Highlights of Spanish Astrophysics VIII, Proceedings of the XI Scientific Meeting of the Spanish Astronomical Society held on September 8–12, 2014, in Teruel, Spain. A. J. Cenarro, F. Figueras, C. Hernández-Monteagudo, J. Trujillo Bueno, and L. Valdivielso (eds.)

Selection of stars to calibrate *Gaia*

J. M. Carrasco[1], H. Voss[1], C. Jordi[1], C. Fabricius[1], E. Pancino[2], and G. Altavilla[2]

[1] Departament d'Astronomia i Meteorologia, Institut del Ciències del Cosmos (ICC), Universitat de Barcelona (IEEC-UB), c/ Martí i Franquès, 1, 08028 Barcelona, Spain, carrasco@am.ub.es
[2] Osservatorio Astronomico di Bologna, INAF, Via C. Ranzani, 1, I-40127, Bologna, Italy

Abstract

Gaia is an all-sky survey satellite, launched by ESA on 19th December 2013, to obtain parallaxes and proper motions to microarcsecond level precision, radial velocities and astrophysical parameters for about one billion objects down to a limiting magnitude of 20. The chosen strategy to perform the photometric calibration is to split the process into two steps, internal and external calibration.
The internal calibration will combine all different transits of a given source to a common reference internal system producing a 'mean' *Gaia* observation. This internal calibration accounts for the differential instrumental effects (in sensitivity, aperture, PSF, etc.). They depend on the colour and type of the source. For this reason, a selection of calibration sources ensuring a good representation of all kind of observed sources is needed. The entire magnitude and colour range of the sources have to be covered by these calibration stars and for all calibration intervals. It is a challenge to obtain a suitable colour distribution for the standards, especially for bright sources and the daily large scale calibration intervals.
Once the mean *Gaia* observations are produced, a final step, the external calibration, transforms them to absolute fluxes and wavelengths. In principle, few calibration sources are needed (about 200 spectrophotometric standard stars, SPSS, are currently being considered). They need to have accurate determinations of their absolute fluxes and their non-variability need to be ensured below 1% precision. For this purpose, a big international observational effort is being done (using telescopes as 2.2m@CAHA, TNG@LaPalma, NTT@LaSilla, LaRuca@SPM, and others). During this observational effort some cases of non-expected variability of the SPSS candidates have been discovered.

1 Introduction

Gaia is the successor of the ESA Hipparcos astrometric mission and improves its capabilities drastically, both in precision (2 orders of magnitude better) and in number (4 orders of magnitude more) of observed sources, offering the opportunity to tackle many open questions about the Galaxy (its formation and evolution, as well as stellar physics). See [4, 1] for a full description of the *Gaia* mission.

The *Gaia* payload consists of three instruments mounted on a single optical bench: the astrometric instrument, the spectrophotometric instrument, and one high-resolution spectrograph to derive radial velocities. The astrometric measurements will be unfiltered to obtain the highest possible signal-to-noise ratio. The mirror coatings and CCD quantum efficiency define a broad (white-light) passband named G. The basic shape of the spectral energy distribution (SED) of every source will be obtained by the BP and RP spectrophotometers, which provide low-resolution spectra in the blue ($330 - 680$ nm) and red ($640 - 1000$ nm) respectively (see [4, 2] for a detailed description). The integrated BP and RP spectra will also produce the corresponding $G_{\rm BP}$ and $G_{\rm RP}$ magnitudes, and hence a colour too.

We describe how to select useful standard sources to calibrate *Gaia* photometry (G, $G_{\rm BP}$ and $G_{\rm RP}$ passbands) and spectrophotometry. After briefly describing the *Gaia* photometric calibration (Sect. 2) we describe the procedure to select the internal (Sect. 3) and external (Sect. 4) calibration *Gaia* standards. Finally, in Sect.5 we present the summary and conclusions of this work.

2 *Gaia* photometric calibration scheme

Gaia photometry is calibrated in DPAC (Data Processing and Analysis Consortium) framework by the fifth coordination unit (CU5), with members from several institutes around Europe (mainly Cambridge, Barcelona, Bologna, Leiden, Edinburgh).

As *Gaia* will observe one billion sources of many different kinds and colours, and also due to the complexity of the instrument itself, it is not feasible to calibrate their observations by using only a small set of calibrators with a limited range of types and neither to calibrate their observations from ground (due to the variety of sources to be calibrated). For this reason, the photometric calibration model for *Gaia* has been designed splitting the process into three phases (see left panel in Fig. 1):

Pre-processing. In this first phase, the raw observations are processed in order to "clean" them from several effects. At this stage bias and background is subtracted and possible contamination and blending effects are considered. The radiation effects on CCDs in space produce image and spectral distortions due to charge transfer inefficiency (CTI) when reading the exposure. This effect should also be accounted in this pre-processing stage.

Internal calibration. This step links all observations into a common "mean" instrumental system. We consider effects like the overall sensitivity variation (due to the optics and the CCDs), flux losses by aperture effect, variations of the PSF/LSF, spectral dispersion and geometry, tilts, etc., and their variations across the focal plane. *Gaia* has the largest focal plane built for space up to now, with 106 CCDs and about one billion pixels spread in $1.04\,{\rm m} \times 0.42\,{\rm m}$. This implies an increase in complexity and

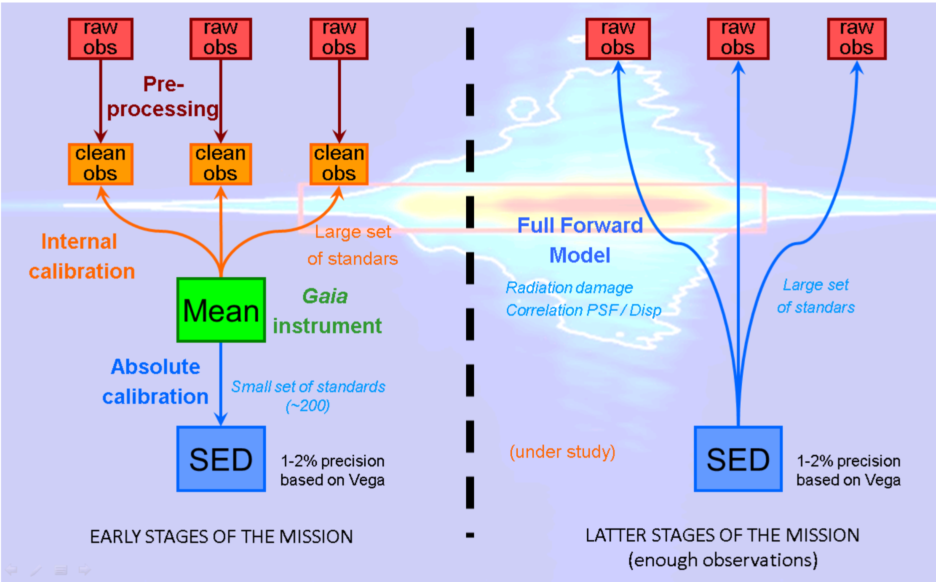

Figure 1: *Gaia* photometric calibration scheme. The calibration model used in the early stages of the mission are shown at left of the figure. The scheme aimed to be used when enough observations are available, called Full Forward Model, is depicted at the right panel.

heterogeneity in the observing conditions for every measurement, and because of this we need a large number (millions) of internal reference stars in order to ensure enough observations in every calibration unit (defined in space and time).

External calibration. The final link of the "mean" instrumental system with the absolute fluxes and wavelengths of each spectra is done by the external calibration. This step relies on a more limited amount of spectrophotometric standards stars (SPSS, about 200).

In a later stage of the mission, when enough observations will be available, we are planning to substitute the scheme explained above by a more direct procedure (Fig. 1, right), called "Full Forward Model", which will allow a direct prediction of *Gaia* observations from the absolute SED without the need of intermediate steps. This approach is still under development.

In the following section we describe the selection strategy for the calibration sources in the current scheme (Fig. 1; left).

3 Internal reference stars

Every individual observation will be done with some particular combination of CCD and pixel sensitivity, PSF, spectral dispersion, geometry, etc. Because of this, we need to ensure to have enough observations at every observing condition to allow its calibration. Then, a large set (millions) of well-behaved sources are needed.

We have split the internal calibration into a large and a small scale calibration.

Large scale calibration is done for the whole CCD on a daily basis (as we are using observations obtained in every pixel inside the CCD, we will have enough observations in a day to allow its calibration). On the other hand, the small scale calibration will analyse groups of pixel columns in a monthly basis (when enough observation will be available in such a small scale).

The *Gaia* photometric calibration needs to ensure that it will be valid for all types of sources observed. For this reason the selected reference stars, which have to be constant in flux, need also to be evenly distributed over magnitude, colour (and reddening) and sky position. But this requirement is quite difficult to accomplish. For instance, the colour distribution changes with magnitude, sky position, etc. The result is that, despite observing one billion sources, there are not enough sources to select such a perfect set of standards in sufficient numbers.

Then, some compromises have to be made. The internal standards selection is done only flattening the colour and sky position distribution, but no flattening is being done in magnitude.

The fraction of sources selected depends on brightness of the source (exposure time and window class), and in order to ensure enough reference stars in the sample, the selection fraction has been considered quite high (up to 50% for bright sources, see Fig. 2), allowing then the presence of some non-constant stars but in minority with respect to the total sample. HEALPix level 3 bins (the sky is divided in 768 equal areas) are being considered to derive the relatively flat spatial distribution in the sky.

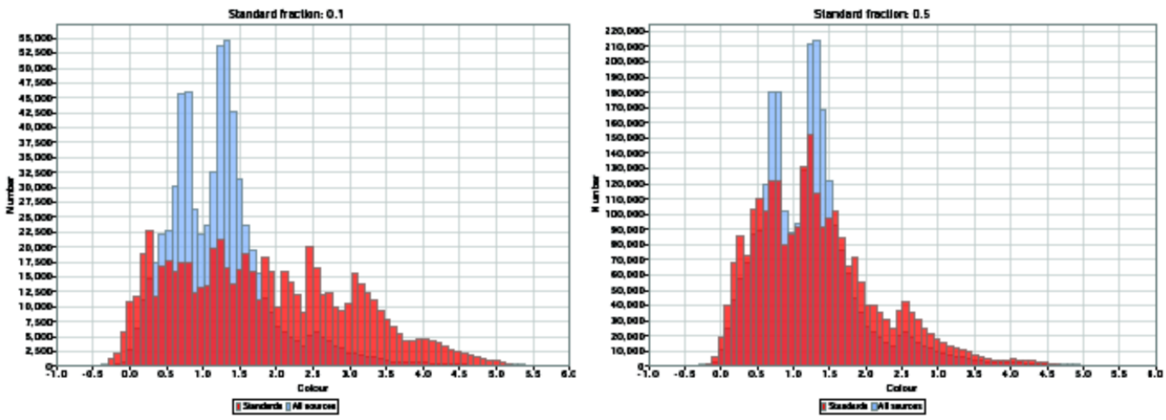

Figure 2: *Gaia* internal calibration selection. When 10% (*left* panel) of the total number of sources (blue histogram) are selected we can get a quite flat distribution in colour (red histogram), but not enough reference sources are present. For this reason the selection fraction has been increased up to 50% (*right* panel) and then, we do not get a so flat distribution. Figure courtesy of D. W. Evans.

4 External reference stars

Once each observation for each object is reported to the internal reference scales, the absolute or external calibration will use an appropriate SPSS set to report the relative flux scale to an absolute flux scale in physical units, tied to the calibration of Vega (see [3] for more details).

The set of (about 200) SPSS SEDs need to have $R = \lambda/\Delta\lambda \sim 1000$ in order to have at least 4–5 times the *Gaia* spectrophotometric resolution. They also have to cover the full *Gaia* wavelength coverage ($330 - 1050$ nm) and different spectral types (although a large fraction should consist in hot stars, as featureless as possible). They should also be constant sources (± 5 mmag) and quite bright ($V = 9 - 15$ mag) in order to have enough signal-to-noise ratio ($S/N \sim 100$) in *Gaia* observations, but without saturating. At the same time, the SPSS set has to have very homogeneous data treatment and quality (their flux tables should have $\sim 1\%$ internal precision).

There was no existing reference stars dataset covering all these requirements and, then, in mid-2006 we started our own observational programme. Up to now more than 450 nights at 8 different telescopes (covering northern and southern hemispheres) have been granted (more than half in visitor mode). The instruments@telecopes used in this observational programme are CAFOS@CAHA, DoLoRes@TNG, EFOSC2@NTT, ROSS@REM, LaRuca@SPM, BFOSC@Loiano, ALFOSC@NOT and Meia@OAdM.

This programme is obtaining spectroscopic and also photometric data for our candidates. Photometric data is needed in order to monitor our candidates for short and long term variability and to get their absolute photometry to fix the spectra zero points when needed

Although this observational programme is aimed to be concluded in mid-2015, we have already released to DPAC a list of 94 SPSS used during commissioning phase (the position in the sky and magnitude and spectral type distributions of the full list of SPSS candidates can be seen in Fig. 3). Some other candidates were rejected due mainly to unexpected variability, binarity or wrong associations in SIMBAD database or other literature problems [3]. The quality of this data is better than 1% in the central wavelength range and $2 - 5\%$ in the red wavelength range (due to fringing issues). The blue edge of the SEDs is also noisier than the central part, due to the decrease in the response of the used detectors.

5 Conclusions

In the case of *Gaia*, several instrumental effects (much more complex than those usually encountered) are affecting the spectrophotometric observations. Because of this, a new approach is required to derive the calibration model and to select the set of reference stars needed to perform the actual calibration.

A flux calibration model is currently implemented in the photometric pipeline, which splits the calibration into an internal and an external part. The internal calibration model uses a large number of well-behaved stars (internal reference stars) to report all observations to a “mean” reference instrument, on the same instrumental relative flux and wavelength scales. After the internal reference scale is defined, the external calibration uses a set of

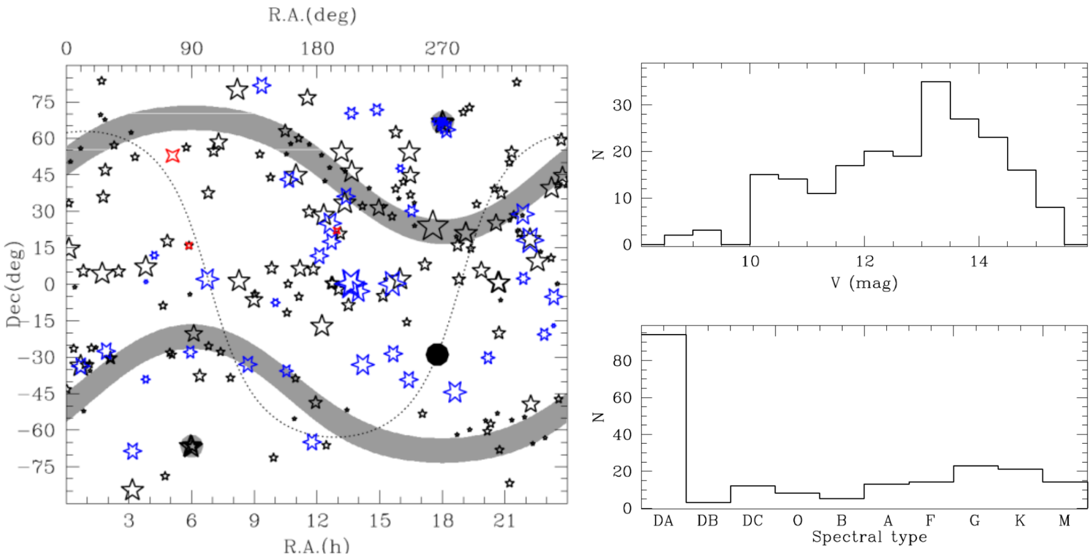

Figure 3: *Gaia* external calibration sources (SPSS) distribution of their positions on the sky (*left*), magnitude (*right top* panel) and spectral type (*right bottom* panel), extracted from [3]. In the left panel, the Galactic plane and center are marked with a dotted line and a black circle, respectively. The Ecliptic poles are marked as two grey circles, and two shaded stripes corresponding to the ecliptic latitude ±45 deg where Gaia is observing more often.

SPSS to derive the absolute flux and wavelength scales in physical units.

In this paper, we presented the strategy and composition of the selected standard candidates to implement both the internal and external *Gaia* photometric calibration.

Acknowledgments

This work was supported by the MINECO (Spanish Ministry of Economy) - FEDER through grant AYA2009-14648-C02-01, AYA2010-12176-E, AYA2012-39551-C02-01 and CONSOLIDER CSD2007-00050.

References

[1] Jordi, C., et al. 2014,"Highlights of Spanish Astrophysics VIII", Proceedings of the X SEA Scientific Meeting 2014 (this volume)

[2] Jordi, C., Gebran, M., Carrasco, J. M., et al. 2010, A&A, 523, 48

[3] Pancino, E., Altavilla, G., Marinoni, S., et al. 2012, MNRAS, 426, 1767

[4] Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, A&A, 369, 339