric precision per FOV crossing is $\epsilon_j/\sqrt{k_j}$ and the mission-averaged precision is

$$\sigma_j = \epsilon_j \left[ n_{obs} k_j \right]^{-1/2} \quad (6)$$

The assignment of slots to the different photometric bands must respect the constraints

$$\sum_j k_j \leq m \quad (7)$$

separately for the BBP, MBP-Blue and MBP-Red.$^2$

$^2$The QE of MBP-Blue is optimized for the blue part of the spectrum and that of MBP-Red for the red part. The crossover wavelength is around 570 nm, but there is in principle no restriction against placing e.g. a blue filter band in MBP-Red.
2.4 G magnitudes

CCDs without a filter define a very wide photometric band called $G$ (for Gaia). However, since Astro and Spectro use different mirror coatings and CCDs, we have in practice (at least) two different $G$ bands designated $G_A$ and $G_S$. The photon fluxes are obtained from (2) by putting $T_j(\lambda) \equiv 1$. The zero point of the magnitude scales are such that $G_A = G_S = V$ for an unreddened A0V star (synthetic spectrum at gaia.am.ub.es/PWG/vega.mod).

Since the integration time per CCD may vary, the $G$ magnitudes are best defined in terms of count rates $(s_0/\tau)$ rather than integrated counts ($s_0$).

The astrometric accuracy (Sect. 3) depends mainly on the $G_A$ magnitude. With the parameters in Table 1 we find that $G_A = 0$ gives the count rate $s_0/\tau = 1.4433 \times 10^{10} \text{e}^{-\text{s}^{-1}}$. Thus:

$$G_A = 25.3984 - 2.5 \log(s_0/\tau) \quad (8)$$

where

$$s_0/\tau = \text{dex}(-0.4V_0) \times F \int_0^\infty N(\lambda)T_0(\lambda)Q(\lambda)\text{dex}[-0.4A(\lambda)]d\lambda \quad [\text{e}^{-\text{s}^{-1}}] \quad (9)$$

(all data referring to the Astro instrument).

3 Parallax accuracy

Design of the Gaia photometric system should take into account that distance information (in the form of trigonometric parallaxes) will be available for many of the stars, depending on their magnitude and distance.

The accuracy of the trigonometric parallax (as a mean value over the sky) is approximately given by (GAIA–LL–048)

$$\sigma_\pi = 0.0639 \times \left[2700 + 530u + 0.05u^2\right]^{1/2} \mu\text{as} \quad (10)$$

where $u = 10^{0.4(G_A-10)}$. For $G_A = 12, 15, 18$ we have $\sigma_\pi = 5, 15, 63 \mu\text{as}$.

4 Constraints on filter curves

4.1 Basic passband shape

The basic transmittance curve versus wavelength is a symmetric quasi-trapezoidal shape with a flat maximum transmittance of $T_{\text{max}}$. The symmetric trapezoid may be parameterized by three numbers: the central wavelength $\lambda_0$, the bandwidth (FWHM) $\Delta \lambda$, and the ‘edge width’ $\delta \lambda$ (i.e. the distance from $T = 0$ to $T = T_{\text{max}}$ on the blue side, and from $T = T_{\text{max}}$ to $T = 0$ on the red side of the idealized trapezoidal shape). Instead of $\lambda_0$ and $\Delta \lambda$ we may use the wavelengths of the blue edge $\lambda_{\text{blue}} = \lambda_0 - \frac{1}{2}\Delta \lambda$ and red edge
\[ \lambda_{\text{blue}} = \lambda_0 + \frac{1}{2} \Delta \lambda. \] The sharp corners of the trapezoid are rounded through convolution with a triangular function whose FWHM is \( w \).

Outside the quasi-trapezoidal filter band, i.e. for \( \lambda < \lambda_0 - \frac{1}{2}(\Delta \lambda + \delta \lambda) - w \) and \( \lambda > \lambda_0 + \frac{1}{2}(\Delta \lambda + \delta \lambda) + w \), it is assumed that \( T = 0 \). (Leakage requirements will be studied separately once a good photometric system has been identified.)

### 4.2 Broad Band Photometer

The transmittance curves \( T_j(\lambda) \) for the BBP filters must satisfy the following constraints:

1. the number of different curves is in the range 3 to 4 (but see below)
2. each curve consists of a single basic quasi-trapezoidal passband
3. \( T_{\text{max}} = 0.9 \)
4. \( 60 \leq \Delta \lambda \leq 300 \) nm
5. \( 10 \leq \delta \lambda \leq 60 \) nm
6. \( \lambda_{\text{blue}} \geq 425 \) nm
7. \( \lambda_{\text{red}} \leq 965 \) nm
8. the bands shall be contiguous (i.e., together covering the whole range 425 to 965 nm), except that one single gap (corresponding to a ‘virtual filter’ as explained below) is allowed.

The BBP consist of 40 CCDs arranged in 4 strips and 10 rows. In principle, filter bands could be distributed among the 40 CCDs in any combination that we may wish from a scientific viewpoint. If not all rows use the same filters then there is a corresponding reduction in the mean number of observations per slot \( (n_{\text{obs}}) \). For instance, if one of the bands is only present in 5 of the 10 rows, then \( n_{\text{obs}} = 41 \) must be used for that band.

In view of this, and because of possible problems with variable stars, it is highly desirable to have the same set of filter bands for all 10 rows. This means that the maximum number of BBP bands equals the number of slots, \( m = 4 \). Within this constraint, two options seem especially interesting:

- **Option 1:** Use 4 broad-band filters covering the whole spectral range, except for one broad gap. The flux in this gap, or ‘virtual filter’, may in principle be obtained by means of the \( G_A \) flux measured in AF01–11, using the background from AF11 and subtracting the flux from the 4 BBP bands, although it is probably better to regard this as an instance of 5 independent bands (BBP1–4 plus \( G_A \)). In any case this option should be equivalent to 5-band photometry.

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3 Actually, the transmittance curve could be described as the convolution of four rectangular functions of width \( \Delta \lambda, \delta \lambda, w \) and \( w \).

4 The constraints are derived from practical limitations on the filter manufacturing and from the need to use the BBP fluxes for chromaticity calibration of the astrometric instrument.

5 However, in order to ensure good determination of chromaticity it is required that at least the two most extreme (the bluest and reddest bands) should be present in every row.
• Option 2: Use a medium-band filter centred on the 510 nm feature and 3 broad bands plus a broad gap. This is equivalent to 4-band photometry plus a narrower band specifically for metallicity.

4.3 Medium Band Photometer

The transmittance curves $T_j(\lambda)$ for the MBP filters must satisfy the following constraints:

1. the number of different curves is at most 16
2. $T_{\text{max}} = 0.9$
3. $\Delta \lambda \geq 5$ nm
4. $2 \leq \delta \lambda = 14$ nm
5. $\lambda_{\text{blue}} \geq 280$ nm
6. $\lambda_{\text{red}} \leq 1000$ nm.
7. one band shall measure the 860 nm band ($\Delta \lambda \simeq 32$ nm centred on 861 nm) with $\lambda_{\text{blue}} = 845 \pm 1$ nm, $\lambda_{\text{red}} = 877 \pm 1$ nm, and $\delta \lambda = 6$ nm. This is the Radial Velocity Filter, RVF (placed as MBP08).


5 Scientific targets

In order to design a photometric system (PS) for Gaia, the Photometry Working Group agreed on defining a set of scientific targets among the objects observable by Gaia, for which the photometric system should be optimized. The selection of targets has to ensure that the scientific goals of the mission can be achieved. A draft definition of scientific targets is given in:


A preliminary quantification of the priorities of the different scientific targets is given in: