Gaia spectro-photometry absolute calibration
and comparison to classical systems

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DU13: provide spectrophotometric standard stars (SPSS)


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DU14: provide integrated photometry and BP/RP calibration model

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Classical spectro-photometry

The aim of spectro-photometric calibration


The ingredients:

- The data: observed magnitude values in various bands or spectra (pre-reduced, i.e. flat-field, bias, dark etc. corrected)

- Knowledge of (and correction from) atmospheric absorption - not needed for space observations

- Knowledge (and use) of the instrument response

- Use of constant brightness standard stars - calibrators
Definition of a spectro-photometric system

M.S. Bessell (1999), PASP, 111, 1426; Altavilla et al. (2010), GAIA-C5-TN-OABO-GA-004

photometry

\[ m_x = C - 2.5 \log \int f(\lambda) T_x(\lambda) \, d\lambda \]

spectro-photometry

\[ s(\lambda) = C [ f(\lambda) T(\lambda) ] \]

- \( f(\lambda) \): the stellar SED in [photons s\(^{-1}\) m\(^{-2}\) nm\(^{-1}\)]
- \( C/C \): zero point defined by a standard star (e.g. unreddened A0V, Vega)
- \( T(\lambda) \): the instrument response function, convolution of
  - area of the telescope primary mirror (entrance pupil area)
  - telescope (mirrors) transmission and optical characteristics
  - camera optics & detector CCD quantum efficiency (QE)
  - filter-coating transmission
  - prism transmission (spectrograph)
Atmospheric absorption

In the optical range, extinction is a combination of:

- **continuous** absorption from Rayleigh scattering of gas molecules - varies with $\lambda^{-4}$ and linearly with airmass (airmass $\approx$ sec $Z$)
- **neutral absorption** from dust and aerosols - non-linear variation with airmass
- **telluric** features

Extinction is measured by observing **standard stars at different airmass** (e.g. in the meridian and at high airmass). Red and blue standard stars are observed to solve for the colour term in the extinction

$\Rightarrow$ extinction coefficients, e.g. $k_i$ (mag/airmass) $\Rightarrow$ extinction law as a function of $\lambda$

The observed instrumental magnitudes ($m_i$) are corrected to outside the atmosphere ($m_{i0}$) by extrapolating to zero airmass $\Rightarrow m_{i0} = m_i - (k_i \times \text{airmass}) - (k_i \times \text{airmass} \times \text{colour})$

The observed instrumental spectra are corrected to outside the atmosphere by applying extinction law $\times$ appropriate airmass
Atmospheric absorption

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> extinction coefficient: $k_i (\text{mag/airmass})$  \rightarrow extinction law as a function of $\lambda$

The observed instrumental magnitudes ($m_i$) are corrected to outside the atmosphere ($m_{i0}$) by extrapolating to zero airmass

> $m_{i0} = m_i - (k_i \times \text{airmass}) - (k_i \times \text{airmass} \times \text{color})$

The observed instrumental spectra are corrected to outside the atmosphere by applying extinction law x appropriate airmass
Photometry: instrument response

Oke (1965): outlined the system of pseudo monochromatic photometry that is the basis of all spectrophotometric calibrations.

Johnson (1966): established the UBVRIJHKLMN system of broad-band photometry extending from 300nm to 10μ that forms the basis of all subsequent broad-band systems. Fluxes are normalized to that of Vega.

Strömgren (1966): devised the intermediate-band uvby system to better measure the temperature, gravity, metallicity and reddening of early-type stars (hotter than the Sun).

Presently, more than 200 photometric systems known

Info on several conventional photometric systems in: http://stsdas.stsci.edu/documents/SyG_95/

Asiago DB: http://ulisse.pd.astro.it/Astro/ADPS/
Lausanne DB: http://obswww.unige.ch/gcpd/gcpd.html
Photometry calibration

Photometric observations are calibrated through the use of networks of constant brightness standard stars (SS)

To put observations on a standard system: derive the calibration equation = difference between the extinction corrected instrumental values $m_{i0}$ and the standard $m$ value as a function of color:

$$m_{i0} - m = ZP + \alpha(\text{color})$$

$\alpha$ (varying extinction across broad band, difference in filter band wrt standard) should be as small as possible ($< \pm 0.05$);

$ZP$ is the zeropoint constant (includes any neutral extinction residual, aperture correction, etc.)

In principle, only one blue and one red SS are needed to solve for the calibration equation $\rightarrow$ derive $ZP$ and $\alpha$ $\rightarrow$ calibrate photometric observations.

In practice, a few more are used for accuracy and reliability:

$\rightarrow$ color range of SS should be large enough to encompass color range of target objects
$\rightarrow$ enough SS should be observed during the night to monitor the changing conditions

Each photometric system has produced a list of standard magnitudes and colors measured at specific bandpasses for a set of stars that are well distributed across the sky.
Spectra: instrument response & calibration

The instrument response curve - $C(\lambda)$ - is obtained by comparing the observed spectrum of spectro-photometric standard stars (SPSS) with the corresponding tabulated absolute flux values - SED($\lambda$)

$$C(\lambda) = \frac{O(\lambda)}{SED(\lambda)} \quad \text{(DOLoRes LR-B)}$$

⇒ flux calibration of any given spectrum:
$$S_{\text{cal}}(\lambda) = \frac{S_{\text{obs}}(\lambda)}{C(\lambda)}$$

In principle, only one SPSS is needed for spectrophotometric calibration

HZ44 spectrum:
- before (left panel)
- after (right panel)
absolute flux calibration
Gaia spectro-photometric system

- same principle as for classical spectrophotometry
- much more complicated instrument model

Courtesy A. Brown
Gaia spectro-photometry

Input data: internally calibrated $G/G_{BP}/G_{RP}$ mean magnitudes (flux/mag) & BP/RP mean spectra – undergone three basic transformations:

→ epoch data: pre-processed (corrected by internal instrumental effects)

→ corrected to a *fiducial instrument* represented by the *nominal* instrument model stored in the PDB

→ averaged to produce mean values on an internally consistent flux scale

To tie the internal flux scale to the absolute flux scale

→ absolute (external) calibration to derive the true (absolute) instrument model using a set of SPSS

► accuracy requirements: order of mmags (phot) or a few % (spectra)
► depends on accuracy of internal calibrated data & SPSS SEDs
► goal: minimum contribution of calibration model on error budget
Goal: derive true filter bandpass (\(FB_{\text{true}}\)) using SPSS data. For all SPSS:

\[
G_i = [S] \times FB_{i,\text{true}} \quad \Rightarrow \quad G_i = [S] \times (FB_{i,\text{PDB}} \times FB_{i,\text{corr}})
\]

- \(G_i\): m-dimen vector of observed integrated flux values
  - \((m = \text{number of SPSS} \sim 200, \text{ see GAIA-C5-TN-OABO-GA-003})\)
- \([S]\): matrix of \(n(\lambda)\) tabular flux data points (SED) per m SPSS
  - \(n(\lambda) \sim \text{a few} \, 10^3 \text{ if SED sampled at high resolution}\)
- \(FB_{i,\text{true}}\): n-dimen vector of filter band \(i\) sampled at \(n(\lambda)\) data points

- calibration model needs to decrease dimensionality to \(n(\lambda) \leq m\)
  - force a continuum filter shape \(\rightarrow\) smoothing procedure
- the \textit{nominal} instrument model \(FB_{i,\text{PDB}}\) sets the basic shape
- the \textit{correction} vector \(FB_{i,\text{corr}}\) defines the residual differences between the predicted (from \(FB_{i,\text{PDB}}\)) and the observed SPSS data
- \(FB_{\text{true}}\) is to be determined by least square fit of these residual differences
G band calibration: preliminary

G bands: fitted (=true) nominal

Ratio of fitted and nominal bands wrt $FB^{\text{true}}$

G − g − ZP (mmag): colour equation

Simulations: the purpose is to account for any colour dependence

→ the calibration model should be the fitted filter band & the zero-point ZP defined by it, no colour equation → G band is OK
BP band calibration: preliminary

BP bands: fitted nominal true

Ratio of fitted and nominal bands wrt $F_{B_P}^{true}$

$G_{BP} - g_{BP} - ZP$ (mmag): colour equation

Simulations: flat colour equation, zero-point $\sim -4\%$ (flux loss ) $\rightarrow$ BP band is OK
RP band calibration: preliminary

RP bands: fitted, nominal, true

Ratio of fitted and nominal bands wrt $FB^{\text{true}}$

$G_{\text{RP}}$ fitted $- g_{\text{RP}}$ obs. - ZP (mmag): colour equation

Simulations: the colour equation is not flat $\Rightarrow$ numerical problems (to be further investigated)
BP/RP spectra: external calibration model

For details see P. Montegriffo: GAIA-C5-TN-OABO-PMN-002, GAIA-C5-TN-OABO-PMN-003, and M09 @ Leiden, 18-20 May 2010

Mean (internally calibrated) spectra can be modeled as:

\[ S_{\text{obs}}(\kappa) = C \int T(\lambda) L_{\lambda}(\kappa - \kappa_p(\lambda)) S_{\text{true}}(\lambda) \, d\lambda \]

discretized as:

\[ S_{\text{obs}}(\kappa_i) \approx C \sum_j T(\lambda_j) L_{\lambda_j}(\kappa_i - \kappa_p(\lambda_j)) S_{\text{true}}(\lambda_j) \, \Delta\lambda \]

\( T(\lambda_j): \) filter response; \( L_{\lambda_j}: \) monochromatic LSF; \( k_i: \) AL px coordinate; \( k_p(\lambda_j): \) dispersion function

write as matrix equation:

\[ S_{\text{obs}} = D \times S_{\text{true}} \]
BP/RP spectra: dispersion functions

Dispersion matrix $D$ for BP (top) and RP (bottom) instruments for FoV 1 and CCD row no 4:

- the profile of the columns represents the $\text{LSF}_{\lambda j}$ that peaks on the dispersion function at the corresponding wavelength

- the profile of the rows shows the distribution as a function of wavelength of the photons contributing to light in each sample

- the elements defining $D$ vary across the focal plane: the absolute calibration refers to the fiducial instrument $D$

GAIA-C5-TN-OABO-PMN-002
BP/RP spectra: external calibration model

Reduce dimensionality of $S_{\text{true}}$ by approximating with a smooth function:

$$S_{\text{obs}} = D \times S_{\text{true}}$$

$S_{\text{true}} \rightarrow S_{\text{smooth}} \rightarrow S_{\text{obs}} \approx D_e \times S_{\text{smooth}}$

- Coefficients $S_{\text{smooth}}$ are known for the SPSS from the approximation model
- Solve for *fiducial* instrument model $D_e$ using the SPSS observations
- Apply $D_e^{-1}$ as the calibration model for the other stars
- Method removes LSF smearing and absorbs residual systematic errors
- Automatically produces wavelength scale to ~ 0.1 of a pixel accuracy (see PMN-004)
BP/RP spectra: hybrid model - preliminary

\[ S_{obs} = \begin{bmatrix} D_e \end{bmatrix} \times S_{smooth} \]

- Express \( D_e \) as the product between the nominal dispersion matrix \( DM \) and a square matrix \( K \) (the kernel) \( D_e = K \times D_n \)
  \[ S_{obs} = K \times (D_n \times S_{smooth}) \]
- \( K \) is fitted with SPSS
- The fitting algorithms:
  - least squares fit on each row independently
  - parametrized fit as in JMC-008:
    \[ K_{ij} = \sum_{l=0,L} c_{il} (i - i_{ref})^l \]
Preliminary results

Cleaner Effective Dispersion Matrix ➔ easier extraction of the Dispersion Curve
Preliminary results

Column # 45 for BP Effective Dispersion Matrix: effective vs. nominal LSF$_\lambda$
Spectro-Photometric Standard Stars

DU13 task: provide the grid of SPSS (homogeneous flux scale)
Details in GAIA-C5-TN-OABO-GA-003

▷ three pillars from CALSPEC, V ~ 11.5 to 13.5, calibrated on Vega
▷ 48 primary standards, V ~ 9 to 14, across the sky
▷ ~ 200 secondary standards, V down to ~ 15, preferentially with maximum number of transits
▷ all spectral types, from bluest (e.g. WDs) to reddest (late types, reddened)

Addition of SEGUE stars (TBD): homogeneous flux scale (to be verified), fainter but several thousands → characterisation of entire focal plane?

Observing campaign:

▷ more than 200 nights already observed
▷ spectroscopy complete to ~ 80%
▷ absolute photometry complete to ~ 22%
▷ short (long) term variability monitoring nearly completed (ongoing)
▷ expected completion by 2013