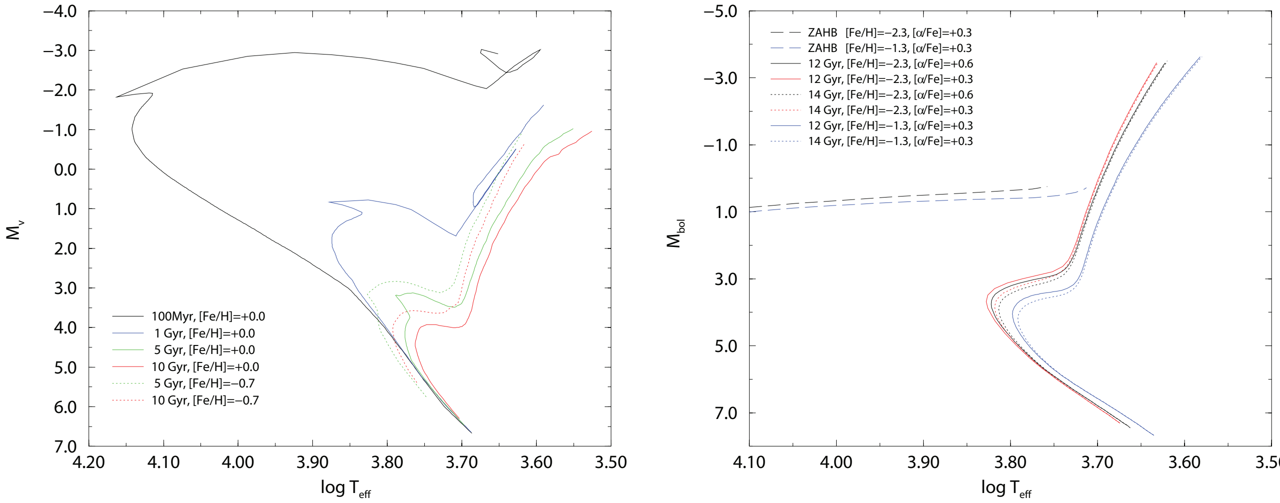


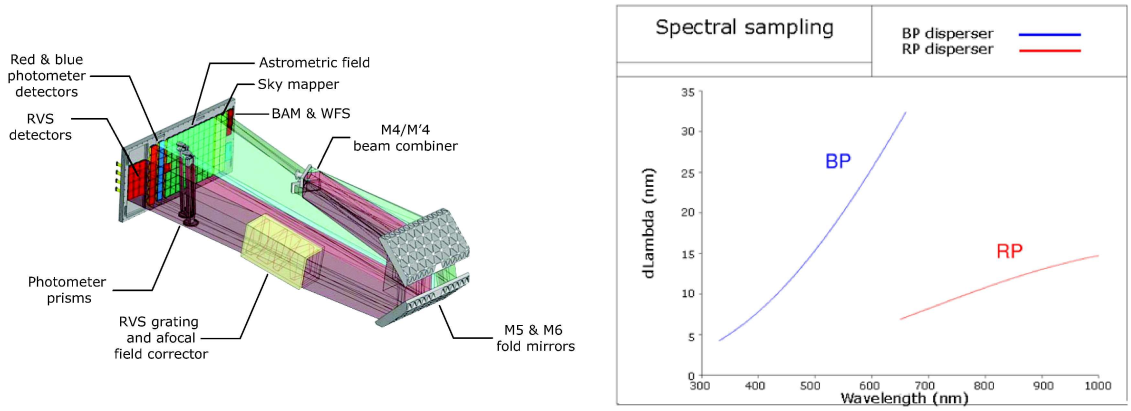
Gaia photometry will allow chemical-abundance and age determination of the Galactic stellar populations over the entire Hertzsprung–Russell diagram. Left: isochrones of 0.1, 1, 5, and 10 Gyr covering the thin disc and the bulge. Right: isochrones of 12 and 14 Gyr and zero-age-horizontal-branch loci for several [Fe/H] and [α/Fe] abundances suitable for the halo and the thick disc.

If Gaia's astrometric measurements would be unsupported by appropriate diagnostic data, the final Catalogue would contain immense numbers of positions and velocities of objects whose astrophysical nature would otherwise be unknown. With such limited data, the key objective of the mission – the study of the structure and history of the Milky Way – could not be met. Therefore, Gaia has therefore been equipped with a photometric instrument with the goal of measuring the spectral energy distributions of all objects. From these measurements, astrophysical quantities such as luminosity, effective temperature, mass, age, and chemical composition can be derived.

In order to meet the astrometric performance requirements, the measured centroid positions must be corrected for systematic chromatic shifts induced by the optical system. This is only possible with the knowledge of the spectral energy distribution of each observed target in the wavelength range covered by the CCDs of the main astrometric field (~330–1000 nm). The photometric instrument also covers this requirement.

Photometric measurements are indispensable in providing the basic tools for classifying stars across the entire Hertzsprung–Russell diagram, as well as in identifying specific and peculiar objects. To achieve this, it is necessary to observe a broad spectral domain, extending from the ultraviolet to the infrared. Gaia's photometric measurements must be able to determine, among others, (i) effective temperatures and reddenings for early-type stars, which serve both as effective tracers of Galactic spiral arms and as reddening probes; (ii) effective temperatures and abundances for late-type stars; and (iii) luminosities for stars with large relative parallax errors. Moreover, in order to be able to reconstruct the Galactic formation history, the distribution function of stellar abundances must be determined to ~0.2 dex, while effective temperatures must be obtained to ~5%. These accuracies allow separation of stars belonging to the various stellar populations in the Galaxy (i.e. thin disc, thick disc, and halo). The determination of abundances of Fe and α-elements is essential for mapping Galactic chemical evolution. Photometric measurements will be performed for every target transiting the focal plane. Hence, astrophysical information will not be limited to stars but will also be available for quasars, solar-system objects, and many other celestial bodies.

A broad-band magnitude, and its time dependence, can be obtained from the analysis and rigorous calibration of the primary mission data (i.e. by determination of the 'amplitudes' of star images in the main astrometric field). Combined with parallaxes and with estimates for interstellar absorption, these so-called G-band magnitudes give a measure of the absolute magnitude. Gaia will provide reliable absolute magnitudes for several hundred million stars.



Left: Schematic view of the photometric instrument and the Gaia focal plane. Right: BP and RP dispersion properties (see text). Figures courtesy of EADS Astrium.

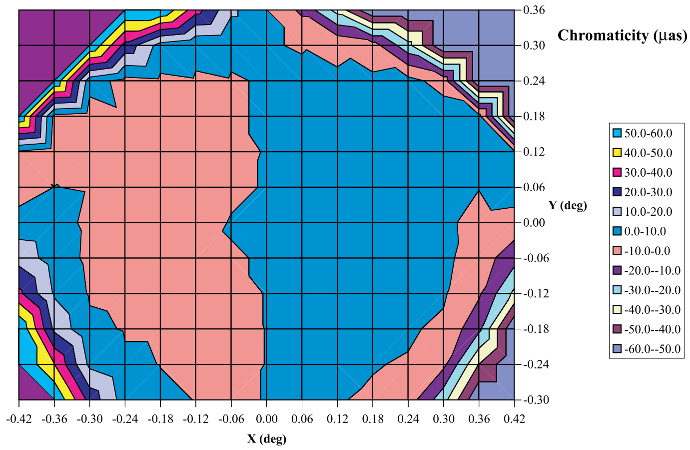
The primary aim of the photometric instrument is to measure the spectral energy distribution of all observed objects. This measurement is mission critical in two respects: it serves (i) to correct the measured centroid positions in the main astrometric field for systematic chromatic shifts, and (ii) to determine astrophysical characteristics, such as effective temperature, mass, age, and chemical composition, for all stars.

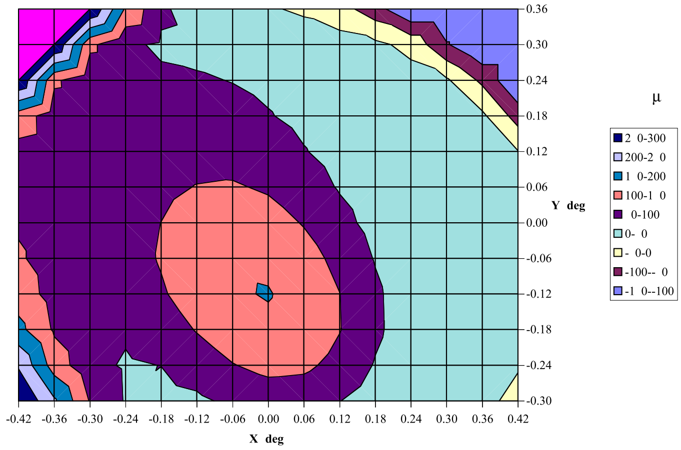
Gaia's photometric instrument is based on a dispersive-prism approach such that starlight is not focused in a PSF-like spot but dispersed along the scan direction in a low-resolution spectrum. The instrument consists of two low-resolution fused-silica prisms dispersing all the light entering the field of view. One disperser – called BP for Blue Photometer – operates in the wavelength range 330–680 nm; the other – called RP for Red Photometer – covers the wavelength range 640–1000 nm. Both prisms have appropriate broad-band filters for blocking unwanted light. The photometric instrument is integrated with the astrometric and spectroscopic instruments and telescopes; the photometric CCDs are located in the Gaia focal plane. As a result, light and objects coming from the two viewing directions of the two telescopes are superimposed on the photometric CCDs. The prisms are located between the last telescope mirror (M6) and the focal plane, close to the latter, and are physically supported by the CCD radiator (see the figure above).

Two CCD strips are dedicated to photometry, one for BP and one for RP. Both strips cover the full astrometric field of view in the across-scan direction. Since BP and RP use the (astrometric) Sky Mapper (SM) function for object detection and confirmation, all objects selected for observation in the astrometric field will also be selected for observation in BP and RP. All BP and RP CCDs are operated in TDI (time-delayed integration) mode. The CCDs have 4500 TDI lines and 1966 pixel columns ($10 \times 30\ \mu\mathrm{m}^2$ pixels). Anti-reflection coatings and device thicknesses, and thus quantum efficiencies, are optimised separately for BP and RP.

The spectral resolution is a function of wavelength as a result of the natural dispersion curve of fused silica; the dispersion is higher at short wavelengths, and ranges from 4 to 32 nm/pixel for BP and from 7 to 15 nm/pixel for RP (see figure). The variation across-scan does not exceed $\pm 9\%$ for BP and $\pm 4\%$ for RP. The BP and RP dispersers have been designed in such a way that BP and RP spectra have similar sizes (on the order of 45 pixels along scan). BP and RP spectra will be binned on-chip in the across-scan direction; no along-scan binning is used. For bright stars, single-pixel-resolution windows are allocated, in combination with TDI gates. RP and BP will be able to reach object densities on the sky of at least 750,000 objects deg^{-2}. Window extensions meant to measure the sky background have been implemented.

Gaia: Photometric Instrument





Above: Chromaticity map for the nominal system of an early Gaia telescope design.
Below: Chromaticity map when all sources of wave-front errors are included.

Although the Gaia optical design only employs mirrors, diffraction effects with residual (achromatic) aberrations induce a small chromatic shift of the diffraction peak. This effect is usually neglected in optical systems, but was relevant for Hipparcos and becomes even more critical for Gaia. The chromatic image displacement depends on position in the field, and on the star's spectral energy distribution, but not on its magnitude. The overall system design must either reduce these chromatic displacements to levels below those relevant for the final mission accuracies - which proved to be impossible for Gaia's selected flight design - or ensure that they can be calibrated as part of the data analysis. One purpose of the photometric instrument is to provide colour information on each observed object in the astrometric field to enable the chromaticity bias calibration on ground.

For a rough quantitative assessment of the effect of chromaticity, a chromaticity measure can be defined which corresponds to the relative displacement (in μas) of the diffraction peak between two stars of extreme spectral types (say B3V and M8V). This measure can be calculated by means of a simple formula for any WFE (wave-front error) map. WFE maps for different points in the field of view can thus be transformed into a 'chromaticity map' showing the variation of the effect across the field of view for a given set of alignment and polishing errors.

A chromaticity map for the nominal system of an early Gaia telescope design is given in the top figure above. In the field of view, where the RMS optical-design WFE is assumed to be $\lambda/30$, chromatic shifts reach $\sim$30 μas. However, the actual chromaticity error will include all sources of WFE, i.e. including optical misalignments and residual polishing residual errors. The lower figure shows an example of a chromaticity map obtained by including all sources of WFE, assuming that polishing errors are $\lambda/30$ RMS for the primary mirror and $\lambda/50$ RMS for the secondary. For constructing this map, the polishing errors were arbitrarily distributed over 3-rd and 5-th order Zernike polynomials. This is a worst case scenario, since the actual polishing error will be distributed over a much larger number of polynomials (the actual spectrum depends sensitively on the polisher and the polishing technique), and since high-spatial-frequency wavefront errors contribute marginally to chromaticity. Nevertheless, this example shows that chromatic shifts of several hundred μas should be expected. This is confirmed by recent simulations of the EADS Astrium Gaia flight-model design. With the aid of the photometric data these shifts can be accurately calibrated by the data processing on ground, thus not impacting the final mission performance.