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Gaia: Astrometric performance and current status of the project

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Abstract. The scientific objectives of the Gaia mission cover areas of galactic structure and evolution, stellar astrophysics, exoplanets, solar system physics, and fundamental physics. Astrometrically, its main contribution will be the determination of millions of absolute stellar parallaxes and the establishment of a very accurate, dense and faint non-rotating optical reference frame. With a planned launch in spring 2012, the project is in its advanced implementation phase. In parallel, preparations for the scientific data processing are well under way within the Gaia Data Processing and Analysis Consortium. Final mission results are expected around 2021, but early releases of preliminary data are expected. This review summarizes the main science goals and overall organisation of the project, the measurement principle and core astrometric solution, and provide an updated overview of the expected astrometric performance.

Keywords. methods: data analysis, space vehicles: instruments, catalogs, surveys, astrometry, reference systems, stars: distances, stars: kinematics

1. Science goals of Gaia

The ESA Gaia mission is an all-sky astrometric and spectrophotometric survey of point-like objects between 6th and 20th magnitude to be carried out over 5–6 years starting in 2012. Some 1 billion stars, a few million galaxies, half a million quasars, and a few hundred thousand asteroids will be observed. Expected accuracies for stellar parallaxes, annual proper motions and positions at mean epoch ($\simeq$ 2015.0) are 7–25 μas (microarcsec) down to 15th magnitude and a few hundred μas at 20th magnitude (see Sect. 5). The astrometric data are complemented by low-resolution spectrophotometric data in the 330–1000 nm wavelength range and, for the brighter stars, radial velocity measurements using a wavelength region around the near-infrared Ca II triplet. Each object will cross one of the instrument's two fields of view some 12–25 times per year at quasi-irregular intervals, providing a good temporal sampling of variability and orbital motion on all time scales from a few hours to years. A very accurate, dense and faint non-rotating optical reference frame will be established through the quasar observations.

The extremely rich and varied science goals of Gaia rest on its unique combination of very accurate astrometric measurements, the capability to survey large flux limited samples of objects, and the collection of synoptic, multi-epoch spectrophotometric and radial-velocity measurements. The proceedings of the symposium *The Three-Dimensional Universe with Gaia* (Turon *et al.* 2005) provides a broad and detailed overview of the science expectations of Gaia.

A primary goal is to study *galactic structure and evolution* by correlating the spatial distributions and kinematics of stars with their astrophysical properties. The determination of number densities and space motions for large, volume-complete samples of stars allows to trace the galactic potential and hence the distribution of matter (including

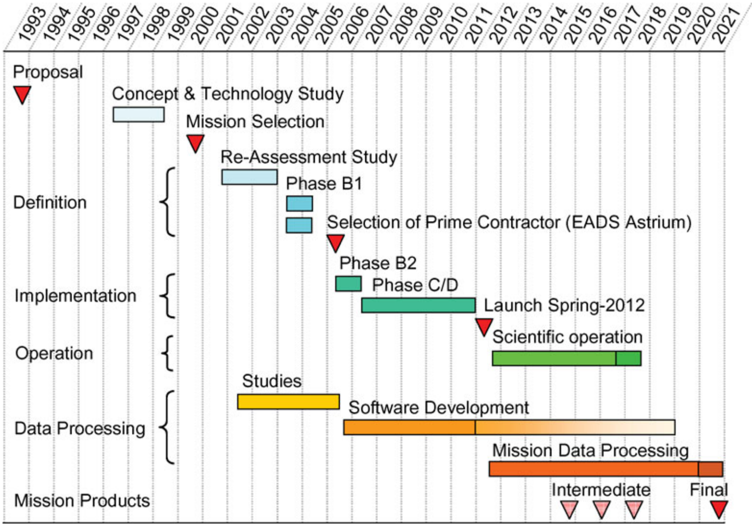

Figure 1. Overview of the main phases of the development of the Gaia project from the original proposal in 1993 to the expected publication of the final catalogue around 2021. The number and dates of the early releases of intermediate mission products are only indicative.

dark matter) in greater detail than has been possible before. The combination of luminosity and colour information for large samples allows to determine the history of star formation, which in combination with kinematic data may provide new insight into how the Galaxy was assembled and evolved. In *stellar astrophysics*, the determination of very accurate ($< 1\%$) parallax distances to literally millions of stars will boost all kinds of investigations based on the intrinsic properties of stars, provide stringent tests of stellar structure models and thereby drive the development of improved theoretical models of stellar atmospheres, interiors, and evolution. Gaia will survey millions of nearby stars for possible giant planetary companions, determine masses and orbital parameters for the detected companions and thereby provide reliable statistics for the occurrence of exoplanetary systems. A huge contribution will be made to *solar system physics* through the systematic observation of all $\sim$300 000 asteroids brighter than Gaia's flux limit. Relatively few new discoveries are expected, but the large number of observations (some 60 epochs per object) and the high accuracy per observation (some 35–1000 μas per epoch) will allow the determination of extremely accurate osculating elements and hence the study of orbit families, their dynamical evolution, and the masses of individual asteroids. Gaia's contributions in the areas of the *reference frame* and *fundamental physics* are discussed in several other papers presented at this symposium; see Mignard & Klioner (2009), Hestroffer *et al.* (2009), Hobbs *et al.* (2009), and others.

2. Project organization and schedule

The Gaia project is the result of a large and complex collaboration between many individuals, teams, and organizations. It involves several formal structures as well as numerous informal groups. The main partners are:

– the European Space Agency (ESA), which has the overall project responsibility for the funding and procurement of the satellite (including the payload and its scientific instruments – there are no PI teams), launch and operations;

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– EADS Astrium, who was selected in 2006 as the prime industrial contractor for designing and building the satellite according to the scientific and technical requirements formulated by ESA in consultation with the scientists;

– the Gaia Data Processing and Analysis Consortium (DPAC), charged with designing, implementing and running a complete software system for the scientific processing of the satellite data, resulting in the 'Gaia Catalogue' a few years after the end of the observation phase;

– national funding agencies and other organizations throughout Europe, who support the many individuals, research teams and data processing centres that constitute DPAC;

– the Marie Curie Research Training Network ELSA, a four-year EU-supported project (2006–2010) addressing certain key issues of the mission (Lindegren *et al.* 2007);

– the international scientific community, being the end users of the Gaia Catalogue, and represented at project level by the ESA-appointed Gaia Science Team (GST) chaired by the Gaia Project Scientist, Dr. Timo Prusti.

The current composition of the GST and other organizational details can be found on the Gaia web pages at `http://www.rssd.esa.int/gaia/`.

Figure 1 is an overview of the main phases of the development of the Gaia project, from the original proposal in 1993 to the expected publication of the final catalogue around 2021. Currently (May 2009) the project is in the middle of the implementation phase, on schedule for a targeted launch in spring 2012. Critical payload elements such as the silicon carbide (SiC) telescope mirrors and optical bench, CCDs and associated electronic units, have been designed and are in the process of being manufactured and tested.

The Gaia Data Processing and Analysis Consortium (DPAC) was formed in 2006 in response to an 'Announcement of Opportunity' issued by ESA (Mignard *et al.* 2008). It consists of individuals and institutes organized in nine 'coordination units' (each responsible for the development of one part of the software: overall architecture, simulations, core processing, photometry, etc.). Currently DPAC has nearly 400 individual members in more than 20 countries, including a substantial team of experts at the European Space Astronomy Centre (ESAC) near Madrid in Spain. Six data processing centres participate in the activities of the consortium. Financial support is provided by the various national agencies, ESA, universities and other participating organizations.

The development of the software system for the scientific processing of the satellite data is progressing in parallel with the hardware activities, with the aim to have a complete processing chain in place at the end of 2011. However, considerable further development and fine tuning of the software is expected to happen after the launch, especially based on the experience of the real data. The final catalogue should be ready three years after the end of the observation phase. Intermediate releases of some provisional results are planned after a few years of observations. Science alerts triggered by the Gaia observations (e.g., detection of extragalactic supernovae and near-Earth objects) require the organization of a programme of ground-based follow-up observations.

3. Observation principle

The Hipparcos mission (ESA 1997) established a new paradigm for efficient optical astrometric observations by a free-flying satellite, benefiting from the full-sky visibility and stable environment in space. The basic principles were formulated already in the earliest descriptions of the Gaia concept (e.g., Lindegren *et al.* 1994):

• Two fields of view, set at a large angle to each other, permit to link widely different areas of the sky in a single measurement.

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Table 1. Summary of the main mission parameters of Gaia and characteristics of the astrometric instrument. Where applicable, dimensions are given as AL × AC, where AL is the along-scan dimension and AC the across-scan dimension.

targeted launch date	spring 2012, Soyuz/Fregat launcher (Kourou)
operational orbit	Lissajous orbit at Sun–Earth L2 (1.5×10^6 km from Earth)
transfer orbit to L2	1 month
nominal mission length	5 years ($\geqslant$90% available for science)
extended mission length (for consumables)	6 years
solar aspect angle (Fig. 2)	$45 \pm 0.1°$
spin rate	60 arcsec s^{-1} (4 rev day^{-1})
no. of astrometric viewing directions (fields of view)	2
basic angle (between viewing dir.)	106.5°
pupil dimension (per viewing dir.)	1.45×0.5 m^2
focal length	35 m
full size of focal plane	0.93×0.42 m^2 (1.52×0.68 deg^2)
active solid angle per astrometric field (AF)	0.44 deg^2
number of astrometric CCDs	62
number of pixels per CCD	4500×1966
pixel size	10×30 μm^2 (58.9×176.8 mas^2)
integration time	4.417 s per CCD (39.75 s per AF transit)
mean number of AF transits per object in 5 years	78 (see Table 3)
down-linked CCD samples	(6–18 pix AL) × (12 pix binned AC)
wavelength region (G magnitude band)	$\lambda \simeq 330$–1000 nm

• The angular measurements are basically one-dimensional, namely, on the great circle connecting the two fields (Fig. 4).

• Continuous scanning permits to measure all programme stars as they pass through the two fields, while minimizing the need for attitude manoeuvres and keeping external influences as constant as possible.

• Rapid rotation of the whole instrument about an axis perpendicular to the two fields permits to determine critical parameters, in particular the scale value and the 'basic angle' between the two fields, from the 360° closure condition on a full rotation. Instrument stability is uncritical on all time-scales longer than the rotation period.

• Two-dimensional positions, and eventually the parallaxes and proper motions of the stars, are built up by slowly changing the orientation of the rotation axis so that each point on the sky is scanned many times, in different directions, over the mission.

• The data processing consists of a simultaneous least-squares adjustment of all the unknowns, whether they represent the instrument, its scanning motion, or the stars. Thus the mission is self-calibrating in the sense that critical calibration parameters, such as the basic angle, are derived from the scientific observations themselves – no special calibration observations are required.

Although the Gaia mission as it is now being realized is entirely different from the concept described in 1994 (cf. Høg 2007), the above principles remain valid. The main mission parameters are given in Table 1.

Figure 2 (left) shows the precessional motion of the spin axis causing the two fields of view (represented by the two viewing directions at the field centres) to successively cover the sky. The precession period is about two months, and after six months every part of the sky is covered by at least two scans intersecting at a large angle. With the ten-fold sky coverage obtained in a five-year mission it is clear that at least the positions and proper motions of the stars can be determined. That their *absolute* parallaxes can also be determined (i.e., without making use of distant 'background' objects assumed to have zero parallax) is shown in the right part of Fig. 2. The large angle between the Sun and the spin axis (45°) and the large basic angle between the viewing directions (106.5°) are essential for Gaia's capability to do global astrometry and determine absolute parallaxes.

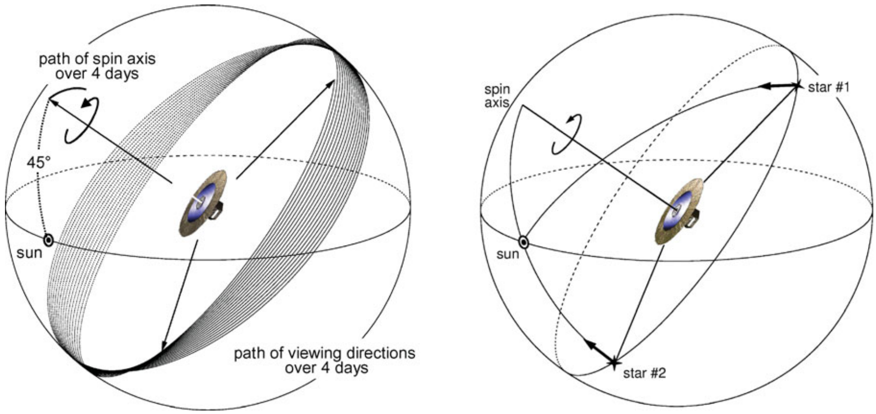

Figure 2. *Left:* the Gaia scanning law over a time interval of four days. The spin axis shifts by some 17° relative to the stars, remaining at a constant angle of 45° from the Sun, while each of the two viewing directions trace sixteen revolutions on the sky (only the path of the preceding viewing direction is shown). *Right:* the principle of absolute parallax measurement. The parallactic displacement of a star is directed along the great-circle arc from the star to the Sun (actually the Solar-System Barycentre). The observed angle between the indicated stars (#1 and #2) therefore depends on the parallax of #1, but is independent of the parallax of #2. At some other time during the mission, the same pair may be observed with the Sun between the spin axis and star #1, in which case the observed angle will depend only on the parallax of #2. In general the observed angle will depend on both parallaxes, but their different projection factors will allow the absolute values to be disentangled.

The Gaia telescope is an off-axis three-mirror anastigmat with 35 m focal length, two entrance pupils of 1.45×0.5 m^2 each, and a combined focal plane of nearly 0.4 m^2 area; the astrometric part of the focal plane consists of a mosaic of 62 CCDs occupying a field of about 40×40 arcmin^2 in each viewing direction. Plane folding mirrors and a beam combiner at the intermediate pupil complete the optical trains of the astrometric instrument. Separate CCDs preceded by filters and dispersive optics form the two photometers and the radial-velocity spectrometer. All the CCDs have a pixel size of 10×30 μm^2 matched to the optical resolution of the telescope with its rectangular pupil.

The satellite is continuously rotating according to the pre-defined scanning law described above at a nominal rate of 1 arcmin s^{-1}; thus the images of the stars in either field of view cross the astrometric CCDs in about 40 s. The autonomous on-board processing system detects any object brighter than $\simeq 20$ mag as it enters the special skymapper CCDs next to the astrometric field, then tracks the object across the various CCDs dedicated to the astrometric, photometric and radial-velocity measurements. The CCDs sample a small window centred on the projected path of the optical image of each detected object (Fig. 3). The pixel values, usually binned in the across-scan direction to reduce the readout noise and data rate, are transmitted to ground for the off-line data analysis. In the astrometric CCDs, the basic measurements are therefore the one-dimensional (along-scan) locations of the image centres in the pixel stream. The across-scan coordinates of the image centres are also determined to a lower accuracy in the skymappers, as part of the real-time object detection, and for a subset of the stars (in particular those brighter than 13th magnitude) in the astrometric CCDs. Although the astrometric measurements are essentially one-dimensional, viz., in the along-scan (AL) direction, the across-scan (AC) coordinates are needed for the attitude determination and certain instrument calibrations. However, it can be seen from elementary geometry that the sensitivity of the AL measurements to errors in the AC direction is reduced roughly

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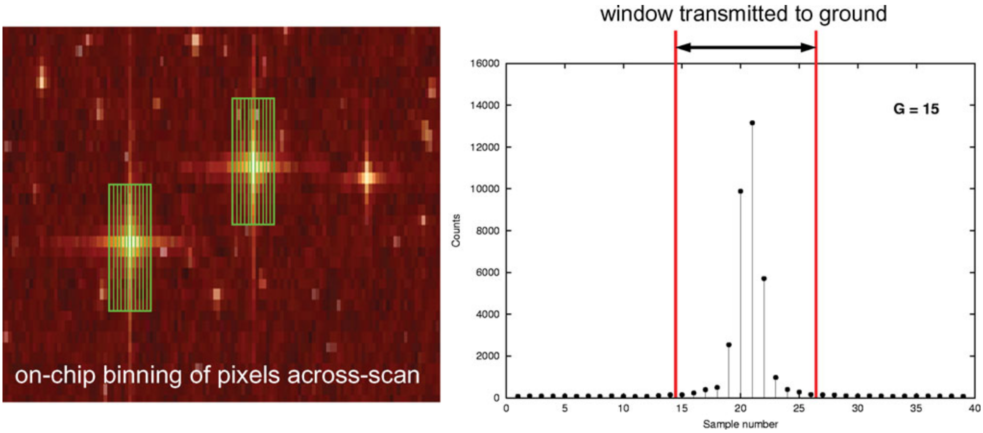

Figure 3. The left image is a simulated CCD image of a stellar field as seen with the astrometric instrument of Gaia (courtesy DPAC/CU2). Horizontal is the along-scan direction. Note the diffraction spikes corresponding to the rectangular telescope pupil. The on-board software causes a rectangular window to be read out around each detected image. The right graph shows the simulated output for a 16th magnitude star. Only values in the indicated window (6 to 18 samples, depending on the magnitude) are transmitted to the ground for further analysis.

by a factor equal to the transverse size of the field of view, or $\simeq 10^{-2}$ (Fig. 4). The AC measurements made by the skymappers for all stars (and by the astrometric CCDs for bright stars) have errors that are about a factor 10 worse than in the AL direction, but this is more than sufficient to provide the necessary information in the AC direction.

4. Astrometric data analysis

It is not possible to give here even a sketchy outline of the complete Gaia data analysis chain. Instead, only some basic principles of the core astrometric data analysis, known as AGIS, will be explained. AGIS is an acronym for Astrometric Global Iterative Solution, which implies the use of an iterative solution method. However, the essential point is rather the *global* nature of the solution: it is a single least-squares adjustment of the global set of parameters needed to describe (a) a subset of the objects (known as 'primary stars'), (b) the celestial pointing (attitude) of the telescope as function of time, and (c) various instrument calibration parameters. However, the resulting system of equations is so large that in practice only iterative solution methods are feasible.

As previously explained, the main observational data resulting from an astrometric CCD crossing is the AL image location in the pixel stream, which may be converted into a time of observation, t^{obs}. For some observations also the corresponding AC image coordinate, μ^{obs} (measured in AC pixels, and fractions thereof, on a particular CCD) is obtained. The time of observation is that of the image crossing a fiducial 'observation line' half-way along the CCD. It is initially expressed on the time scale of the on-board clock, but later transformed to the barycentric coordinate time (TCB) through correlation with an atomic clock at the receiver station. The spatial coordinates in the BCRS of the event are also known from the orbit determination mainly using ranging data. The orbit also gives the barycentric velocity of Gaia at the time of observation.

The field angles η (AL) and ζ (AC) give the proper direction of the object in a local reference system rotating with the satellite. The fiducial observation line for a particular CCD can be thought of as the central line of pixels, half-way through the CCD, traced out in the (η, ζ) angles. Formally, the observation line is defined by the functions $\eta_{fn}(\mu|\mathbf{c})$,

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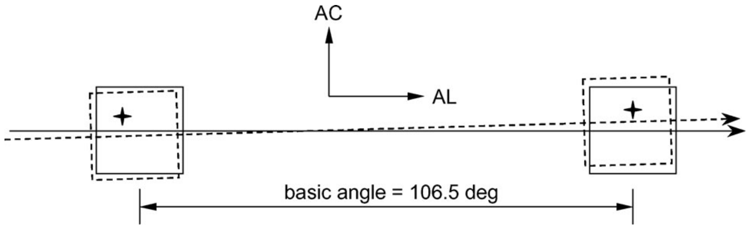

Figure 4. The use of primarily one-dimensional measurements (in the along-scan, AL, direction) is essential for the Gaia observation principle. It means that the measured angle between any two stars is to first order independent of the instrument's orientation in space (the attitude). Attitude errors in the across-scan (AC) direction are multiplied by a factor which is of the order of the size of the field of view, or $\simeq 0.01$ rad. The geometric calibration in the AC direction is similarly less critical than the AL calibration by the same factor.

$\zeta_{fn}(\mu|\mathbf{c})$, describing the field angles as functions of the AC pixel coordinate μ. These functions are different for each CCD (distinguished by the index $n = 1$ through 62 for the different astrometric CCDs) and for each field of view (index $f = 1$ and 2 for the preceding and following fields). They also depend on the calibration parameters in the array $\mathbf{c}$. In the simplest case, the calibration parameters could be the coefficients of polynomials in μ, different for each combination of indices fn. Temporal evolution of the instrument can be taken into account by having a different set of calibration parameters for each time interval (of days or weeks).

On the other hand, the field angles of a particular object at the time of observation can also be calculated from its astrometric parameters and the telescope attitude at that time. This calculation involves the full general-relativistic model for transforming from the astrometric parameters to the proper direction in the co-moving Lorentzian frame, and the subsequent spatial rotation of the reference system to take into account the attitude. This calculation can formally be written as $\eta(t^{\rm obs}|\mathbf{s},\mathbf{a})$, $\zeta(t^{\rm obs}|\mathbf{s},\mathbf{a})$, where the array $\mathbf{s}$ contains the astrometric parameters of all the primary stars and $\mathbf{a}$ contains the complete set of attitude parameters.† The adopted attitude model is a cubic spline (with a knot interval of some 5 to 15 s) for each of the four components of the attitude quaternion as function of time. The array $\mathbf{a}$ then contains the corresponding B-spline coefficients.

The core astrometric data analysis consists in setting up and solving the least-squares problem

$$\min_{\mathbf{s},\mathbf{a},\mathbf{c}} \quad \sum_{\rm AL} \frac{\left[\eta_{fn}(\mu^{\rm obs}|\mathbf{c}) - \eta(t^{\rm obs}|\mathbf{s},\mathbf{a})\right]^2}{\sigma_{\rm AL}^2 + \sigma_0^2} + \sum_{\rm AC} \frac{\left[\zeta_{fn}(\mu^{\rm obs}|\mathbf{c}) - \zeta(t^{\rm obs}|\mathbf{s},\mathbf{a})\right]^2}{\sigma_{\rm AC}^2 + \sigma_1^2}\,, \qquad (4.1)$$

where the sums are taken over all AL and AC observations, respectively, of the primary stars. $\sigma_{\rm AL}$ and $\sigma_{\rm AC}$ are the formal errors (expressed in angular units) of $t^{\rm obs}$ and $\mu^{\rm obs}$ as derived from the photon statistics and CCD readout noise. The additional noises σ_0 and σ_1 represent all other error sources, including modelling errors in the astrometry, attitude, and calibration. σ_0 and σ_1 are not constant numbers but could depend on the object and be functions of time. They have to be modelled and estimated as part of the data analysis process, which includes the selection of primary stars (i.e., relegating objects with consistently large σ_0 to the status of 'secondary stars', to be handled by the off-line object processing) and the systematic detection and down-weighting of outliers.

† These functions may depend on additional 'global parameters' such as the PPN γ parameter (Hobbs *et al.* 2009).

The iterative solution of Eq. (4.1) can be done according to a number of different schemes, the most obvious one being equivalent to a Gauss–Seidel block-iterative solution of the normal equations. In this scheme, which was originally proposed for AGIS, the astrometric, attitude and calibration parameters are cyclically adjusted, so that for example the astrometric parameters are adjusted, one star at a time, while the attitude and calibration parameters are kept fixed at their most recent estimates. As demonstrated by numerical experiments, this simple scheme converges to the correct solution, but rather slowly, requiring over a hundred such cycles (iterations) for full numerical accuracy. An accelerated scheme, requiring about half this number of iterations, is currently used in AGIS. For the final implementation of AGIS it is planned to use a conjugate gradient scheme, which will reduce the number of iterations by another factor of two. An important conclusion from numerical experiments carried out with the small-scale simulation tool known as AGISLab (Holl *et al.* 2009) is that the end results of the different iteration schemes are all equivalent to a rigorous solution of the least-squares problem (4.1). For example, the final astrometric parameters are independent of the starting values used to initiate the iterations.

The core astrometric data analysis contains a final step that produces a kinematically non-rotating catalogue aligned with the ICRS. This uses a subset of the primary stars (or quasars) that either have accurate parameters in the VLBI frame or can be assumed to be extragalactic zero-proper motion objects (i.e., quasars). It is expected that about 500 000 quasars can be used for this purpose; they have to be securely identified as such primarily based on photometric information (colours, variability) and ground-based surveys; see Mignard & Klioner (2009) for further details.

The current implementation of AGIS (at ESAC, Spain) routinely handles solutions based on realistic simulations for several million primary stars and tens of millions of secondary stars. The data processing system will be extended in several steps over the coming years, and tested with increasingly larger data sets, so that at the time of launch it will be ready to handle the full-size problem, including the projected astrometric solution for 100 million primary stars.

5. Expected astrometric performance

The predicted astrometric performance of Gaia has been calculated by means of the Gaia Accuracy Analysis Tool (de Bruijne 2005) using current mission and instrument data. A nominal mission length of 5 years is assumed, with an average dead time of 7%. The accuracy analysis takes into account all identified relevant error sources, assuming that the engineering specifications of the individual components (CCD quantum efficiency, wavefront errors, etc) are met. It also makes certain assumptions about the accuracy of the instrument calibration which in some cases are still uncertain. The rms errors therefore include a science margin factor of 1.2. Table 2 summarizes the resulting predictions for single, unperturbed solar-type stars.

The astrometric accuracy is mainly a function of the magnitude of the object and its ecliptic latitude (β). The values in Table 2 are averages over the celestial sphere. For arbitrary spectra and positions on the sky, the accuracy can be estimated as follows.

The relevant magnitude, denoted G, represents the flux in the broad wavelength band ($\simeq$ 330–1000 nm) defined by the mirror coatings and CCD quantum efficiency. Given the V magnitude and the (Johnson–Cousins) colour index $V-I$, the G magnitude is approximately given by

$$G = V - 0.0107 - 0.0879(V-I) - 0.1630(V-I)^2 + 0.0086(V-I)^3\,, \qquad (5.1)$$

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Table 2. Sky-averaged rms errors of the astrometric parameters for G2V stars (no extinction).

V magnitude	6–13	14	15	16	17	18	19	20	unit
parallax	8	13	21	34	54	89	154	300	μas
proper motion	5	7	11	18	29	47	80	158	μas yr^{-1}
position at mid-epoch ($\simeq$2015)	6	10	16	25	40	66	113	223	μas

valid for $V-I \lesssim 7$. This and other relevant photometric relations (e.g., to the Sloan system) can be found in Jordi (2009). The sky-averaged standard errors of the parallaxes of stars in the magnitude range $6 \leqslant G \leqslant 20$ are then approximated by

$$\sigma_\varpi = (4 + 515z + 5z^2 + 2 \times 10^{-8} z^6)^{1/2} \ \mu\text{as}, \tag{5.2}$$

where $z = \max(0.11,\ 10^{0.4(G-15)})$. The quantity z is inversely proportional to the number of detected photons from the star per CCD transit, normalized to 1 for $G = 15$ mag. The floor at $z = 0.11$ represents the onset of the CCD gating strategy to avoid pixel saturation for stars brighter than $G \simeq 12.6$. For all magnitudes brighter than $G = 20$, the expression in Eq. (5.2) is dominated by the second term, viz. $\sigma_\varpi \propto z^{1/2}$, showing that photon noise is the main contribution to the error budget at all magnitudes. The other terms represent the contributions from attitude and calibration errors at the bright end, and from CCD readout noise, sky background and missed detections at the faint end.

In order to obtain the standard errors of the different astrometric parameters at a particular point on the sky, the sky-averaged parallax error from Eq. (5.2) should be multiplied by factors that depend in a complex way on the number of observations of the object, the geometry of the scans across the object, and their temporal distribution. However, thanks to the symmetry of the Sun-centred scanning law with respect to the ecliptic, these factors depend mainly on the ecliptic latitude of the object, β, which can be approximately calculated from the equatorial (α, δ) or galactic (ℓ, b) coordinates as

$$\sin\beta \simeq 0.9175\sin\delta - 0.3978\cos\delta\sin\alpha \tag{5.3}$$

$$\simeq 0.4971\sin b + 0.8677\cos b\sin(\ell - 6.38^\circ)\,. \tag{5.4}$$

Table 3 gives the average factors within equal-area zones in ecliptic latitude. The sky-averaged standard errors in the position and annual proper motion components are

$$\sigma_{\alpha*} = 0.802\sigma_\varpi\,, \quad \sigma_\delta = 0.693\sigma_\varpi\,, \quad \sigma_{\mu_{\alpha*}} = 0.565\sigma_\varpi\,, \quad \sigma_{\mu_\delta} = 0.493\sigma_\varpi\,, \tag{5.5}$$

where the asterisk indicates true arcs on the sky ($\sigma_{\alpha*} = \sigma_\alpha\cos\delta$, etc). The values in Table 2 are approximately reproduced for a star of colour index $V-I = 0.75$.

6. Conclusions

The Gaia mission is well on track towards its targeted launch in early 2012, with both the hardware and software developments halfway through their implementation phases. The core astrometric data analysis will implement a rigorous simultaneous least-squares solution of the astrometric parameters for 100 million primary stars together with the corresponding attitude and instrument calibration parameters. There is good confidence that the mission will achieve the overall astrometric performance projected in Sect. 5.

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Table 3. Numerical factor to be applied to the sky-averaged parallax error in Eq. (5.2) for the different astrometric parameters as function of ecliptic latitude, β. N_{tr} is the mean number of field-of-view transits over the mission. All values are for a 5 yr mission with 7% dead time.

$\lvert \sin\beta \rvert$	N_{tr}	$\alpha*$	δ	ϖ	$\mu_{\alpha*}$	μ_δ
0.0–0.1	59	1.036	0.746	1.176	0.730	0.534
0.1–0.2	60	1.016	0.750	1.167	0.715	0.534
0.2–0.3	62	0.984	0.744	1.154	0.693	0.537
0.3–0.4	65	0.925	0.722	1.121	0.655	0.524
0.4–0.5	70	0.856	0.701	1.082	0.608	0.504
0.5–0.6	80	0.757	0.675	1.030	0.538	0.482
0.6–0.7	106	0.598	0.630	0.950	0.426	0.446
0.7–0.8	120	0.520	0.619	0.831	0.362	0.430
0.8–0.9	86	0.628	0.654	0.764	0.437	0.455
0.9–1.0	74	0.687	0.686	0.721	0.478	0.476
mean sky	78	0.802	0.693	1.000	0.565	0.493

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