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Gaia astrometric instrument calibration and image processing

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Abstract

The astrometric instrument calibration and image processing is an integral and critical part of the *Gaia* mission. The data processing starts with a preliminary treatment on daily basis of the most recent data received and continues with the execution of several processing chains included in a cyclic reduction system. The cyclic processing chains are reprocessing all the accumulated data again in each iteration, thus adding the latest measurements and recomputing the outputs to obtain better quality on their results. This cyclic processing lasts until the convergence of the results is achieved and the catalogue is consolidated and published periodically. In this paper we describe the core of the data processing which has made possible the first catalogue release from the *Gaia* mission.

1 Introduction

Gaia is one of the most ambitious astrometric space mission of the European Space Agency (ESA)[3]. *Gaia* aims to measure with very high accuracy the positions and velocities of a large number of stars and galactic objects. Consequently, a detailed three-dimensional map of more than 1 billion stars of our Galaxy will be obtained, including most of the objects up to the 20^{th} magnitude. The precision of the final angular coordinates will be of about 20 μas at 15^{th} magnitude.

This work is organized as follows. In Section 2 we provide an overview of the *Gaia* data reduction, explaining its main goals and players. In Section 3 we describe the raw data treatment identifying the main processing tasks that compose the core of the data reduction approach adopted for *Gaia*. Finally, Section 4 is devoted to summarize our main contributions to the first *Gaia* catalogue release and the envisaged improvements to be included in the next release.

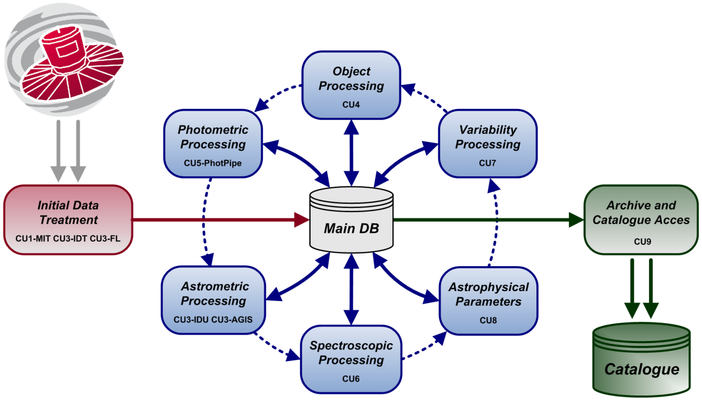

Figure 1: *Gaia* data reduction overview; identifying the main processing systems and differentiating those involved in the cyclic processing (in blue).

2 *Gaia* data reduction

The goal of the data reduction is to transform the raw telemetry data into the final science data, consisting of an astrometric and spectrophotometric catalogue based on all the measurements made of each observed object, meeting the final accuracies of mission goals [3].

This data reduction starts with a preliminary treatment on daily basis of the most recent data received and continues with the execution of several processing chains included in a cyclic reduction system (shown in Fig. 1). The cyclic processing chains are reprocessing all the accumulated data again in each iteration or Data Reduction Cycle (DRC), thus adding the latest measurements and recomputing the full set of outputs to obtain better quality on the final results. This cyclic processing lasts until the desired convergence is reached and the catalogue is consolidated and published.

As shown in Fig. 2, we first obtain from *Gaia* the observed images, the instrument configuration and the corresponding orientation of the spacecraft or attitude. With the attitude and the ephemeris of the spacecraft we can determine the observing direction of both telescopes from which we can identify the correspondence between the images and the sources in the sky. Then, we derive the flux and an accurate location of the object photocentres. Combining all the image parameters estimated for each individual source, the astrometric and photometric parameters can be derived to an internal reference system which is then transformed to absolute source parameters using small sets of reference calibration sources. These three main processing chains are then iterated just bringing the source parameters updates into the raw data treatment and vice versa. These updates improve the source to observation cross–match and the parameterisation of the models used in the image processing.

The raw data treatment is performed in two processing pipelines: for the daily and the cyclic operations.

- The daily pipeline or Intermediate Data Treatment (IDT) is in charge of processing the data newly received from the spacecraft on a daily basis. This pipeline runs in

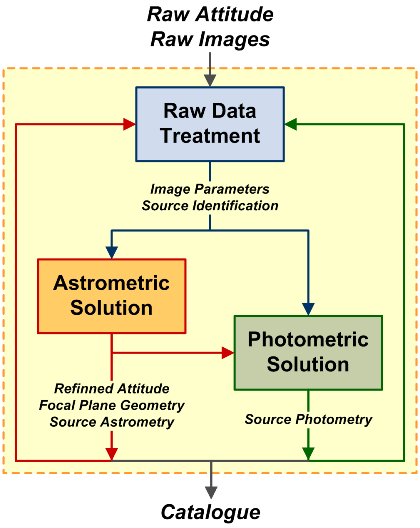

Figure 2: Main processing chains and interdependencies; from spacecraft raw data to the source catalogue parameters.

near real time over the 50-90 million observations (50-100 GB) received every day. Processing this amount of data in a short time period introduces certain limitations on the complexity and dependencies of the calibration models. Nevertheless, this pipeline is crucial to guarantee the scientific health of *Gaia* and detect anomalies in the spacecraft to perform corrective actions if needed.

- The cyclic pipeline or Intermediate Data Updating (IDU) runs within each data reduction loop over all the accumulated raw data. This reprocessing is crucial and allow us to apply more sophisticated calibration models and new data interfaces from other processing systems. Thanks to this pipeline the quality of the intermediate data is consolidated and largely improved which benefits at the end the results of the astrometric and photometric solutions.

IDU is one of the most demanding systems in data volume and processing power and its execution is in charge of the Data Processing Centre of Barcelona (DPCB). DPCB is one of the six Data Processing Centers (DPCs), responsible towards ESA for the reduction of data of the mission and is the only center providing enough resources for the proper operation of IDU, the Marenostrum super-computer hosted by the Barcelona Supercomputing Center (BSC).

3 From photo counts to a 3D star map

Gaia measurements consist on tiny windows of pixels around selected objects from a wide range of magnitudes. Depending on this magnitude, the windows differ in size even being reduced to 1D line profiles as shown in Figure 3.

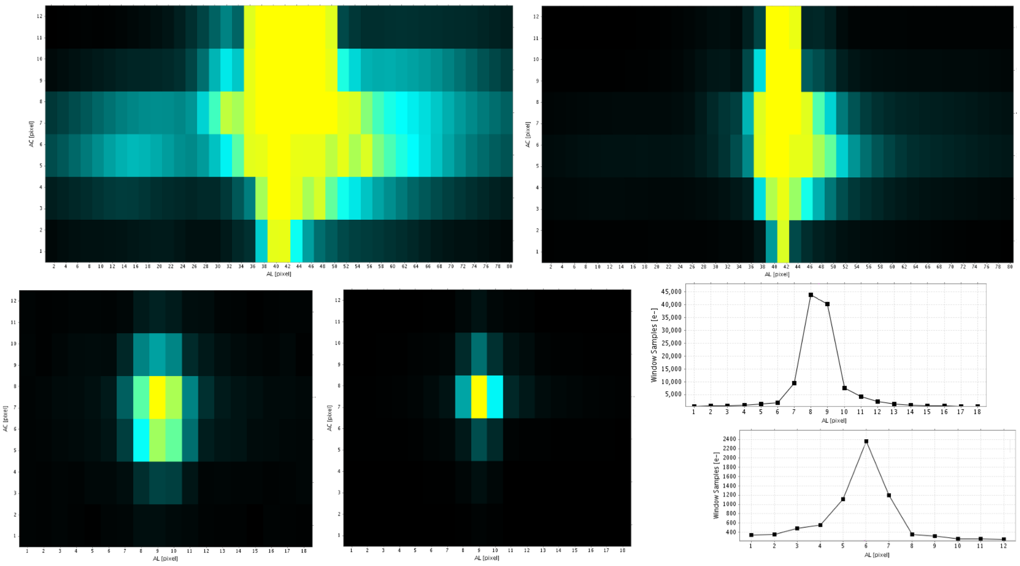

Figure 3: Astrometric 2D and 1D observation window examples. Total window flux decreases from top-left to right-bottom pane.

These windows basically contain the digital counts acquired by the CCDs and we need to reconstruct the original photo electrons. The first step is the recovering of the instrument parameters related to how the window was acquired: with/without gate, if it was overlapped and truncated by another window, the sample pixel binning, etc.

In *Gaia* as in other image-based astrometry missions, is common the need of applying a signal offset (Bias) over the measured samples to improve the acquisition of faint observations. This offset is not completely stable and need to be calibrated. This calibration is feasible thanks to periodic pixel measurements of non illuminated areas of the CCDs allowing to fit a time dependent function of this bias. Additionally, as commented above, not all the CCD pixels are kept, only small windows around the selected objects. The reading of the discarded pixels due to the limited resources and tight timing constrains are done in a higher speed than the useful ones. The change on the reading speed and some other construction limitations introduce fluctuations on the A/D conversion of the signal which need to be calibrated and restored to remove any systematic error in the flux and position estimations while processing the samples.

After the bias correction, we need to disentangle the flux coming from the source observed from any other source of light, mainly the astrophysical background of the sky region being observed. For *Gaia* the complexity of this calibration has been increased due to the straylight issue where unexpected light paths and reflections induce an additional background signal across the focal plane which varies periodically with the satellite spin.

Once the observed image has been recovered, the LSF/PSF model is then calibrated against the reconstructed window samples to be able to determine afterwards the location of the source photocentre and the source flux for all observed windows. This response is cali-

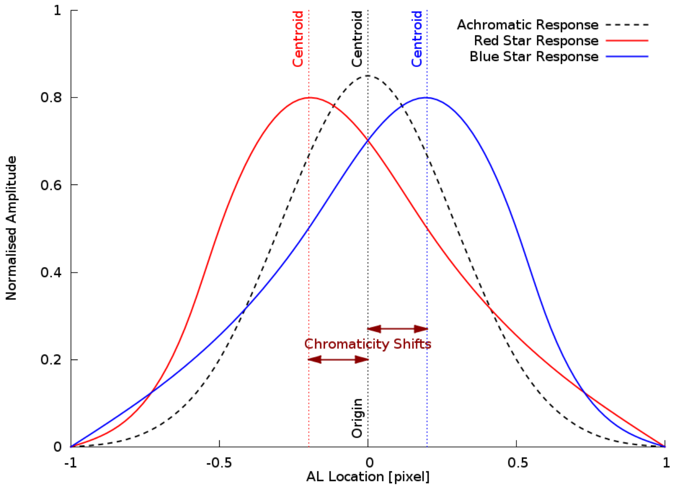

Figure 4: Definition of LSF origin with respect the image geometric centroid adopted for chromatic shift correction

brated in the form of an LSF/PSF profile, currently build as a combination of basis functions driven by several parameters including the observation time, telescope, CCD, magnitude, colour, window geometry, etc. However due to the non symmetric response observed in the 2D images, a new model based on a 2D numerical mapping representation is pursued.

It is very important to note the need to disentangle the colour/chromatic dependency on the model depicted in Fig. 4. In an achromatic instrument the image centre or centroid always matches the photocentre but this is not the case in real life where the instrument presents a different response for stars of different colour and thus different spectral shapes from red to blue stars.

The correction of this colour response dependency is accomplished by introducing the colour as a driven parameter in the LSF/PSF and by fixing the reference photocentre to the position given by the astrometric solution. Following this procedure in the calibration of the LSF/PSF we can correct the chromaticity effects and provide better and more accurate locations to the astrometric global solution. This chromaticy correction would not be possible in a single run of the pipelines and it is through the iteration between them when the accuracy mission goals can be achieved.

Finally, with the calibrated LSF/PSF model we can compute the locations and flux estimations for all the observations improving and superseding the daily or previous cycle results. The results of this last process will be then used to update the source positions, motions and fluxes based on the combination of all the estimated parameters of the observations related to each individual source.

The observations applicable to each source is obtained through three different modules (also included in IDU):

- Cross-Match: to link the observations with the catalogue sources not only for grouping the observations for the astrometric and photometric reduction but also to be able to use the source parameters as part of the calibration of the instrument, mainly the LSF/PSF, further described in [1].

- Detection Classifier: to clean the *Gaia* observations from undesired spurious detections, further described in in [5].
- Scene: to predict which catalogue sources and Solar System Objects entered the *Gaia* field of views and may have an impact on the later image processing.

In the next cycles, all these modules are executed again but using the updated source parameters bringing the corresponding improvements on the source identification, LSF/PSF model calibration, etc.

4 Conclusion

Gaia is an ambitious space mission with a very complex instrument which requires a demanding data processing system on both data volume and processing power. This processing has been designed as an iterative process between several modules each one solving different aspects of the data reduction system.

IDU is the system in charge of the reprocessing of all the accumulated raw data and the calibration of the instrument response. Without this system, *Gaia* would not be able to provide the envisaged accuracies and its presence is key to get the optimum convergence of the iterative process on which all the data processing of the spacecraft is based.

In the first *Gaia* Data release [4], most of the data processing described have already been run as described in [2] but large improvements are envisaged for the second release where a more advanced LSF/PSF calibration will be enabled.

Acknowledgments

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