Gaia Data Release 3: Processing and validation of BP/RP low-resolution spectral data

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ABSTRACT

Context. Blue (BP) and Red (RP) Photometer low-resolution spectral data is one of the exciting new products in Gaia Data Release 3 (Gaia DR3). These data have also been used to derive astrometry and integrated photometry in Gaia Early Data Release 3 and astrophysical parameters and Solar System Object reflectance spectra in Gaia DR3.

Aims. In this paper we give an overview of the processing techniques that allow converting satellite raw data of multiple transits per source into combined spectra calibrated onto an internal reference system, resulting in low-resolution BP and RP mean spectra. We describe how we overcome challenges due to the complexity of the on-board instruments and to the various observation strategies. Furthermore, we show highlights from the scientific validation of the results. This work covers the internal calibration of BP/RP spectra onto a self-consistent mean instrument, while the calibration of the BP/RP spectra to the absolute reference system of physical flux and wavelength is covered in Montegriffo, P. et al. (2022a). This should be seen as an essential companion to this paper.

Methods. We calibrate about 65 billion individual transit spectra onto the same mean BP/RP instrument through a series of calibration steps, including background subtraction, calibration of the CCD geometry and an iterative procedure for the calibration of CCD efficiency as well as variations of the line-spread function and dispersion across the focal plane and in time. The calibrated transit spectra are then combined for each source in terms of an expansion into continuous basis functions. We discuss the configuration of these basis functions.

Results. Time-averaged mean spectra covering the optical to near-infrared wavelength range [330, 1050] nm are published for approximately 220 million objects. Most of these are brighter than $G = 17.65$ but some BP/RP spectra are published for sources down to $G = 21.43$. Their signal-to-noise ratio varies significantly over the wavelength range covered and with magnitude and colour of the observed objects, with sources around $G = 15$ having S/N above 100 in some wavelength ranges. The top-quality BP/RP spectra are achieved for sources with magnitudes $9 < G < 12$, having S/N reaching 1000 in the central part of the RP wavelength range. Scientific validation suggests that the internal calibration was generally successful. However, there is evidence for imperfect calibrations at the bright end $G < 11$, where calibrated BP/RP spectra can exhibit systematic flux variations that exceed their estimated flux uncertainties. We also report that due to long-range noise correlations, BP/RP spectra can exhibit wiggles when sampled in pseudo-wavelength.

Conclusions. The Gaia DR3 data products are the expansion coefficients and corresponding covariance matrices for BP and RP separately. Users are encouraged to work with this data in this format, with full covariance information showing that correlations between coefficients are typically very low. Documentation and instructions on how to access and use BP/RP spectral data from the archive are also provided.

Key words. catalogs – surveys – instrumentation: photometers; spectrographs – techniques: photometric; spectroscopy

1 Introduction

The European Space Agency (ESA) mission Gaia (Gaia Collaboration et al. 2016) has already released to the astronomical community three catalogues of increasing richness in terms of content, precision and accuracy. Researchers from many branches of astrophysics have shown great interest in the published data leading to the publication of more than 6000 refereed papers based on Gaia data to date.

With respect to the previous Gaia Early Data Release 3, Gaia Data Release 3 (Gaia DR3) Gaia Collaboration & et al. (2022) introduces a number of new data products based on the same source catalogue, including a total of 1.8 billion objects and based on a period of 34 months of satellite operations. A large fraction of the objects in the catalogue has astrophysical parameters determined from the medium (Radial Velocity Spectrometer, RVS) and low-resolution (Blue and Red Photometers,
BP and RP) spectral data as well as from the photometric data (Andrae, R. et al. 2022; Creevey, O. et al. 2022). For many of these objects the actual RVS and/or BP/RP data itself are part of the release; RVS spectra are released for about 1 million sources, while mean low-resolution BP/RP spectra are available for about 220 million objects, selected to have a reasonable number of observations and to be sufficiently bright to ensure good signal to noise ratio at this stage in the mission. New estimates of mean radial velocities, variable-star classification and epoch photometry are released for a subset of sources. A large set of Solar System objects, including new discoveries, with preliminary orbital solutions and individual epoch observations are available in the Gaia DR3 release. A selection of these have also their reflectance spectra estimated from the epoch BP/RP spectral data (Galluccio, L. et al. 2022). The release includes also results for non-single stars, Quasars and Extended Objects. Finally, an additional data set is also released, called the Gaia Andromeda Photometric Survey (GAPS), consisting of the photometric time series for all sources located in a 5.5 degree radius field centred on the Andromeda galaxy (Evans, D. W. et al. 2022). A number of papers have been prepared by the Data Processing and Analysis Consortium (DPAC) describing all aspects of the data processing and the results of the performance verification activities. In this paragraph we have only included specific citations to papers that have made use of the BP/RP spectral data. A full list is available at https://www.cosmos.esa.int/web/gaia/dr3-papers.

This paper focuses on the BP/RP low-resolution spectral data and on the processing that led to the generation of the BP/RP spectra included in Gaia DR3. Some aspects of the BP/RP processing have already been introduced in recent papers which should be considered essential companions to this one. In particular, calibrations that were also required for the generation of the BP/RP integrated photometry have been detailed in Riello et al. (2021) and will be described only very briefly in this paper. The algorithm adopted for the internal calibration of the BP/RP spectral data is presented in the dedicated paper Carrasco et al. (2021). We refer to Carrasco et al. (2021) for the detailed justification of the model definition and complement that work providing information on the actual model configuration adopted to generate the Gaia DR3 BP/RP spectra. The focus of this paper is the processing leading to the generation of a homogeneous catalogue of source spectra from the raw Gaia BP/RP observations. While Gaia DR3 does not provide access to individual observations, knowing the complexities related to the instruments, observing strategies, and processing is important to understand the final product. This paper also contains useful information about the representation of the spectra and the strategies adopted to optimise such representation and minimise the noise in the final spectra. The validation shown in this paper focuses on these aspects. The calibration of the BP/RP spectral data to the absolute reference system (both in terms of flux and wavelength) is detailed in Montegriffo, P. et al. (2022a), also accompanying the Gaia DR3 release. Users interested in systematic effects present in the final BP/RP products should refer to that paper presenting the results of the validation of the externally calibrated data with respect to external absolute spectra. Finally, Babustiaux, C. et al. (2022) presents the overall results of the independent DPAC validation process, with useful insights into the limitations and recommendations for BP/RP spectral data.

The paper outline is the following: in Sect. 2 we describe the general concept of low-resolution spectroscopic data and the specific aspects of the Gaia BP/RP data that are relevant for this paper. Sect. 3 is dedicated to the data processing, with considerations on the processing strategies, algorithms and results; a description of the composition of the BP/RP spectral catalogue in Gaia DR3 is provided in Sect. 4 highlights from the internal validation activities are given in Sect. 5 and Sect. 6 offers some recommendations for the users.

2. Input data

During its operations, the Gaia satellite scans the entire sky every 6 months while spinning around its principal axis and precessing around the Earth-Sun direction. The light from two Fields of View (FoVs) is focused on the same focal plane. Images of sources crossing the focal plane move over an array of Charge-Coupled Devices (CCDs) operating in Time Delayed Integration (TDI) mode, such that the charges generated by a point-like astronomical source are clocked through the CCD at the same speed of the apparent motion of the source due to the satellite scanning motion. In the following, we will use transit to refer to a full focal plane crossing of a source and CCD transit when referring to the crossing of a single CCD, generating one observation.

Throughout this paper, time will be expressed in On-Board-Mission-Time (OBMT) in units of satellite revolutions (1 OBMT-Rev = 21 600 s). A formula to convert OBMT to barycentric coordinate time (TCB) is provided by Eq. (3) in Gaia Collaboration et al. (2016).

In the focal plane array (see Fig. 4 in Gaia Collaboration et al. 2016 or Fig. 2 in Carrasco et al. 2021), the CCDs are arranged in rows (in the along scan direction, AL) and strips (in the across scan direction, AC). The largest section of the focal plane array (including 62 Astrometric Field, AF, CCDs, arranged in 7 rows of 9 CCD each, except for one row where there are only 8) is dedicated to the collection of the observations in the broad G-band which are used for the astrometric measurements and for the photometry. Following these, two strips of 7 CCDs each are dedicated to the BP and RP instruments. Finally, 4 rows and 3 strips of CCDs collect the RVS observations. Obviously, not all sources crossing the focal plane will also cross the RVS CCDs.

Colour information for all sources is essential to achieve the high-accuracy that characterises the Gaia astrometry. An initial design where the flux of sources in a variety of medium bands would be measured on different CCD strips to fulfill this requirement (Jordi et al. 2006), was abandoned in favour of low-resolution aperture prism spectroscopy. This observational technique is frequently used to obtain a large number of spectra with a single exposure in large-scale astronomical surveys, starting from the Draper catalogue in the early 20th century (Pickering 1890) all the way to future applications such as in Euclid (Costille et al. 2016) and NGST (formerly known as WFIRST) (Lee et al. 2019). The BP/RP instruments were added to the satellite payload to collect this data covering the wavelength ranges [330, 680] nm and [640, 1050] nm respectively with varying resolution depending on the position in the spectrum and on the CCD (the resolution covers the range 100 to 30 for BP and 100 to 70 for RP in ∆λ/λ, see Fig. 3 in Carrasco et al. 2021).

In normal operation mode, observations transmitted to the ground from the satellite are cut-outs of a small area surrounding the position where each source was detected on board. In the case of BP/RP observations, because of the need to cover the full range of the dispersed light, these cut-outs (windows in Gaia terminology) need to be much longer in the direction in which the light is dispersed, which is aligned with the AL direction. This is why the size of the BP/RP windows is 60 pixels in AL (as opposed to a maximum of 18 pixels for the AF windows assigned to the brightest objects) by 12 pixels in AC direction,
corresponding to an area in the sky of approximately 3.5 arcsec by 2.1 arcsec. This affects the possibility to assign different windows to nearby sources in crowded regions. As a consequence of this, not all detections result in a BP/RP observation and the average number of BP/RP observations is lower than the average number of transits per source on the focal plane. Partly overlapping windows can in some cases be allocated by the on-board software. When this happens, the window of the brightest sources is transmitted fully to the ground, while only the non-overlapping section of the other window is transmitted to the ground. These truncated windows are not included in the data leading to Gaia DR3 as they are normally rather disturbed by the nearby brighter source and require special treatment which will only be implemented for future data releases.

Detections on board can be taken in different configurations depending on the on-board magnitude estimate of the source. The activation of a given configuration can also affect simultaneous observations nearby.

Different configuration aspects include the AC resolution within a window which is only achieved for sources brighter than 11.5 mag in the G-band, while windows assigned to fainter sources are binned in the AC direction on board before transmission thus resulting in a spectrum with 60 AL samples, where each sample contains the overall flux measurement from 12 pixels. Figure 1 shows the case of a 2D spectrum. The top panel shows the 1D spectrum resulting from the binning in the AC direction. The different window strategy is not active within the G-band. This allows reducing the exposure time. The exposure time of an ungated observation is approximately 4.4 seconds, the shortest gate active in BP/RP (Gate05) reduces this to 0.06 seconds. Each gate is activated on-board as required based on a configured set of magnitude ranges and the on-board magnitude estimate for each transit. The configuration changes for different instruments (BP/RP) and across the focal plane (even within a CCD). See Fig. 2 to see the distribution of different gate and WC configuration vs on-board magnitude for BP and RP. As already mentioned, the activation of the appropriate gate configuration is based on the on-board magnitude estimate which can show up to 0.5 magnitude uncertainties at the bright end. This implies that a given source may be observed in different gate configurations in different transits, some of these gate configurations will be sub-optimal and therefore some saturation cannot be excluded. Moreover the activation of a gate will affect all observations taken at the same time (within 60 pixels or 0.06 s AL) in the same CCD, thus generating gated observations for fainter sources that would normally be observed without any gate. This can also cause what are called complex gate cases, where different gates are active in different sections of a window. Complex gate cases are also not included in the processing leading to Gaia DR3.

An ad hoc strategy is also available to prevent saturation when observing bright sources. Different gates can be activated at different locations in the CCD to limit the section of the CCD where the charges are accumulated and therefore effectively reduce the exposure time. The exposure time of an ungated observation is approximately 4.4 seconds, the shortest gate active in BP/RP (Gate05) reduces this to 0.06 seconds. Each gate is activated on-board as required based on a configured set of magnitude ranges and the on-board magnitude estimate for each transit. The configuration changes for different instruments (BP/RP) and across the focal plane (even within a CCD). See Fig. 2 to see the distribution of different gate and WC configuration vs on-board magnitude for BP and RP. As already mentioned, the activation of the appropriate gate configuration is based on the on-board magnitude estimate which can show up to 0.5 magnitude uncertainties at the bright end. This implies that a given source may be observed in different gate configurations in different transits, some of these gate configurations will be sub-optimal and therefore some saturation cannot be excluded. Moreover the activation of a gate will affect all observations taken at the same time (within 60 pixels or 0.06 s AL) in the same CCD, thus generating gated observations for fainter sources that would normally be observed without any gate. This can also cause what are called complex gate cases, where different gates are active in different sections of a window. Complex gate cases are also not included in the processing leading to Gaia DR3.

Figure 3 shows the implications for the fraction of BP (top) and RP (bottom) transits available for processing of some of the mission aspects mentioned in this section (size of BP/RP windows, gates and truncation). The different curves show the fraction of transits that will not contribute a BP/RP observation to the processing leading to the Gaia DR3 catalogue for various reasons: the blue curve shows the fraction of BP transits affected by truncation, the red line those acquired with a complex gate, the orange line shows the fraction of transits that do not have a BP or RP window acquired, and the green line simply shows the

Fig. 1. An example of a 2D spectrum is shown in the central panel. The dashed and continuous horizontal lines show the AC centre of the window and the AC predicted position based on the source astrometry, the satellite attitude and the BP CCD geometry. The top and right panels show the result of binning in the AC and AL direction respectively. The AL coordinate is given in units of samples.

Fig. 2. Distribution of the number of BP/RP observations acquired in BP (top panel) and RP (bottom panel) with a given gate and WC configuration vs on-board magnitude labelled as G_{VPU}. The gated observations for sources fainter than $\approx$ 11.5 mag in the G-band are due to occasional misalignment of these sources with brighter objects triggering the activation of a gate.

Fig. 3 shows the implications for the fraction of BP (top) and RP (bottom) transits available for processing of some of the mission aspects mentioned in this section (size of BP/RP windows, gates and truncation). The different curves show the fraction of transits that will not contribute a BP/RP observation to the processing leading to the Gaia DR3 catalogue for various reasons: the blue curve shows the fraction of BP transits affected by truncation, the red line those acquired with a complex gate, the orange line shows the fraction of transits that do not have a BP or RP window acquired, and the green line simply shows the

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\[ \text{Gate05 2D} \]

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\[ \text{Gate07 2D} \]

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\[ \text{Gate09 2D} \]

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\[ \text{Gate11 2D} \]

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\[ \text{None 2D} \]

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\[ \text{None 1D} \]

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\[ \text{G}_{VPU} \]

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\[ \text{BP} \]

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\[ \text{RP} \]

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\[ \text{Gate} \]

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\[ \text{WC} \]

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\[ \text{G}_{VPU} \]

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\[ \text{BP} \]

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\[ \text{RP} \]

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\[ \text{Gate} \]

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\[ \text{WC} \]

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\[ \text{G}_{VPU} \]

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sum of the three previous quantities and therefore the fraction of transits that will not have an observation that can be processed at this stage. Both fractions of truncated and not-acquired windows increase significantly at the faint end as expected.

![Graph](image)

**Fig. 3.** Fraction of transits that will not contribute a BP observation to the processing leading to \textit{Gaia} DR3 due to either the BP window not having been acquired (orange line), or to the BP window being truncated (blue line), or to the BP window having been observed with multiple gates active within the window (red line). The green line shows the total effect. This is shown as a function of the on-board magnitude estimate as this is the parameter that defines the observation strategy applied to each observation. Truncation for instance is only applied to 1D windows and therefore the corresponding fraction is 0 for on-board magnitude brighter than 11.5 mag.

The total number of transits acquired in the period covered by \textit{Gaia} DR3 was almost 78 billion. The processing of the BP/RP spectral data produced calibrated BP/RP epoch spectra (i.e. spectra generated from one single observation) for about 65 billion transits, and mean BP/RP spectra (i.e. spectra averaged over the many observations for a given source) for 2,094,515,608 more than 2 billion sources. Not all transits nor sources had a complete set of BP and RP spectra. Please refer to Section 4 for more information on the selection criteria that lead to the composition of the \textit{Gaia} DR3 catalogue.

3. Processing

When calibrating the BP/RP data, the characteristics of the various CCDs, the effects introduced by the different optical paths for the two FoVs and by the configuration activated for each observation and the variation in time of all these elements will need to be taken into account. We refer to a set of validity time range (i.e. interval in time where a given calibration is applicable), CCD, FoV, WC and gate as a configuration or calibration unit. A set of calibrations per configuration (for a total of several tens of thousands configurations) will be produced as part of the instrument calibration process to describe each effect that needs calibrating. Due to the complexity of the system (effectively equivalent to many instruments), the calibration of the data cannot rely on any existing catalogue of standards (all too limited in number and quality), but needs to be solved for internally in the first instance, using a large subset of the BP/RP data itself. This subset is selected to contain data for a sufficiently large catalogue of sources (referred to as calibrators, see Sect. 3.2) covering all calibration units as homogeneously as possible within the limits imposed by nature (e.g. in terms of magnitude and colour distribution). The goal of the internal calibration is to define a reference instrument which is homogeneous across all configurations and time. It is then the responsibility of the external or absolute calibration to define the link between the internal system and the absolute system using a carefully assembled catalogue of spectro-photometric calibrators (Pancino et al. 2021; Marino et al. 2016; Altavilla et al. 2015, 2021) and other objects that present features in their spectra that are useful to calibrate specific aspects of the instrument and for which suitable absolute spectra are already available. The internal reference system is in essence defined by the calibrations, i.e. the actual calibration coefficients. Once the reference system is established, all the data can be brought to the same system by applying the calibrations. The same approach has been followed for the processing of the \textit{Gaia} photometric data (Carrasco et al. 2016). In this paper we focus on the internal calibration of the BP/RP spectral data, while the external calibration is the subject of Montegriffo, P. et al.[2022a].

The internal calibration includes many different individual calibration steps that are solved for in separate stages of the data processing, often relying on different subsets of calibrators and requiring different strategies for accessing the data in an optimal way. Figure 4 shows a schematic overview of the major steps and dependencies of the process starting from the input raw observed spectra until the output mean spectra. The two main inputs to the process are the BP/RP observed spectra and the source catalogue containing astrometry and photometry information for all sources observed so far. In the flow diagram, dashed lines are used to represent data flow for calibrators only, while solid lines are used to indicate that the entire set of the observed spectra is used as input into a given stage. The process flows from left to right and top to bottom: so the first calibrations are the ones grouped in the Initial Calibrations block (see Sect. 3.1), which are repeated after the crowding assessment to ensure only the best suited data is used. The output of these calibrations is part of a database of calibrations that are needed in various stages of the process. The other block of calibrations is the one labelled Flux and LSF Calibration (see Sect. 3.3), which can only start after the initial calibrations are finalised. This is an iterative process that calibrates effect of different response, varying LSF across the focal plane and small deviations from the nominal differential dispersion functions. When all calibrations are defined, the final steps in the process produce the output catalogues of internally calibrated spectra. In this paper we focus on the mean source spectra (see Sect. 3.4), produced using all the observations for a given source, while the process producing the epoch spectra (one calibrated spectrum per observed spectrum) is only briefly described in Sect. 3.3. While the epoch spectra are not directly available in \textit{Gaia} DR3, they contributed to the generation of mean reflectances for Solar System objects.

3.1. Initial calibrations

Starting at the top left corner from the raw BP/RP data we find a first block of calibrations labelled Initial Calibrations. Some of these have been described in previous papers (Riello et al. 2018, 2021) because they are required also for the photometric processing: the computation of integrated BP/RP fluxes and Spectrum Shape Coefficients (SSCs) which are the input to the photometric processing together with the corresponding G-band fluxes require the application of the background and AL geometric calibrations.
The background calibration for Gaia DR3 is a two-stage process: high resolution straylight maps are first generated to remove the effects due to diffraction from loose fibres in the sunshield (Fabricius et al. 2016); a k-nearest neighbour approach is then applied to the map residuals to describe the local astrophysical background (e.g. non-resolved sources, diffuse light from nearby objects, zodiacal light) at a resolution of about 25 arcsec. More details about this calibration and a validation of the results are provided in Riello et al. 2021 (see their Sect. 3.2).

Due to small inaccuracies in on-board detection and window assignment, sources are usually not perfectly centred within the acquired windows. In order to be able to align spectra taken at different times and in different configurations for a given source we need to rely on a detailed geometric calibration, an accurate attitude reconstruction and high accuracy astrometry for all observed sources. Attitude and astrometry are inputs to the BP/RP processing, while the geometric calibration is a product of one of the calibration steps (AL and AC Geometric Calibration in Fig. 4). The AL geometric calibration provides a correction in the AL direction to the location of a reference wavelength within the observed window as computed using our pre-launch knowledge of the CCD geometry. Once the reference wavelength is located within the window, this can also be used as reference position for the application of nominal differential dispersion functions that mitigates the difference in dispersion across the focal plane. More details about the AL geometric calibration can be found in Riello et al. (2018) and Carrasco et al. (2016). The AC geometric calibration is similarly defined as a correction to the predicted location on the source centroid in the AC direction as obtained from the pre-launch knowledge of the CCD geometry, the satellite attitude and the source astrometry.

The two geometric calibrations (AL and AC) are required for the generation of accurate BP/RP transit time and AC coordinate predictions for all sources in the catalogue, the Scene Computation in Fig. 4. An assessment of the crowding status of a given transit (the assessment needs to be done per transit rather than per source due to the overlapping of the two FoVs on the focal plane and the varying scan direction) cannot be purely based on the acquired surrounding windows. As we have already mentioned, crowding and priorities imply that a given source may not be assigned a window in the BP/RP CCDs, therefore such an assessment would be incomplete. This is why the scene is generated starting from the source catalogue containing objects that have been observed at all times during the mission operations so far. The astrometric information from the source catalogue is combined with the satellite attitude and with the geometric calibrations of the CCD of interest to generate the predictions. A detailed description of the scene computation and crowding evaluation has been included in (Riello et al. 2021) due to its relevance in the generation of crowding information included in Gaia EDR3.

As shown in the schematic view, the Initial Calibrations are repeated after the Crowding Evaluation to include only data that has been assessed as not significantly affected by crowding thus minimising the disturbing effects of crowding on the calibrations. After this second run of the Initial Calibrations, the spectra are used to generate integrated BP/RP fluxes and Spectrum Shape Coefficients (a set of ad hoc filters designed for the photometric calibration, see Riello et al. 2021). At this point 2D spectra are marginalised in the AC direction to form 1D spectra and all subsequent processing only deals with 1D spectra.

3.2. Internal calibrators

Each calibration step normally relies on a specifically designed set of calibration data. For the background calibration, for instance, only Virtual Objects (empty windows acquired on a pre-defined pattern for calibration purposes) and observations of objects fainter than $G = 18.95$ mag were used to avoid systematic effects due to the target source flux biasing the background measurement obtained from the first and last few samples in the window. For the AL geometric calibration, the need to find the best alignment of the spectra implies a requirement on their shape being approximately similar and therefore on the colour range of calibrators being quite narrow. For the AC geometric calibration finally, 2D spectra are essential to resolve the location of the peak in the flux distribution in the AC direction.

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**Fig. 4.** Schematic view of the processing leading to the generation of the BP/RP mean spectra in Gaia DR3.
In the case of the Flux and Line Spread Function (LSF) calibration, the most important requirement is that all configurations are well covered by the set of calibrators. Calibrators covering more than one configuration are particularly valuable. This is naturally the case for time, FoV and CCD (sources are observed an average of about 40 times in the time range covered by Gaia DR3, in different FoVs and CCDs). While in the case of gates and WC only a limited subset of the calibrators will have observations in two or more observation configurations. These will be sources that have a magnitude close to the boundary of the magnitude range where that strategy is active and that, due to inaccuracies of the on-board magnitude estimate, may therefore be observed in different configurations in subsequent transits. The following criteria were tailored to ensure a clean but well populated set of calibrators. Only sources in the colour range $-2.0 < (G_{BP} - G_{RP}) < 5.0$ mag and magnitude range $5.0 < G < 17.0$ mag based on the Gaia DR2 photometry were considered. Sources with $G$-band magnitude brighter than 11.5 mag were selected as long as they had more than 10 transits in BP/RP, this is to ensure that the magnitude range where gates are activated is well covered. Sources fainter than 11.5 mag with at least one 2D or gated observation were selected as long as their number of usable transits was larger than the median of the distribution of the number of transits in the same HEALPix pixel of level 6 minus the uncertainty estimated as the median absolute deviation of the distribution. This particular criterion was designed to avoid cases of faint sources that happened to be observed in a gated configuration because of their proximity to a bright object: in these cases, a large fraction of the transits of the faint source would be acquired with multiple gates (a case that is not currently processed) and would therefore not be usable. Only the few transits acquired when the two sources were observed at the same time would be usable. These would be likely to be significantly disturbed by the nearby bright source and therefore hardly suitable for calibration purposes. Finally, to enhance the fraction of sources with extreme colours (within the allowed range) with respect to sources of intermediate colours, the distribution of sources fainter than 11.5 mag that are only observed in un gated configuration and in 1D window strategy is flattened in colour as much as possible. Blue sources in particular are essential to constrain the internal calibration at short wavelengths and a poor calibration for blue sources may affect the absolute calibration given that the catalogue of external calibrators contains a large fraction of white dwarfs. The colour flattening is achieved in ranges of magnitude and HEALPix pixels by considering the distribution in colour of the possible calibrators and selecting calibrators from the least populated colour ranges first: each time a number of calibrators are added to the list of selected calibrators from the least populated colour bin an equal number of calibrators are selected from each of the other colour ranges, giving priority to the sources with the largest number of transits. The process is repeated until the number of selected calibrators has reached the desired number of calibrators per HEALPix. These criteria generated a list of internal calibrators including about 7.6M objects.

As very blue sources are naturally rare, during the calibration process measurements coming from sources from less populated areas of the colour magnitude diagram were given larger weight in the least squares solution of the calibration. These additional source-based weights were computed from the density of calibrators in the colour-magnitude diagram and were only applied for the calibration of the BP instrument.

3.3. Flux and LSF calibration

The flux and LSF calibration model has been described in detail in Carrasco et al. (2021). This calibration has been defined to take into account sensitivity differences, LSF variations, deviations from the nominal dispersion function and AC flux loss. However, flux loss terms were not activated for the processing that lead to Gaia DR3. The calibration model describes the overall effect of these different aspects on the BP/RP spectra.

It is useful to recall here Eq. 9 from Carrasco et al. (2021) as the basic formulation of the Flux and LSF calibration:

$$h_{s,k}(u_i) = \sum_{n=0}^{N-1} b_{sn} \sum_{j=0}^{J} A_k(u_i, u_{ij}) \varphi_n(u_{ij})$$

(1)

which describes the observed spectrum of source $s$ in calibration unit $k$, $h_{s,k}$, as a discrete convolution via the instrument model $A_k$ of the mean spectrum. The mean spectrum is in turn defined as a linear combination of some basis functions $\sum_{n=0}^{N-1} b_n \varphi_n$. In the following, basis functions and bases will be used interchangeably. Here $u$ refers to a pseudo-wavelength system, close to the AL coordinate of the samples within a window but adjusted for AL geometry and differential nominal dispersion function. We use $u_i$ to indicate the coordinate of sample $i$ in the pseudo-wavelength system and consequently $h_{s,k}(u_i)$ is the flux measured in the sample $i$, corrected for effects calibrated in the initial calibration stage (see Sect. 3.1). In this formulation, all the information about the individual source BP/RP spectra is encoded in the $b_n$ coefficients, while the $A_k$ describes the instrument properties. The spectra available in Gaia DR3 are in this format (see Sect. 4 for more details on the archive content).

The discrete convolution kernel $A_k$, the actual calibration, describes the transformation to be applied to the mean spectrum to predict an observation in calibration unit $k$. Only differential effects between the reference system and the calibration unit it refers to are calibrated in this process. These include contributions from LSF, response and dispersion. The calibration $A_k$ depends on both the pseudo-wavelength of the sample $i$ that the model is trying to predict and the pseudo-wavelength of the sample $i + j$ that is contributing to the discrete convolution. As explained in Carrasco et al. (2021), given the expected smooth behaviour of $A_k$ across the pseudo-wavelength range, the discrete kernel is replaced by a linear combination of polynomial bases. A smooth variation of the calibration with AC coordinate (within a CCD) is ensured by defining the coefficients of the polynomial in pseudo-wavelength to be a polynomial in AC coordinate (see Eq. 13 in Carrasco et al. 2021). A quadratic dependency within the best fit of the pseudo-wavelength and a cubic dependency in AC coordinate were used for Gaia DR3, where the AC coordinate refers to the centre of the window for both 1D and 2D spectra. Given the size of the LSF (see Fig. 5 in Carrasco et al. 2021) and of the expected deviations from the nominal dispersion function, only contributions from neighbouring samples are expected to be significant. Two adjacent neighbours on each side (i.e. $J = 2$ in Eq. 1) were considered in the processing leading to Gaia DR3. The number of neighbours and the possibility of introducing a step between neighbours have been adjusted during trial runs to offer the best balance between residuals and number of calibration parameters.

At the start of the calibration process, both the mean spectra for the internal calibrators (the $b_n$ coefficients) and the instrument calibrations ($A_k$) are unknown. An identity calibration is therefore assumed to compute a first set of reference mean spectra for the internal calibrators, effectively solving for the $b_{sn}$ pa-
rameters the simplified equation

\[ h_{s,k}(u_i) = \sum_{n=0}^{N} b_{s,n} \varphi_k(u_i) \]  

(2)

The resulting mean spectra are then used to solve for a first set of calibrations \( A_k \), using Eq. (1). With these in hand we can update the reference mean spectra, by solving again the same Eq. (1) for the \( b_k \) coefficients. The process then proceeds via iterations. The step where the mean spectra are solved for is called Source Update, while the one where the calibrations are computed is the Instrument Calibration. When solving for the BP or RP mean spectrum for a given calibrator, its all observed spectra in that calibration unit need to be collected and used to set up the least squares problem. When solving for the instrument calibration of a specific calibration unit instead, all observed spectra for the calibrators that happened to be observed in that calibration unit and their corresponding mean spectra need to be combined to form the least squares problem. This iterative algorithm had been developed using the Map/Reduce paradigm (Dean & Ghemawat 2008) which provides a simple parallelisation model; the Hadoop implementation provided a very efficient horizontally scalable I/O and processing capacity (see e.g. Riello et al. 2018). Since the algorithm described above groups the data in two different ways (by source, when producing the mean spectrum, and by calibration unit when solving the instrument model), the implementation required two Map/Reduce jobs to perform a single iteration. Although the execution time of individual iterations was quite reasonable, the cost of running a large number of iterations and testing different configuration parameters for the instrument model proved to be the main limitation of this approach. For iterative algorithms, such as the one required for the instrument model computation, a better alternative to Map/Reduce has proven to be Apache Spark\(^3\) which was used for the Gaia EDR3 photometric processing. For Gaia DR4 the iterative instrument model solution will be ported to Spark, allowing for in-memory iterations between source update and instrument model which will dramatically reduce the cost of running large number of iterations.

Given the large systematic effects present in the data due to water-based contamination in the payload (Gaia Collaboration et al. 2016), particularly at the start of the mission, and the discontinuities caused by the various decontamination campaigns aimed at reducing those effects, also for the BP/RP processing and in analogy to what was done for the Gaia EDR3 photometry (Riello et al. 2021), the iterations aimed at initialising the reference system were restricted to use only data collected during a specific time range, chosen to have the lowest and most stable contamination level. We refer to this time period as INIT. The ranges adopted are approximately [2574.7, 2811.7] and [4121.4, 5230.1] in OBMT-Rev (these are the same used for the photometric processing, see Riello et al. 2021). This effectively implies that the set of calibrators is defined not as a list of sources but as a list of observations, restricted in a specific time range and to a specific subset of sources. A consequence of this is that at the end of the iterative process described above, only instrument calibrations covering the INIT period will be available. Calibrations for all the other periods (collectively called CALONLY) can be computed with a final Instrument Calibration step using all the observed spectra from the CALONLY time ranges for the sources used as calibrators combined with their reference mean spectra. This is shown in the flow diagram in Fig. 5 where dashed lines are used for calibrators’ data and the labels INIT and CALONLY indicate the time ranges covered by each calibration step. When calibrations are available to cover the entire time range, a final Source Update using all observed spectra for all sources, not only calibrators, produces the catalogue of mean spectra.

It should be mentioned that in all steps of this process, weighted least squares solutions are obtained via QR-decomposition using Householder reflection to ensure numerical robustness (van Leeuwen 2007). Each solution is computed iteratively: at a given iteration, we use the solution computed at the previous iteration to reject observations that have residuals larger than 5\(\sigma\). Sample flux measurements are weighted by the inverse variance computed from the flux error for each sample. In the last run of the source update, the one that applies the instrument calibration to all observations to generate the catalogue of mean spectra, sample flux errors are re-scaled taking into account the scatter in the normalised residuals to mitigate the effects of error underestimation in the wings of the spectra.

### 3.3.1. Exact solution

Calibrations can also be applied to a single observed spectrum to obtain an internally calibrated epoch spectrum. This process appears as Exact Solution in the schematic overview in Fig. 4. In this case the system of equations to be solved is

\[ h_{s,k}(u_i) = \sum_{j=0}^{J} A_k(u_i, u_{i+j}) g_j(u_{i+j}) \]  

(3)

where \( g_j \) is the output internally calibrated epoch spectrum and \( A_k \) is the instrument calibration for the calibration unit \( k \) of the observed spectrum \( h_{s,k} \) being calibrated. In this case, the solution is simply obtained by inverting the matrix representing the instrument calibration and the resulting spectrum has the same sampling (in terms of number of samples and their location in

\(^3\) [https://spark.apache.org](https://spark.apache.org)
pseudo-wavelength space) as the observed spectrum, as opposed to the mean spectrum that being defined as a linear combination of some analytic bases is effectively a continuous function in pseudo-wavelength. The instrument calibration matrix $A_i$ was generally non-singular and the inversion could be done successfully. Only very few epoch spectra could not be calibrated using this procedure.

Epoch spectra are particularly valuable for objects that vary in time (either due to intrinsic variability or due to different distance or orientation such as is the case for Solar System objects). For these type of objects the mean spectrum will be ill-defined. Although epoch spectra are not included in Gaia DR3, they are relevant here because they have been the input to the generation of the reflectances for Solar System objects.

3.3.2. Calibrations

Calibrations are obtained in time intervals or scopes of about 20 OBMT-Rev (corresponding to about 5 days) for most calibration units. Only for the shortest-exposure configurations, with Gate 05 or Gate 07 active, due to the much smaller number of calibrators in these magnitude ranges, it has been necessary to extend the length of the time intervals to about 100 OBMT-Rev (i.e., 25 days). The length of the time intervals will vary slightly between calibrations due to the few events that cause discontinuities in the calibrations (such as decontamination campaigns and re-focus events, see also Riello et al. 2021). As within a time scope the calibration is assumed to be constant in time, time scopes need to be defined so that such events happen at the boundary between two subsequent intervals.

A set of calibration parameters was solved for each of the 31860 calibration units. For Gate 05 and Gate 07 the number of nominal calibration units was 1064 per gate case, while for other gate configurations or in the un gated case the number of nominal calibration units was 5708 (the un gated case having twice as many as the others because of the two possible window strategies active for objects with magnitude fainter than 11.5 mag). This implies a total of 24960 nominal calibration units, however there are often cases of non-nominal calibrations that get a sufficient number of observations to allow a robust calibration. These are cases of faint sources being observed with a gate triggered by a nearby bright source being observed at the same time (see also Fig. 2).

Displaying detailed information for such a large number of calibrations is challenging. To facilitate this we have defined two parameters describing each calibration:

- One is defined as the sum over $j$ of the $A_k(u_i, u_{ij})$ values weighted by the distance between $u_i$ and $u_{ij}$. In the case of a perfectly symmetric calibration (seen here as a convolution kernel) this would be 0. In general it indicates the location of the peak of the kernel. A skewed kernel might be caused by small deviations from the nominal dispersion.

- The second parameter is given by the sum over $j$ of all $A_k(u_i, u_{ij})$ values, i.e. the integral of the kernel. Variations in this parameter show differences in the response across the focal plane and between different calibration units.

Figure 6 shows an example of the calibration for a given calibration unit, evaluated in the central part of the spectrum and of the CCD. This particular case has the peak parameter equal to −0.80 and the integral parameter equal to 0.98.

The plots shown in Fig. 7 offer a quick view of the calibrations computed for the preceding and following FoVs, ungated and 1D configuration in terms of the two parameters just defined.

Fig. 6. The $A_k(u_i, u_{ij})$ values defining the instrument calibration for one specific configuration (RP, CCD row 1, preceding FoV, ungated, 1D) in the time range including OBMT-Rev 5000 evaluated at $u_i = 30.0$ and AC coordinate 1000.
Fig. 7. Overview of the BP and RP calibrations for the preceding (first row of plots) and following (second row) FoVs, ungated 1D configuration: peak and integral parameter variations vs wavelength, time and AC coordinate are shown for each CCD. Each set of 14 panels show the peak (first two sets) and integral (second two sets) variations (see the top title label and colour bar next to each set) as a function of different parameters: the first set shows the variation of the peak parameter in time (expressed in OBMT-Rev) and pseudo-wavelength, while the second set shows the variation of the same parameter in AC coordinate and pseudo-wavelength, the third and fourth sets show the same dependencies for the integral parameter. When showing the dependency in time and pseudo-wavelength the parameters have been evaluated at the centre of each CCD in the AC direction (i.e. AC = 1000), while when showing variations with AC coordinate and pseudo-wavelength the reference time OBMT-Rev = 5000 was used. Within each set, the 14 panels show the BP case in the left column of 7 panels (one per CCD) and the RP case in the right column.

The plots in Fig. 8 include only data and calibrations for the INIT period. As explained before, once a stable set of calibrations for the INIT period have been obtained and a reference set of mean spectra for the calibrators is established, this is used to generate consistent calibrations covering all the rest of the mission data collected so far. The distribution in time of the relative residuals covering the whole period included in Gaia DR3 is shown in Fig. 9 for BP and RP in the top and bottom panels respectively. The top panel shows that the calibration algorithm was not able to fully remove the large systematics affecting the BP data due to the contamination in the early phases of the mission. Considering the long period of time with minimal contamination available, it was decided to ignore all BP data collected before the decontamination event that took place shortly before OBMT-Rev 2340 when generating the final catalogue of mean spectra.

3.3.3. Convergence

Convergence of the iterative process was monitored looking at different parameters: the median standard deviation of the solutions, the overall absolute change in parameters and the average $\chi^2$ of the residuals for a subset of the calibrators were all considered.
Fig. 8. Relative residual distribution for a subset of the calibrators covering the $G$-band magnitude range $[5, 18]$. The first row of plots shows the BP results, while the bottom row shows RP. In each row the first plot shows the distribution of relative residuals vs AL coordinate in the range $[10, 50]$ where most of the flux is observed. In the second plot the same distribution is shown including only data from sources in AL coordinate in the range $[13, 17]$. In these first two plots the 2D histogram is normalised to the number of measurements in each column and the relative number of sources is shown by the colour bar. The red line shows the median value, while the orange dashed lines show the 15.865 and 84.134 percentiles. The following two plots show the robust width of the distribution of relative residuals defined as the difference between the 84.134 and 15.865 percentiles divided by 2 vs $G$-band magnitude and $G_{BP} - G_{RP}$ colour and AL coordinate for the entire magnitude range covered by this subset.

Fig. 9. Relative residual distribution for a subset of the calibrators covering the magnitude range $[5, 18]$. The top panel shows the BP residuals, while the bottom one shows the RP residuals. Only samples with AL coordinate in the range $[10, 50]$ are included in this plot. The 2D histogram is normalised to the number of measurements in each column.

Each least squares solution for a calibration unit is assigned a standard deviation. The normalised median standard deviation of all least squares solutions over the OBMT-Rev range $[3000, 4000]$ grouped by gate and window class combination versus iteration number is shown in Fig. 10. Each panel shows a combination of photometer (BP/RP), gate and window class as indicated in the label. There are some configurations where the evolution of the median standard deviation is not monotonically decreasing, particularly in the first few iterations. If the calibration of each configuration was solved independently, one would expect the corresponding standard deviation to decrease in subsequent iterations. However, in the iterative process described in Sect. 3.3 all calibration units are linked together by the common catalogue of reference spectra that is updated at each source update. For this reason, the fact that the standard deviation does not decrease for all configurations is not showing lack of convergence over all.

Overall convergence is assessed looking at the absolute relative change in the values of model parameters $A_k$ between two subsequent iterations. Figure 11 shows how these evolve during the iterations for different nominal combinations of gate and window class in BP (top panels) and RP (bottom panels). Given the large number of parameters, only results for ROW4 are shown here, other rows showing similar trends. Different colours are used for different pseudo-wavelength and different line styles for different neighbours (the solid line being used for the central sample). The absolute relative change in calibration parameters are over all at or below 1% well before iteration 50, particularly for the central part of the spectra and for $j = 0$. For BP there seem to be larger relative changes (at about the 10% level) in the wings of the spectra and for $j \neq 0$. This is not completely unexpected and is probably due to correlations between the parameters.

Finally, Fig. 12 shows the evolution through the iterations of the normalised median $\chi^2$ for the same random subset of the calibrators used for which residuals were shown in Sect. 3.3 in blue and red symbols for BP and RP respectively. In this plot the normalised median $\chi^2$ value at each iteration is obtained by dividing the corresponding median $\chi^2$ to the value at the first iteration. The $\chi^2$ value for each epoch spectrum is given as the sum of squared residuals between the observed spectrum and the predicted spectrum divided by the observed flux error. It is important to point out that the normalised median $\chi^2$ shown here...
Fig. 10. Median standard deviation for all solutions covering the OBMT-Rev range \([3000, 4000]\), normalised to the median standard deviation of all calibrations obtained for the same photometer (BP/RP), gate and window class at iteration 50 (by that iteration the system seems to have become quite stable). The top panels show the BP solutions, one panel per nominal combination of gate and window class. The bottom panels show the RP solutions. Different colours indicate different CCD rows and solid and dashed lines are used for the preceding and following FoV respectively.

is not the quantity that is being minimised within the iterative process, which will be the sum of squared residuals for all observations of all calibrators within each calibration unit when solving the instrument model and the sum of squared residuals for all observations of each calibrator when solving the source update step. The increase in late iterations for BP shown in Fig. 12 could be due to changes in the distribution of \(\chi^2\) due to the iterations trying to catch a few extreme outliers at the expense of slightly degrading the residuals for other sources.

There are indications from both the standard deviation and \(\chi^2\) analyses that in late iterations the solutions start diverging. We have mentioned a possible cause but this is not fully understood. The additional weighting introduced to give more leverage to blue sources seems to have an effect in this respect. Alternative strategies are being considered in future data releases. From the analysis of all criteria, iterations 55 and 40 were finally adopted for BP and RP respectively to proceed with the generation of a reference catalogue of mean spectra to be used for the calibration of the CALONLY data.

3.4. Mean spectra representation

Once the internal reference system has been established by the flux and LSF calibration and calibration solutions are available covering all calibration units, a final source update is run including all observed spectra to generate the catalogue of mean spectra that are released as part of Gaia DR3. The algorithms described in this section have been applied only to this last run of the source update.
3.4.1. Internal reference system

The flux and LSF calibration procedure described in Sect. 3.3 leads to the definition of an internal reference system. This can be seen as an average instrument. The monitoring of intermediate results during the iterative process showed that in late iterations some of the spectral features in mean spectra assumed a smoother, shallower shape with respect to what is observed in the predicted and observed spectra. In order to maintain the reference system and the corresponding mean spectra as close as possible to the actual instrument and to the actual data, we have decided to use instead a specific epoch instrument and to represent the final mean spectra as observed in this system. The epoch instrument was chosen somewhat arbitrarily to be the one corresponding to CCD row 7 for BP and row 5 for RP at a time equal to 4500 in OBMT-Rev.

To avoid having to invert the instrument model to derive mean spectra directly in this new system, we have computed a transformation matrix $T$ where each row $k$ contains the coefficients that need to be applied to the canonical Hermite function bases to reproduce the prediction of the $k$-th basis in the chosen epoch instrument. These are the result of a fit of each predicted basis function, obtained by applying Eq. 1 to a mean spectrum where only one coefficient is equal to 1 while all others are 0, with the same set of 55 Hermite function bases. In the new system, the mean spectra are defined by the array of coefficients $b'$ computed by multiplying the transformation matrix by the array of coefficients in the starting reference system $b$, i.e. $b' = T b$. The covariance matrix of the source update least squares solution needs also to be converted by computing $C' = T^T C T'$ where $C$ is the covariance matrix in the starting reference system and $C'$ is the covariance matrix in the new system.

3.4.2. Bases function optimisation

As described in Carrasco et al. (2021) see Sect. 5) and introduced in Sect. 3.3 the source mean BP/RP spectrum is described as a combination of basis functions. At the start of the calibration process little is known about the instrument and therefore a generic set of basis functions is used throughout the initialization phase. Hermite functions, i.e. Hermite polynomials multiplied by a Gaussian, were used in this stage: they provide an orthonormal set of basis functions, are centred around 0 and allow to increase details and range by adding higher order bases. They also tend to 0 for sufficiently high absolute values of the independent variable. This resembles the behaviour of BP/RP spectra where the combination of CCD efficiency and response ensures that the measured flux tends to 0 for increasing distance from the source location.

We denote the $n$-th Hermite function $\phi_n(x)$. In order to make the Hermite functions efficient in representing the BP/RP spectra, a linear transformation between the pseudo-wavelength and the argument of the Hermite functions is required. This transformation includes a shift $\Delta \theta$ such that the Hermite functions are centered approximately on the centre of the spectra, and a scaling factor $\Theta$ that adjusts the width of the Hermite functions to the width of the spectra to be represented. Furthermore, a suitable number of Hermite functions needs to be chosen. The BP/RP spectrum of a source $s$, $f_s(\lambda)$, is then represented by the linear combination

$$f_s(\lambda) = \sum_{n=0}^{N-1} b_{s,n} \phi_n \left( \frac{\lambda - \Delta \theta}{\Theta} \right)$$

In Eq. 4 the mean spectrum $f_s(\lambda)$ appeared as $\sum_{n=0}^{N-1} b_{s,n} \phi_n$. Here we have made explicit the transformation of the pseudo-wavelength $\lambda$ into the argument of the Hermite functions $\phi_n$. The values of $\Theta$, $\Delta \theta$, and $N$ cannot be chosen independently from each other. Since the pseudo-wavelength range covered by most BP/RP spectra is $[0, 60]$, a value of $\Delta \theta$ around 30 is required to center the Hermite functions on the spectra. Furthermore, the linear combination of Hermite functions need to cover the range from $-30$ to $30$. Increasing the number of Hermite functions used in the representation results in the coverage of a wider range of arguments, while increasing the scaling factor results in a reduction of the range of arguments (Carrasco et al. 2021). To find a suitable combination, we first determined the values of $N$ for $\Delta \theta = 30$, for values of $\Theta$ from 2 to 3.5, such that the local minimum or maximum at the largest value of $\lambda$ of the $N - 1$-th basis function is closed to 30. For all resulting combinations of $\Theta$ and $N$, a fixed number of five iterations of the instrument calibration was performed. A random subset of approximately 50 thousand internal calibrators was used for this purpose. The total residuals in the epoch spectra were then computed and compared for different combinations of parameters. We selected the combination of parameters that resulted in the smallest value for the summed squared residuals. In both, BP and RP, $N = 55$ is used, implying that 55 coefficients will be available for each BP/RP spectrum in Gaia DR3. The values for $\Theta$ and $\Delta \theta$ are slightly different for BP and RP, with $\Theta = 3.062231$ for BP and $3.020529$ for RP, and $\Delta \theta = 30.00986$ for BP and $30.00292$ for RP. The slight deviations from round numbers result from adjusting the parameters to the smallest and largest values in pseudo-wavelength in the set of internal calibrators used.

Once the catalogue of mean spectra for the calibrators is established based on the set of standard Hermite functions, the set of bases can be optimised to improve the efficiency of the representation. This is achieved when most of the information is contained in the coefficients for the lowest-index bases and allows reducing the number of coefficients required to describe each spectrum by dropping coefficients that are within the noise.

The optimisation algorithm used normalised mean spectra for the subset of calibrators already used to define the best configuration for the standard Hermite functions. L2 normalisation was used to ensure equal weights for sources of different magnitude in the decomposition. The $N$ coefficients representing each of these sources in the canonical set of bases are normalised with respect to their $l_2$-norm and are used to populate a matrix $M \times N$.
where $M$ is the number of sources. Singular Value Decomposition of this matrix gives the orthogonal matrix $V$ that represents a rotation of the canonical Hermite basis into a new set of optimised bases.

Figure 13 shows the first few bases in the canonical Hermite function set (in the top panel) and in the optimised BP and RP sets of bases (in the following two panels). Darker shades are used for lower-index bases. The first optimised bases, being tailored to the actual spectra, reproduce the average spectrum and exhibit the imprint of the transmission curve. Higher order bases become increasingly complex with narrower wavy structures required to fit the sharpest features in the spectra.

3.4.3. Truncation

As explained in Sect. 3.4.2, by expressing the mean spectra in terms of an optimised set of basis functions, a particular spectrum is essentially described by a small number of basis functions with low indices. The coefficients corresponding to higher order basis functions have small absolute values, and, taking their errors into account, are close to zero. Their effect in representing an BP/RP spectrum is therefore essentially adding noise, which manifests itself in wavy structures in the sampled spectrum. It is therefore of interest to suppress the insignificant high order coefficients and with it, reduce the noise on the spectra.

A simple criterion to decide whether a number of high-order coefficients is insignificant or not has been suggested by Carrasco et al. (2021). The criterion is based on the standard deviation of the $M$ coefficients with the highest indices, i.e. the coefficients with indices ranging from $N - M$ to $N - 1$. If the standard deviation of the $M$ coefficients with highest indices, normalised to their errors, is above a specified multiple of the standard error of the standard deviation above the expected mean standard deviation, it is assumed that the coefficients are not only random values consistent with a mean of zero, but are actually contributing significantly to the spectrum. Otherwise, they are considered insignificant and can be set to zero. For the standard deviation of a set of $M$ samples from a normal distribution with zero mean we assume the simplified expression of $1 / \sqrt{2(M - 1)}$, and a mean of one. Thus, if the standard deviation of the $M$ coefficients with highest indices, divided by their error, is smaller than $1 + x / \sqrt{2(M - 1)}$, with $x$ being an adjustable threshold, the coefficients are assumed to be consistent with being zero, and can be truncated. We used a value of $x = 2$, and for each BP/RP spectrum, progressively increasing values of $M > 2$ were tested for truncation until the truncation threshold is exceeded for the first time for some $M$. If the truncation threshold is never reached, i.e. all coefficients are considered being consistent with being zero, the full number of $N = 55$ is kept. This happened for a small number of sources, in particular for BP spectra of faint and very red sources, where the flux in the BP spectrum is so low that it is indeed essentially consistent with being only noise.

This criterion makes two simplifications. First, the assumed mean and standard deviation is inaccurate for very small numbers of $M$. However, the resulting overestimation of the truncation threshold is on the level of a few per cent in the worst case, and has no significant impact on the truncation levels. Second, the truncation ignores correlations between the errors on the coefficients. For sources for which the optimised basis was constructed, the correlations are indeed very low, and the negligence is justified. This is by number the vast majority of sources. For sources for which the optimised basis is less efficient, correlations might however be larger, and the truncation unreliable. This is in particular the case for extremely red sources, or sources with spectral energy distributions that are very different from typical stellar spectral energy distributions, such as QSOs or sources with strong emission lines. In the latter case the truncation is to be used with caution, as it might affect the representation of narrow spectral features.

In the following, we illustrate the effect of truncation for four example cases. First, we consider the case of a typical, bright star ($G \approx 11.5$ mag and $G_{BP} - G_{RP} \approx 1.0$ mag) in Fig. 14. The top panels compare the sampled BP and RP spectra, represented by all 55 coefficients, and by the number of coefficients considered significant according to the procedure described above. These numbers of coefficients are 35 and 15 for BP and RP, respectively, for this example source. No difference in the sampled spectra is visible to the eye, although the number of basis functions used in the representation of the sampled spectrum is significantly smaller. The bottom panels of the figure illustrate the truncation process. The black symbols show the values of the coefficients, normalised to their errors. The red curve shows the standard deviation of the $M$ normalised coefficients, starting from $M = 3$ on the right hand side. The blue shaded region is the cone given by $1 \pm 2 / \sqrt{2(M - 1)}$. When the red curve exceeds the blue cone, the corresponding number of coefficients is considered significant.

The truncation becomes more significant for noisier spectra. As a second example, we therefore consider a source with a similar colour as the first example, but fainter magnitude ($G \approx 18.1$ mag and $G_{BP} - G_{RP} \approx 1.0$ mag). This case is shown in Fig. 15, which is analogous to Fig. 14. In this case, more coefficients are in agreement with being zero, and the number of significant coefficients is only 2 and 11 for BP and RP, respectively. Truncating the representation of the spectra at these numbers of basis functions maintains the general shape of the spectra, but suppresses the wavy patterns introduced by the noisy higher indices coefficients. We furthermore show examples for sources with emission lines. The first case is a bright source ($G \approx 11.5$ mag) with multiple emission lines in BP and RP, shown in Fig. 16. Here, the truncation criterion is exceeded already for $M = 3$, as all coefficients are required to represent the complex spectra for this source. The specified number of significant coefficients however is the number of coefficients when the truncation criterion is ex-
ceeded, which is 53 in this case. The use of all 55 coefficients is recommended in case of the number of significant coefficients is 53.

Finally, we consider a faint QSO with emission lines as an example. Figure 17 shows the BP and RP spectra of a QSO ($G = 18.7$ mag and $G_{BP} - G_{RP} = 0.5$ mag), with all 55 coefficients, and with the truncated representation, using 3 and 11 coefficients in BP and RP, respectively. The spectral energy distribution from SDSS is shown for comparison. In particular the strong emission line visible in the SDSS spectrum coincides with a line in the BP spectrum. This line is removed by the truncation process. The truncation in the case of complex spectral shapes might therefore be too strong.

Fig. 14. Sampled BP (left) and RP (right) spectra are shown in the top panels for source Gaia DR3 6210089815971933056 ($G \approx 11.5$ mag and $G_{BP} - G_{RP} \approx 1.0$ mag). Each panel contains two curves: a blue curve showing the non-truncated spectrum using all 55 coefficients, a red curve showing the truncated spectrum. The number of coefficients used for each spectrum is given in the label within the plot. The bottom panels show the truncation assessment. This is run independently for BP and RP. The black circles indicate the coefficients normalised by their formal errors, the red line shows the standard deviation of the $M$ normalised coefficients, starting from $M = 3$ on the right hand side. The blue shaded region is the cone given by $1 \pm 2/\sqrt{2(M-1)}$.

The truncation procedure was also tested by the sub-system dedicated to the estimation of astrophysical parameters within the DPAC analysis pipeline, referred to as Apsis (see Creevey, O. et al. 2022). Most Apsis modules found that the truncation would have negative impact on the quality of the scientific results, as far as emission lines in quasars or certain types of stars are concerned. These tests were conducted at a very early stage when no external calibration was available yet, such that the conclusions were uncertain and it was considered by most Apsis modules to be the safer option to not truncate the coefficients. In the extreme case of ultra-cool dwarfs, which are very red and very faint stars, the truncation was found to have a positive impact and has been employed specifically for the Apsis module ESP-UCD focusing on this type of stars. For these faint stars, the suppression of noise might aid the data analysis.

The result of the truncation assessment is provided as part of the Gaia DR3 in the parameters bp_n_relevant_bases and rp_n_relevant_bases available in the xp_summary table and in the mean continuous spectra available via Datalink (see also Sect. 4). In case of very faint and typical stars, the use of the truncated representation of BP and RP spectra might be useful. In particular for sources with unusual spectral energy distributions, such as sources with emission lines, the use of all 55 coefficients for BP and RP, respectively, is advised. The full array of 55 coefficients is available via the archive. Users will need to decide if the suggested truncation is appropriate for their use case.

Fig. 15. Illustration of the effects of truncation on the mean spectra of source Gaia DR3 6776468319762629932 ($G \approx 18.1$ mag and $G_{BP} - G_{RP} \approx 1.0$ mag). Please see the caption of Fig. 14 and the text for details.

Fig. 16. Illustration of the effects of truncation on the mean spectra of source Gaia DR3 3932940844556081408 ($G \approx 11.5$ mag). Please see the caption of Fig. 14 and the text for details.
4. Output data

This Section describes the BP/RP data available via the Gaia archive. The exact number of sources with BP/RP mean spectra in the Gaia DR3 release is 219,197,643. This list is the result of several selection criteria. Sources with G-band magnitude brighter than 17.65 mag and more than 15 CCD transits contributing to the generation of the mean spectra for both BP/RP were automatically selected. The criterion based on the number of transits leads to a (slightly) non-uniform completeness across the sky (see the density sky distribution in Fig. 29). From this initial list, sources that had shown poor estimates of SSC values (Riello et al. 2021, see Sect. 8.2 for more details) were excluded unless they were part of one of the lists of specific objects (see below). An additional 35K sources were excluded to allow further processing and validation within DPAC which is likely to be finalised only after Gaia DR3. A few lists of specific objects for which other criteria would not apply were defined: these included about 500 sources used for the calibration of the BP/RP data, a catalogue of about 100K WD candidates, 17K galaxies, about 100K quasars, about 19K ultra-cool dwarfs, 900 objects that were considered to be the most representative sources (or centroid) for each of the 900 neurons of the Self Organising Map used by the Outlier Analysis module (Creevey, O. et al. 2022) and finally 19 solar analogues. All these selections are specific to Gaia DR3 and will not affect the content of future releases.

In Gaia DR3, there is one source (Gaia DR3 5405570973190252288) that has only an RP spectrum.

The gaia_source table in the archive contains a boolean column has_xp_continuous that is true if the corresponding source has BP/RP mean spectra available. After retrieving a list of gaia_source entries, BP/RP spectra can be downloaded from the archive via Datalink in various file formats. This can be done either from the archive web interface or programmatically. In Appendix A we provide instructions for downloading the data from Python.

The spectra are provided in the continuous representation (see also App. B for more details): for each BP and RP the spectrum is defined as a set of coefficients (bp/rp_coefficients), the corresponding array with the coefficient formal errors defined as the standard uncertainties from the least square solution multiplied by the standard deviation of the solution (bp/rp_coefficient_errors), the correlation matrix (bp/rp_coefficient_correlations) and various parameters from the source update process, such as number of measurements, number of degrees of freedom, χ² and standard deviation of the solution.

In addition to the data available via Datalink, the xp_summary table provides access to some of the parameters listed in the previous paragraph via queries (to enable for instance selecting sources based on the standard deviation of their mean spectrum solution) and to other relevant information. Users interested in retrieving the number of CCD transit spectra (and individual measurements) that contributed to the generation of the mean spectrum or that want to know how many of these were assessed as contaminated or blended should interrogate this table, not the main gaia_source table which instead provides similar counters for the photometric data. While BP/RP spectra and G-band and BP/RP photometry share part of the processing and filtering criteria, there are also some important differences that can lead to apparent inconsistencies in these counters.

The Python package GaiaXPy has been developed to help the users of BP/RP spectra. It offers the following functionalities: generation of a sampled version of the original continuous representation in both internal and absolute flux and wavelength systems, computation of synthetic photometry in various photometric systems and simulation of Gaia-like mean spectra from an input absolute spectral energy distribution (SED). For more information on these tools please refer to the package on-line documentation.

5. Validation

5.1. Errors

In order to test the performance of the calibration, a special validation dataset was generated where for each source the available transits were randomly divided into two groups and processed separately to generate two mean spectra for BP and two for RP. This allows us to compare the calibration results from two sets of transits for the same sources. We refer to this dataset as the BP/RP split-epoch validation dataset. Further details (including how to access the dataset) are available in App. D.

For this comparison we computed the Mahalanobis distance, $D_M$ between the two solutions for each source, given by

$$D_M = \sqrt{(c_1 - c_2) \Sigma_1^{-1} (c_1 - c_2)^T}.$$  

Here, $c_1$ and $c_2$ denote the coefficient vectors for the two solutions, and $\Sigma_1$ and $\Sigma_2$ the corresponding covariance matrices.

\footnote{https://gaia-dpci.github.io/GaiaXPy-website/}
Under the idealized circumstances of normally distributed noise, correct covariance matrices, and absence of intrinsic photometric variability of the sources used in the test, \( D_M \) follows a chi distribution with the degree of freedom corresponding to the length of \( c_1 \) and \( c_2 \). Deviations from a chi distribution therefore indicate unreliable covariance matrices \( \Sigma_1 \) or \( \Sigma_2 \).

We analysed the distribution of the \( D_M \) in comparison to the chi distribution as a function of colour, magnitude, and indices of coefficients. The dependency on colour is only weak, with slightly larger values of \( D_M \) for very red sources, with \( G_{BP} - G_{RP} \geq 3.0 \) mag. The magnitude dependency is more pronounced, and depends on the indices of the coefficients. This is illustrated in Fig. 18. The top panels of this figure show the distribution of the \( D_M \), normalised to the total number of sources in each magnitude bin, for all 40K test sources, for the first five and the last five coefficients in BP, respectively. For the first five coefficients, the values of \( D_M \) are in general too large compared to what is expected from a chi distribution, an effect that is more pronounced for bright sources. For the five coefficients corresponding to the highest order basis functions, the magnitude dependency is weaker, with values being slightly smaller than expected from a chi distribution for the brighter sources.

The bottom panels of Fig. 18 show the density histograms for bright sources, with \( G < 10 \) mag in grey, and faint sources, with \( G > 16 \) mag in green, respectively, in comparison with the chi distribution for five degrees of freedom. For the first five coefficients, the distribution is much wider than the chi distribution, in particular for the bright sources, and shifted to larger values. For the last five coefficients, the faint sources are in good agreement with a chi distribution, while the distribution for the bright sources is shifted towards smaller values of \( D_M \).

An underestimation of the error results in larger \( D_M \) than expected from a chi distribution, while an overestimation of the error results in smaller values. The differences in \( D_M \) with respect to the chi distribution can therefore be interpreted as an underestimation of the errors for the coefficients with low indices, and an overestimation of the errors for coefficients of high indices for bright sources. For high indices and faint sources, the errors are however reliable. While the results shown here are from BP spectra, the situation for RP is similar.

### 5.2. Specific cases

Although most of the spectra have a good behaviour, there are few cases where we have some peculiar shapes due to several factors. We analyse in the following a few of the most common situations.

In the case of very faint sources, the fitting procedure generating the mean spectrum will be poorly constrained and may produce unrealistic features. For example, Fig. 19 shows the spectra of a faint red source (with \( G_{BP} = 17.6 \) mag and \( G_{RP} = 17.8 \) mag). For this type of spectra the parameters \( \text{bp\_n\_relevant\_bases} \) and \( \text{rp\_n\_relevant\_bases} \) in the \text{xp\_summary} table in the Gaia DR3 archive are particularly relevant, as they indicate the number of coefficients that are significant considering the noise level (see Carrasco et al. [2021] and Sect. 3.4.3 in this paper for more details). In this case, only 1 of the 55 coefficients defining the BP spectrum is considered significant. Our adopted truncation procedure suggests that for BP all coefficients beyond the first one are only fitting the noise fluctuations rather than real spectral features and can be ignored when using the mean spectra for further investigations. For RP the number increases to 11 thanks to the larger signal to noise ratio.

In crowded areas, it is possible that two or more sources are so close in the sky to cause their observations to be always or often contaminated or blended. We refer to blended spectra when two or more sources fall within the observed window, while contamination refers to flux belonging to a source that is located outside the window. If this happens in a large fraction of the observations of a given source, then the mean spectra for that source will be affected. To enable users assess the reliability of BP/RP mean spectra the \text{xp\_summary} table in the archive includes several parameters (bp\_rp\_n\_blended\_transits and bp\_rp\_n\_contaminated\_transits) indicating the number of transits affected by blending or contamination for all sources for which BP/RP spectra are published. Figure 22 shows the case of four sources in the globular cluster 47 Tuc that have all their observations flagged as blended. Users are strongly encouraged to make use of the available crowding flags to detect problematic cases.

The wings of the spectra should normally have low flux level, due to the combined action of LSF, dispersion and response. If this is not the case it could be due to the presence of residual background flux not fully removed in the background calibration stage or diffused flux due to the source being extended. For example, Fig. 21 shows the BP and RP internal spectra for a source with the in\_galaxy\_candidates flag in the gaia\_source\_table set to true. Both spectra present a larger than normal flux in the wings. This source shows also a significant mismatch between the photometry in the different bands (\( G = 18.7 \) mag, \( G_{BP} = 15.7 \) mag and \( G_{RP} = 14.3 \) mag), the two BP/RP integrated flux values being much brighter than the value in the \( G \)-band, due to the much larger size of the BP/RP windows with respect to the AF ones.

A similar effect is seen when considering objects that are close to a very bright source. Their spectra will appear to be contaminated by flux coming from the nearby bright object. The resolution of the background calibration is not sufficient to remove completely this effect and may actually over/under-estimate the background in the regions surrounding very bright sources. Figure 22 shows the BP/RP spectra for two sources near Sirius. Source Gaia DR3 2947050466531872640, at 30 arcsec from Sirius, is clearly contaminated by diffuse flux coming from the nearby bright source. Also in this case, the photometry indicates a much brighter source in the BP/RP integrated bands than in the \( G \)-band: \( G = 15.7 \) mag, \( G_{BP} = 13.2 \) mag and \( G_{RP} = 13.2 \) mag. The second source (Gaia DR3 2947047202356748672) is located further away at about 3 arcmin. In this case the background seems to have been overestimated causing negative flux values in the wing of the spectra in both BP and RP.

### 5.3. Signal to noise ratio

An overall indication of the signal to noise ratio \( S/N \) for a given source and photometer can be obtained directly from the coefficients by dividing the \( L2 \)-norm of the vector of coefficients by the \( L2 \)-norm of the vector of errors on the coefficients. Figure 22 shows a colour magnitude diagram of the sources with BP/RP spectra in Gaia DR3 colour coded by this global \( S/N \) in the BP and RP photometers in the left and right panel.

A user that is interested in the \( S/N \) at different wavelengths will have to consider the representation of the spectrum by the linear combination of basis functions that do have an explicit wavelength dependency rather than rely on the mere coefficients. The panels in Fig. 24 show typical \( S/N \) distribution of internally calibrated spectra over the BP (left panels) and RP (right panels) pseudo-wavelength ranges covered by the BP/RP spectra. In the
Fig. 18. Top panels: Distribution of the Mahalanobis distances of all test sources as a function of $G$-band magnitude. The grey horizontal line indicates the mean of the chi distribution. Bottom panel: Histograms of the Mahalanobis distances for sources with $G < 10$ mag (grey) and $G > 16$ mag (green). The red line is the corresponding chi distribution. The left hand side plots are for the first five coefficients, with indices 0 to 4, the right hand side plots for the five coefficients of highest order, with indices 50 to 54.

Fig. 19. BP (left) and RP (right) spectra for the faint red source Gaia DR3 1252666141462905344 ($G_{BP} = 21.6$ mag and $G_{RP} = 17.8$ mag). The blue curves show the spectra defined by the 55 coefficients (errors are shown as a shaded area). The red curves show the truncated spectra where only the first $bp/rp\_n\_relevant\_bases$ have been used.

Fig. 20. BP (left) and RP (right) normalised internal spectra of some sources with all transits blended by other nearby sources in the 47 Tuc cluster. The top two panels each curve shows the S/N for sources of different magnitude, as reported in the colour bar, $G_{BP} - G_{RP}$ colour close to 1.0 and with typical global S/N (for sources of similar magnitude and colour). In the bottom two panels instead, each
Fig. 21. BP (left) and RP (right) internally calibrated spectra of a source (Gaia DR3 1252344813484742272) flagged as galaxy in the gaia_source table. The spectra are broader than expected and the corresponding integrated magnitudes are much brighter compared with the $G$-band photometry.

Fig. 22. BP (left) and RP (right) internally calibrated spectra of two sources near Sirius: one located at 30 arcsec (in red) and the other at 3 arcmin (in blue). The source closest to Sirius shows clear signs of contamination from the nearby object.

Fig. 23. Colour magnitude diagram of a random 10% of the sources for which BP/RP spectra are available in Gaia DR3, colour coded in a logarithmic scale by the global S/N as computed directly from the continuous representation coefficients and their errors. BP S/N is shown in the left panel while RP S/N is used in the right one.

curve shows the S/N for sources of different colour, as reported in the colour bar, $G$-band magnitude close to 16.0 and with typical global S/N (for sources of similar magnitude and colour). Only sources with $|c_*| < 0.02$ have been considered for these plots, $c_*$ being the corrected BP/RP flux excess factor as defined in [Riello et al. 2021]. As in previous figures the top axes showing the correspondence with absolute wavelengths are only indicative.

Due to the fact that the mean BP/RP spectra are a combination of many single observations for each object, intrinsic variability will result in larger uncertainties in the mean spectra. This is confirmed by the fact that the S/N for a sample of known RR Lyrae (extracted from [Clementini, G. et al. 2022]) is significantly lower than the S/N for a sample of random (mostly non-variable) sources with similar apparent $G$.

The dependency of the S/N from pseudo-wavelength is linked to the spectrum itself. Looking at the right top panel of Fig. 24 the maximum S/N ratio in RP is achieved for sources with $G - 10$. Saturation and occasional gate mis-configuration could be responsible for this: while the mean spectra of very bright sources do not show clear signatures of saturation, the presence of some saturated epoch spectra among those contributing to the mean spectrum, possibly due to gate mis-configuration caused by large on-board magnitude errors at the bright end, could lead to a larger scatter around the peak and therefore a larger error and a smaller-than-expected S/N ratio.

6. Recommendations

The mean spectra are available in the archive in the form of a set of coefficients that define a continuous function over the pseudo-wavelength range. This is the fundamental product of the BP/RP spectral data processing. When sampling the spectra on a discrete grid in pseudo-wavelength (or wavelength if working in the absolute system), some information is unavoidably lost. In particular, the continuous representation comes with full covariance information, whereas a spectrum sampled on a (pseudo-)wavelength grid with more points than the number of coefficients in the continuous representation cannot. Users are therefore strongly encouraged to consider using the continuous representation to exploit at best the BP/RP spectra in Gaia DR3 (e.g. to derive astrophysical parameters or analyse the presence of spectral features) and avoid sampling the spectra or deriving...
Fig. 24. S/N vs pseudo-wavelength (and approximate absolute wavelength) for internally calibrated spectra. The top panels show the S/N for sources of different magnitude and similar colour (close to 1.0), while the bottom panels focus on sources with similar G-band magnitude (close to 16.0) and a range of colours.

synthetic photometry from them, losing information in the process.

Figure 25 shows that the coefficients can be used to successfully classify sources in different regions of the Hertzsprung-Russell diagram. At least for the few cases shown in the plot, most of the information required for classification is already available in the first few coefficients of the continuous representation. Figure 26 shows the corresponding plot with the more familiar sampled spectra.

Figure 13 clearly shows that narrow spectral features in the spectra can only be reproduced with larger higher order coefficients. For example, Fig. 27 shows an example of two sources with rather similar RP spectra except for the presence of a strong emission line. One of the two sources is a QSO. As it can be seen in the bottom right panel, higher order coefficients for the QSO have larger values.

6.1. Effects of noise

The correlations between the coefficients of a source, both, for BP and RP, are in general rather low, with median correlation coefficients well below 0.1 in both, BP and RP. When construct-

Fig. 25. First eight coefficients of the continuous representation in BP (left) and RP (right) for some sources with different astrophysical parameters.
Fig. 26. Normalised internal mean spectra in BP (left) and RP (right) for the same sources shown in Fig. 25.

Fig. 27. Comparison of the mean spectra obtained for a QSO with a strong emission line (Gaia DR3 1255795527649038720 in blue), and another source with similar shape and flux level but without strong features (Gaia DR3 4689627408431598336 in orange). BP is shown in the left panels and RP in the right ones. Sampled spectra are shown in the top panels, while the bottom panels show the corresponding coefficients.

7. Conclusions

In this paper we have focused on the processing that generated the internally calibrated BP/RP spectra contributing to Gaia DR3 starting from the raw satellite data. The released data are time-averaged source spectra that result from the combination of all single observations of a given source. Only a selection of all generated spectra will be included in the release at this stage, but several other new products are based on the entire dataset. The main challenges faced by this step in the data processing are due to the vast amount of data (about 65 billion single BP/RP transits were processed), to the nature of the low-resolution aperture prism spectroscopy with the additional complications added by the TDI mode, to the large number of different observing configurations effectively corresponding to different instruments that need to be calibrated onto the same homogeneous system. We have explained how we have dealt with these challenges and have shown how we have been monitoring the intermediate performances of our calibration procedures. We also described the somewhat unfamiliar format of the BP/RP spectral data in the archive. Rather than providing spectra defined as a flux value corresponding to a sample covering a given wavelength range, the BP/RP spectra are represented by an array of coefficients, their errors and correlations, to be applied to a set of basis functions to obtain a continuous function. This approach allows combining multiple transit spectra, each having its own pixel/wavelength sampling, dispersion and LSF (Carrasco et al. 2021). The set of bases has been optimised to ensure maximum efficiency. Iterating the sampled spectrum as a function of pseudo-wavelength (or wavelength), the correlations might become much more important. Since there are only 55 basis functions for BP and RP, respectively, any sampled spectrum with more than 55 sample points needs to have linear dependencies among the samples. Furthermore, even if the coefficients would be uncorrelated, the non-local character of the basis function representation introduces correlations between different pseudo-wavelengths. This effect is illustrated in Fig. 28 for the RP spectrum of one particular source, with $G = 17.89$, $G_{BP} - G_{RP} = 2.74$. The BP/RP split epoch validation dataset (see App. D) has been used for this analysis. The two sets of transits for this source contain 18 transits and 3 transits, respectively. Consequently, the signal-to-noise ratio in the first set is higher than in the second one. This is seen in the first column of Fig. 28 where the coefficients for the calibration using only three transits are noisier and have larger error bars than for the 18 transits set. The second column in this figure shows the correlation matrices for the two cases. In general the correlations are low, with little structure in the off-diagonal entries. For the noisier case, the correlations are however larger. The third column shows the sampled RP spectra for the 18 transits and the three transits cases. The larger noise in the latter case manifests itself in a wavy structure in the sampled spectrum. In the correlation matrix for the sampled spectrum, shown in the fourth column, this manifests itself in the form of alternating short-scale patterns of positive and negative correlations. These patterns are again more pronounced when the signal-to-noise ratio is lower.

Since random noise in the BP/RP spectra manifests itself in the sampled spectra as wavy structures, and correlations within the sampled spectra are not negligible, the interpretation of the coefficients, being much less affected by correlations, might be more convenient.
leaving higher-order coefficients to be constrained by narrow spectral features.

We want to conclude this paper by showing some sky distributions related to the BP/RP data in Fig. 29. All maps are in Galactic coordinates and show the entire catalogue of sources with BP/RP spectra in Gaia DR3. The first map shows the density distribution in the sky. As expected most of the sources are concentrated along the Galactic plane. The two Magellanic Clouds also stand out as well as a few clusters. The darkest areas close to the Galactic plane in the map correspond to both regions obscured by dust and regions with extremely high density where the BP/RP data are particularly affected by strong crowding (both in the acquisition and in the processing). Some regions with lower density off the Galactic plane still show imprints of the scanning law (compare this with the map showing the median number of transits). These are expected to disappear with the addition of more observations in future releases. The second map shows the distribution of \(G_{BP} - G_{RP}\) colour. The third map shows the median number of transits per source (in RP). This is clearly defined by the satellite scanning law. A similar map of BP would be very similar with the exception of the occurrences of larger number of transits near the Ecliptic poles. These are due to the first month of operations in Ecliptic scanning law. This period was not included in the generation of average source BP spectra as explained in Sect. 3.3. The fourth map shows the median fraction of contaminated or blended transits with respect to the number of transits per source for RP. The equivalent maps for BP would look very similar. The areas showing higher density in the first map stand out also in this map as regions where the mean spectra are more affected by crowding. This is justified by the fact that the crowding evaluation is limited to the Gaia source catalogue itself. Finally the last two maps show the distribution in the sky of the median of the 84th percentile of the S/N distribution over the BP and RP wavelength ranges. As expected the scanning law signature is very evident in these maps with errors being lower in the most observed regions. Areas at low Galactic latitude show lower S/N in the BP spectra due to the abundance of red-colour sources. The S/N distribution of the internally calibrated spectra shows values larger than 1000 for bright sources in some wavelength ranges (see Fig. 24). Gaia DR3 will contain about 700 thousand BP spectra and 4.3 million RP spectra with the 84th percentile of the S/N above 500.

Various parameters available from the archive can be useful to clean the catalogue from disturbed spectra. A very useful quantity already introduced for Gaia DR2 is the \texttt{phot\_bp\_rp\_excess\_factor}. This parameter is available from the \texttt{gaia\_source} table and is defined as the ratio between the sum of BP and RP integrated fluxes and the \(G\)-band flux for the same source. Due to the shape of the \(G\), \(G_{BP}\) and \(G_{RP}\) passbands some colour dependency of this ratio is expected and may bias selections based on \texttt{phot\_bp\_rp\_excess\_factor}. To correct for the expected colour trends, users should apply the equation recommended in [Riello et al. (2021)] to form what is known...
as $C^\star$. The deviation of this parameter from 0.0 indicates the presence of inconsistencies between the flux measured in the BP/RP windows with respect to the flux in the $G$-band. These inconsistencies can be due to different source properties (e.g. in the case of extended sources) or systematic errors in the calibration procedures (e.g. in the case of residual background due to nearby bright sources). Section 9.4 in Riello et al. (2021) provides also a function reproducing the 1$\sigma$ scatter for a sample of well behaved isolated stellar sources with good quality photometry. Users wishing to use $C^\star$ and its 1$\sigma$ scatter to select the most reliable spectra, would find that 90% of the sources have $C^\star < 3\sigma$ while 79% fulfil the criterion $C^\star < 1\sigma$. Figure 30 shows the distribution of $C^\star$ together with the 1- and 3-$\sigma$ limits.

In terms of BP/RP spectral data, future releases will see a vast increase in the number of average source spectra and the addition of calibrated epoch spectra, i.e. spectra derived from one single observation in BP/RP. From the processing and validation
point of view this will focus the attention on calibrations that de-
viate from the average behaviour. While when generating mean
spectra robust techniques help mitigate these problems, the ap-
lication of noisy calibrations can generate unreliable data. This
needs to be mitigated to ensure the quality of calibrated BP/RP
epoch spectra, planned to be included in future releases. One
other area where some improvement is being sought, is in the
bluest wavelength range covered by BP (350 − 400 nm) where
the small fraction of calibrators makes the flux and LSF cali-
bration particularly challenging. The effect of this can be seen in
some systematics offsets in the bluest part of the wavelength
range covered by BP/RP data. These can be quantified when
comparing BP/RP spectra with external absolute spectra [Montegri-
frigo, P. et al. (2022a) and/or synthetic photometry generated
from BP/RP spectra in various bands and photometric systems vs
existing catalogues [Montegri, P. et al. (2022b)]. In particular,
in the latter work, the comparison of synthetic photometry from
externally calibrated BP/RP spectra with state-of-the-art ground
based photometric standard stars suggests that in the wavelength
range spanned by SDSS u band (and/or Johnson-Kron-Cousins
U) differences can be as large as 20%, for some spectral types
and in some color ranges. In the range covered by SDSS g band
(and/or Johnson-Kron-Cousins B band) systematics reach the
5% level at most, while for redder passbands are typically be-
low the 2% level.

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The Gaia mission website is [https://www.cosmos.esa.int/gaia]. The Gaia
archive website is [https://archives.esac.esa.int/gaia]. Acknowledgements are given in App. F.

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Appendix A: Downloading BP/RP data from the Gaia DR3 archive

Not all sources included in Gaia DR3 will have BP/RP spectra available. The main gaia_source table in the archive contains a field has_xp_continuous that is true if a BP/RP spectrum is available for that source. Users can therefore query the gaia_source table to select sources with their favourite combination of parameters and use the additional criterion has_xp_continuous='true' to restrict their selection to sources that have BP/RP spectra available from the archive.

The support of the Datalink feature in the archive includes an independent service for the serialization of the BP/RP spectra. Other types of data such as photometric light curves are served using similar services. A dedicated tutorial is available here.

In this section we provide an example of how to download BP/RP spectra using the Python programming language. By splitting the list of sources identifiers (ids['source_id']) in the following code snippet, users can overcome the Datalink limitation on the number of sources. A bulk download option will also be implemented for users interested in getting all the BP/RP spectra in Gaia DR3.

```python
from astroquery.gaia import GaiaClass

# Connect to Gaia archive
gaiadr3 = GaiaClass(gaia_tap_server='https://gea.esac.esa.int/', gaia_data_server='https://gea.esac.esa.int/')</p>

# Login

gaiadr3.login(

# Run your ADQL query to get a list of source_ids
example_query = "select TOP 1000 source_id from gaiadr3.gaia_source where has_xp_continuous = 'True'"

ids = gaiadr3.launch_job_async(example_query, dump_to_file=False)

result = gaiadr3.load_data(ids=ids['source_id'], format='csv', data_release='Gaia DR3', data_structure='raw', retrieval_type='XP_CONTINUOUS', avoid_datatype_check=True)

# Now retrieve the BP/RP mean spectra in the continuous representation

result = gaiadr3.load_data(ids=ids['source_id'], format='csv', data_release='Gaia DR3', data_structure='raw', retrieval_type='XP_CONTINUOUS', avoid_datatype_check=True)

# Result will be a dictionary, so you can check the available keys by running result.keys()

# In this example we are looking in particular for the XP_CONTINUOUS_RAW key
continuous_key = [key for key in result.keys() if 'continuous' in key.lower()]

# The first element is the result we want as an Astropy table

data = result[continuous_key][0]

# Astropy has a 'write' method for tables

# Write the table to CSV
data.write('filename.csv', format='csv')
```

The data can be downloaded in different file formats. For a complete list of the available formats and for instructions on alternative download procedures, please refer to the archive pages and tutorials.

Once downloaded, the files can be given in input to GaiaXPy utilities to obtain sampled spectra or synthetic photometry. GaiaXPy also offers the possibility of providing a list of source IDs. In this case the download of the spectra from the archive is done within the GaiaXPy utility (users will be prompted for credentials).

Appendix B: Data format details

This Section provides more detailed information on the structure of the data representing BP/RP mean spectra in the archive. For completeness, all fields are described here, even though some have been mentioned and explained in the main part of the paper. Detailed descriptions are also available from the Gaia DR3 documentation and from the archive documentation.

We first describe the fields available via Datalink when retrieving XP_CONTINUOUS data:

- **source_id** Source identifier. Among other information, this encodes the approximate position of the source in the equatorial system (ICRS) using the nested HEALPix scheme at level 12 (Nside = 4096), which divides the sky into ~200 million pixels of about 0.7 arcmin².
- bp/rp_basis_function_id Identifier of the set of bases functions used in the Source Update process (see Sect.13.3). Different sets were used during trial runs and validation but all the released spectra were created using the same set of bases. This implies that the identifier in Gaia DR3 is different for BP and RP spectra, but the same for all sources in each band. When sampling the spectra in the internal reference system, care must be taken to ensure that the right basis configuration is used.
- bp/rp_degrees_of_freedom Number of degrees of freedom in the Source Update least squares solution.
- bp/rp_n_parameters Number of parameters in the Source Update least squares solution. This will be always 55 for the Gaia DR3 BP/RP spectra.
- bp/rp_n_measurements Number of measurements contributing to the Source Update least squares solution. This counts the single samples contributing rather than full epoch spectra.
- bp/rp_n_rejected_measurements Number of samples rejected in the Source Update least squares solution. This is based on a k-sigma rejection algorithm.
- bp/rp_standard_deviation The final standard deviation of the Source Update least squares solution for this BP/RP and source.
- bp/rp_chi_squared The $\chi^2$ of the Source Update least squares solution for this BP/RP and source.
- bp/rp_coefficients The array of coefficients of the mean spectrum representation as a superposition of basis functions. These are the $b_{i,n}$ in Eq.4. This array will have length equal to bp/rp_n_parameters.
- bp/rp_coefficient_errors The errors on the coefficients, one error per coefficient. This array will have length equal to bp/rp_n_parameters. The errors in this array are computed multiplying the formal errors (as obtained from the covariance matrix of the source update least square solution) by the standard deviation of the solution. This is a standard methodology and can also account for when the modeling of the data introduces a systematic that adds a pseudo-random error to the individual input data not accounted for in quoted errors.
- bp/rp_coefficient_correlations The matrix containing the information on correlations between coefficients. Only the elements located in the upper triangular section of the matrix, excluding the diagonal where all elements are equal to 1.0 by definition, are stored as an array of constant
size $n(n - 1)/2$ where $n$ is equal to \texttt{bp/rp.n.parameters}.
The order of the elements in the linear array follows a
column-major scheme, i.e. for $n = 55$
\[
M = \begin{bmatrix}
1 & C[0] & C[1] & C[3] & C[6] & \ldots & C[1431] \\
1 & C[2] & C[4] & C[7] & \ldots & C[1432] \\
1 & C[5] & C[8] & \ldots & C[1433] \\
1 & C[9] & \ldots & C[1434] \\
1 & \ldots & \ldots & \ldots & \ldots & \ldots & 1 \\
1 & \ldots & \ldots & \ldots & \ldots & \ldots & 1 & C[1484] \\
1 & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & 1
\end{bmatrix}
\]
- \texttt{bp/rp.n.relevant.bases} Number of coefficients that
were considered above the noise according to the criterion
described in Sect. 3.4.3
- \texttt{bp/rp.n.relative.shrinking} Ratio between the L2-
norm of the truncated and full BP/RP spectrum.

In the following, we also describe the additional fields avail-
able in the \texttt{xp.summary} table (fields that duplicate information
given in the above data structure are not repeated here):
- \texttt{bp/rp.n.transits} Number of epoch spectra contributing
to the mean spectrum.
- \texttt{bp/rp.n.contaminated.transits} Number of transits
assessed as contaminated among those that contributed
to the mean spectrum. A transit is considered contaminated when
some of the flux within the window is estimated to come from
a nearby (on the focal plane) source located outside the
acquired window. Crowding assessment for \textit{Gaia} DR3 was
based on the \textit{Gaia} DR2 source catalogue. The contaminating
flux was estimated as detailed in Sect. 3.1 in [Riello et al.
(2021)].
- \texttt{bp/rp.n.blended.transits} Number of transits assessed
as blended among those that contributed to the mean spectrum.
A transit is considered blended when more than one
source is within the acquired window. A transit is flagged
as blended also when the non-target source is just outside the
window (within 5 TDI periods in the AL direction and 2
pixel in the AC direction).

### Appendix C: Bases configuration and spectrum sampling

The optimised bases finally adopted to represent the \textit{Gaia} DR3
mean spectra are defined as an orthogonal transformation of the
first $N$ Hermite functions. The orthogonal transformations are
different for BP and RP, and the $N \times N$ transformation ma-
trices are denoted $V_{BP}$ and $V_{RP}$, respectively, where $N = 55$
for both. The two transformation matrices are embedded in the
Python package GaiaXPy, that uses them when computing sam-
plesd mean spectra in the internal reference system. The same
xml configuration file used in GaiaXPy is also available via Zenodo.

Users that prefer to use this file directly rather than relying on
GaiaXPy will have to pay attention to the following:

- The file contains a \texttt{bpConfig} and an \texttt{rpConfig} ele-
  ment. Each configuration element is identified with
an unique id (\texttt{uniqueId}) which must agree with the
\texttt{bp/rp.basis.function_id parameter in the Gaia DR3}
BP/RP spectral data.
- The ranges \texttt{range} and \texttt{normalizedRange} give the con-
version rule from the pseudo-wavelength system to the argu-
ment of the Hermite functions. With reference to Eq. 4 the
scaling factor $\Theta$ will be given by $\Theta = (r_s - r_\infty)/(n_s - n_\infty)$
while the offset $\Delta \theta$ will be given by $\Delta \theta = r_s - n_\infty \cdot \Theta$ where
$r_s$ and $n_s$ are used to indicate the higher (+) and lower (−)
boundaries of the ranges \texttt{range} and \texttt{normalizedRange}
respectively.
- The element \texttt{transformationMatrix} lists all matrix ele-
ments for $V_{BP}$ and $V_{RP}$, stored in a row-major scheme.

The sampled spectrum on a discrete grid of $n$ pseudo-
wavelengths $u = \{u_i\}_{i=1...n}$ is computed easily in a matrix for-
malism. First, the values of the first $N$ Hermite functions are
computed on the pseudo-wavelength grid and arranged into an
$n \times N$ matrix $D$. The elements of this matrix are
\[
D_{i,j} = \varphi_{j-1}(u_i - \Delta \theta)/\Theta .
\] (C.1)
Multiplying this matrix with $V_{BP/RP}^{T}$ from the right transforms
from Hermite functions to the optimised Hermite basis. The sample-
d spectrum $f(u)$ is thus obtained as
\[
f(u) = D \cdot V_{BP/RP}^{T} \cdot C \cdot u .
\] (C.2)
The covariance matrix for $f(u)$, $C''$ is
\[
C'' = D \cdot V_{BP/RP}^{T} \cdot C_{BP/RP} \cdot V_{BP/RP} \cdot D^{T}
\] (C.3)
with $C_{BP/RP}$ the covariance matrix for the coefficient vector
$c_{BP/RP}$. Correlations might not be negligible in $C''$. In particu-
lar if $n > N$, $C''$ is singular.

If users desire to apply the suggested truncation,
they will simply have to drop coefficient, coefficient
error and associated row/column in the correlation ma-
trix with index larger than \texttt{bp/rp.n.relevant.bases}. Only the first
\texttt{bp/rp.n.relevant.bases} columns of the
\texttt{transformationMatrix} will be required.

### Appendix D: The BP/RP split-epoch validation
dataset

During the validation activities leading to \textit{Gaia} DR3 (see Sects.
5.7 and 6.1) and in the preparation of [Andrae, R. et al. (2022)
and Montegriffo, P. et al. (2022b)], we have found very useful
a dataset containing about 43 thousand sources for which two
mean spectra per source were generated using only about half
of the available epoch spectra (randomly chosen to avoid pos-
sible problems due to the distribution in time of their observa-
tions). This dataset, referred to as BP/RP split-epoch validation
dataset, is made available via Zenodo, in the same format used
in the archive for mean BP/RP spectra (with the exception of the
truncation-related parameters \texttt{bp/rp.n.relevant.bases} and
\texttt{bp/rp.n.relative.shrinking} that will not be available. We
hope the wider community will find this useful to assess the un-
certainties of their particular science cases.

The source list for this dataset was initially defined as a se-
lection of the flux and LSF calibrators but was later augmented
to include more bright sources and to increase the number of
sources in the magnitude range [11, 12], i.e. around the bound-
ary between 1D and 2D BP/RP configurations. The dataset cov-
covers the magnitude range $4.2 \leq G \leq 20.7$ mag and the colour
range $-0.6 \leq G_{BP} - G_{RP} \leq 7.1$ mag. While the initial selec-
tion came from the set of calibrators that were selected to have
at least 10 usable FoV transits (thus leading to at least 5 transits
when these are split in two groups, although the random gener-
aton of the two groups could in fact lead to smaller numbers),
the following additions included also sources with fewer transits. Moreover, the criterium based on the number of FoV transits for the selection of the calibrators was assessed on the number of usable observations and these were then subject to availability of calibrations and outlier rejection which could have the effect of decreasing the number of transits contributing to the mean spectrum below the quoted limit. This implies that this dataset contains mean spectra that have been generated from a number of transits that is lower to the limit adopted for the release. About 6 thousand of these sources will not have BP/RP spectra in Gaia DR3, mostly due to their magnitude being fainter than 17.65 (see Sect. 4) Nevertheless they were not excluded from this dataset as they provide an opportunity to probe uncertainties at fainter magnitudes where some BP/RP spectra are still released.

Users are strongly discouraged from trying to look for consistency in number of transits and measurements between this dataset and the Gaia DR3 catalogue of BP/RP spectra: rejection and filtering at epoch and sample level will act differently depending on the filtering of transits available to the software.

### Appendix E: Gaia-related acronyms

| Acronym | Description | See |
|---------|-------------|-----|
| AC      | ACross scan direction | Sect. 2 |
| AF      | Astrometric Field | Sect. 1 |
| AL      | ALong scan direction | Sect. 1 |
| BP      | Blue Photometer | Sect. 1 |
| CCD(s)  | Charge Coupled Device(s) | Sect. 1 |
| DPAC    | Data Processing and Analysis Consortium | Sect. 1 |
| DR      | Data Release | Sect. 1 |
| ESA     | European Space Agency | Sect. 1 |
| FoV(s)  | Field(s) of View | Sect. 2 |
| GAPS    | Gaia Andromeda Photometric Survey | Sect. 1 |
| LSF     | Line Spread Function | Sect. 3.2 |
| OBM(T)  | On-Board Mission Time | Sect. 2 |
| OBM(T)-Rev | On-Board Mission Time in units of satellite revolutions | Sect. 2 |
| RP      | Red Photometer | Sect. 1 |
| RVS     | Radial Velocity Spectrometer | Sect. 1 |
| SED     | Spectral Energy Distribution | Sect. 4 |
| SSC     | Spectrum Shape Coefficient | Sect. 3.1 |
| SSO     | Solar System Objects | Sect. 3.5 |
| TCB     | Barycentric Coordinate Time | Sect. 3.5 |
| TDI     | Time Delayed Integration | Sect. 2 |
| WC(s)   | Window Class or strategy | Sect. 2 |

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