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The *Gaia* mission delivers its first data release

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Abstract

Gaia astrometric satellite is in its science operational phase since July 2014. At an average rate of about 500 million elementary observations per day, *Gaia* scans the full sky once every six months. *Gaia* Data Release 1 (DR1), published on Sep 14^{th} 2016, contains astrometric and photometric results for more than one billion sources brighter than magnitude $\sim$20.7 based on observations acquired during the first 14 months of the operational phase. For about two million of the brighter stars (down to magnitude $\sim$11.5) positions, parallaxes, and proper motions have been obtained to Hipparcos-type precision through a combination with the earlier Hipparcos and Tycho-2 positions. For the remaining stars, positions at epoch J2015.0 have been obtained by essentially neglecting their proper motions and parallaxes. Positions and proper motions are given in a reference frame aligned with the ICRF radio/VLBI frame at epoch J2015.0. We give an overview of the current status of the mission, the Data Processing and Analysis Consortium operations, the validation processes, the contents of *Gaia* DR1, and the prospects for the future releases. We emphasize that although *Gaia* DR1 data are based on very provisional and incomplete calibrations, the results represent a huge improvement in the available fundamental stellar data.

1 Introduction

The European Space Agency mission *Gaia* was launched in 2013. It is located at the Sun-Earth Lagrangian L2 point and started its nominal science operations on the 25th of July 2014 after the commissioning phase. It is a global astrometric and photometric mission with two telescopes continuously scanning the sky (Fig. 1). The fields of view are separated a basic angle of 106.5 deg, and the spin axis precesses in 63 days in an angle of 45 deg around the *Gaia*–Sun direction. While spinning, the two telescopes observe stars around great circles, and the full sky is covered about every six months. Over its 5-yr nominal mission each sky position is observed an average of 70 times. The design of the telescopes and response of the

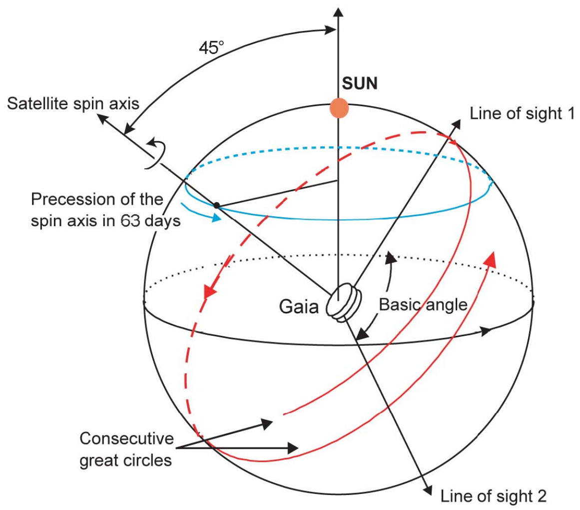

Figure 1: *Gaia* has two telescopes separated a basic angle of 106.5 deg, with an spin axis that precesses in 63 days in an angle of 45 deg around the direction *Gaia*–Sun. While spinning, the two telescopes observe stars around great circles. Credit: DPAC.

CCDs establish a limiting magnitude of about 20.7 in white light meaning more than 10^9 sources ($\sim$1% of the Milky Way).

The Data Processing and Analysis Consortium (DPAC) is in charge of the full data treatment and processing necessary to build the final products for the scientific community. DPAC is organized in several coordination units (CUs), see Fig. 2. Every CU deals with a specific type of data or specific part of the processing based on its corresponding Data Processing Center (DPC). There are nine CUs and seven DPCs.

The observations acquired during the first 14 months of the science operational phase constitute the basis of the first *Gaia* Data Release (DR1), made public on Sep 14^{th} 2016. The publication of *Gaia* DR1 is a great success for all DPAC. In spite that DPAC has had to deal with several unexpected issues with the payload (contamination, stray light, basic angle variations, as examples), it is delivering much more parallaxes and proper motions than previously anticipated (2 million instead of 100,000 stars). The processing is simplified, but still it is extremely valuable for science.

This paper is organized as follows: Sec. 2 describes the status of the mission, Sec. 3 explains the data processing for *Gaia* DR1, Sec. 4 deals with the content of *Gaia* DR1, Sec. 5 provides recommendations on how to use *Gaia* DR1, Sec. 6 outlines the next release of data, and finally Sec. 7 summarizes the conclusions.

2 The status of the mission

After launch and insertion into the Lissajous orbit around the L2 point of the Earth–Sun system, *Gaia* started its commissioning phase and later on its nominal science operational

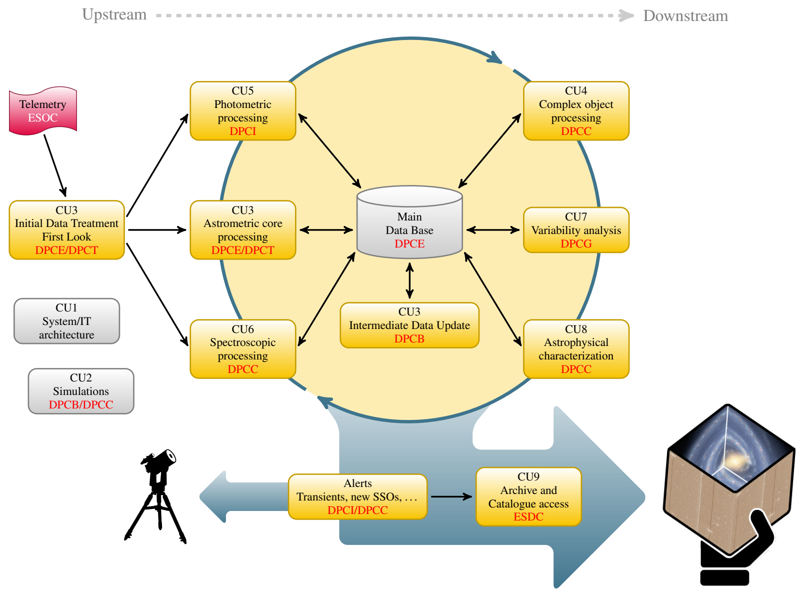

Figure 2: The Data Processing and Analysis Consortium is based on nine Coordination Units (CUs) and seven Data Processing Centers (DPCs). The several arrows show the interdependences among them. The final products are the alerts of transients sources and new Solar System objects and the full archive with the several releases. Credit: DPAC.

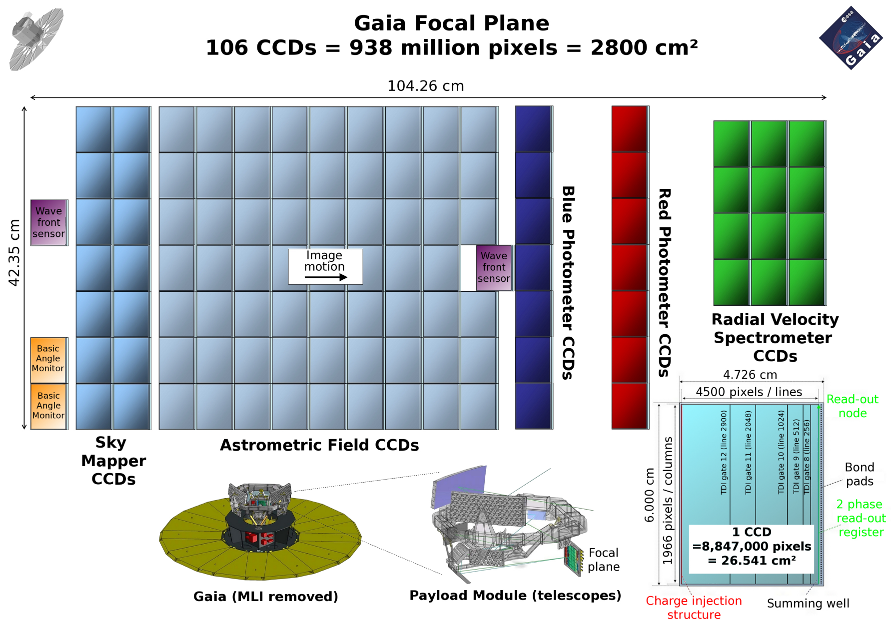

Figure 3: The *Gaia* focal plane with its 106 large-format CCDs. The focal plane is common to both telescopes. All CCDs are operated in TDI mode. The size of the pixels is 10 μm along scan by 30 μm across scan (59 mas $\times$ 177 mas). Source images cross the focal plane from left to right. Figure taken from [2].

phase in July 2014. The collected data is transmitted to ground and from ESOC to ESAC. The health of the satellite is monitored by DPAC from the daily downloaded data. From time to time, decontamination operations are performed by heating the optics and the focal plane to get rid of contaminant material (most probably water ice) decreasing the overall response of the instrument. The decontamination events are followed by re-focussing operations when cooling of the payload has occurred.

The observations are acquired with the two telescopes sharing a common focal plane (Fig. 3), which has dedicated sections for the detection of sources (the sky mappers), and the astrometric, photometric and radial velocity measurements. The mean rate of the observations is of 55 million transits per day over the focal plane, delivering 500 million individual images, 110 million low-resolution and 20 million high-resolution spectra. More details about the *Gaia* mission and DPAC can be found in [9].

The quality of the data was soon confirmed in the commissioning phase by the raw astrometry in the Initial Data Treatment (IDT), the essential step that prepares the data for down stream processing. Such quality of raw astrometry, the light curves accuracy of known variables, the detection of Solar System objects, the photometric alerts (the first one was issued in Aug 2014) and many, many other indicators allowed DPAC to go ahead with *Gaia* DR1.

In parallel to the production of *Gaia* DR1, the daily operations in DPAC continue and the preparations for release 2 as well. Until July 2016, we have accumulated 370 billions of individual images, 85 and 15 billions of low and high resolution spectra, respectively, more spectra than ever collected.

3 Data processing of Data Release 1

Figures 4 and 5 show the complete Astrometric Global Iterative Solution (AGIS) and PhotPipe processing scheme and their interdependences. The first figure is the ideal complete scheme and the latter is the one used in *Gaia* DR1. To put them in context, astrometry and photometry are derived from:

- the centroid and white-light G flux measurement of the individual images in the astrometric section of the focal plane (see Fig. 3) through a PSF or LSF fitting, performed by the Image Parameter Determination,
- the proper direction of the satellite, derived by the Attitude reconstruction that accounts for micro-meteoroid impacts and micro-clanks of the payload global structure, and
- the geometry of the focal plane, obtained from the observations themselves.

All the information together establishes the relation between positions in the focal plane and celestial positions at any time.

The PSF/LSF used in *Gaia* DR1 by the Image Parameter Determination does not account for colour dependences or across scan motion during the transit, i.e. the PSF/LSF

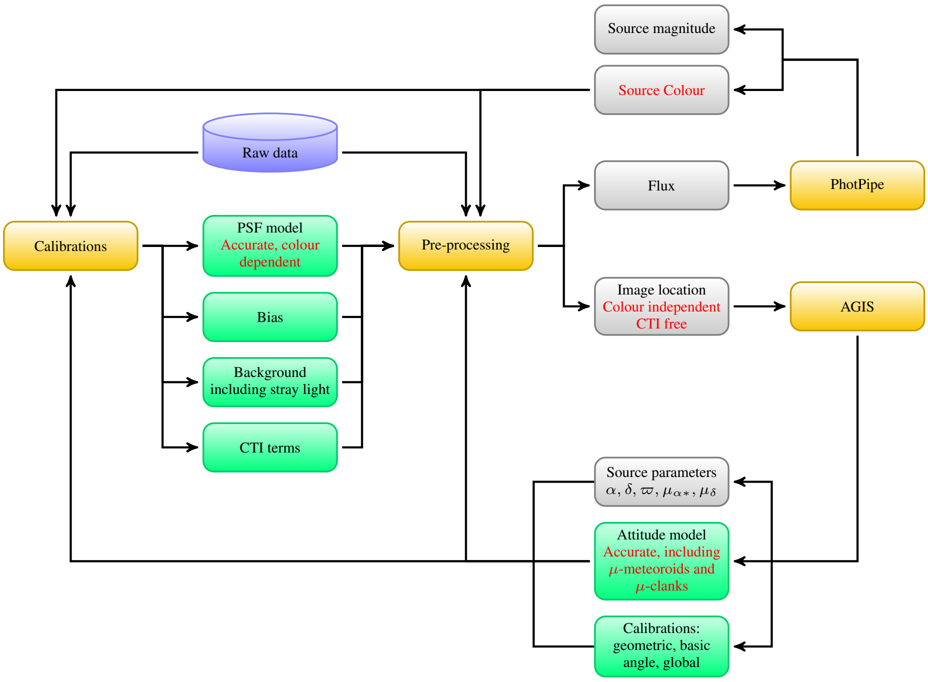

Figure 4: Ideal scheme of the complete AGIS and PhotPipe processing with their interdependences with the pre-processing and the calibrations. Credit: A. Brown.

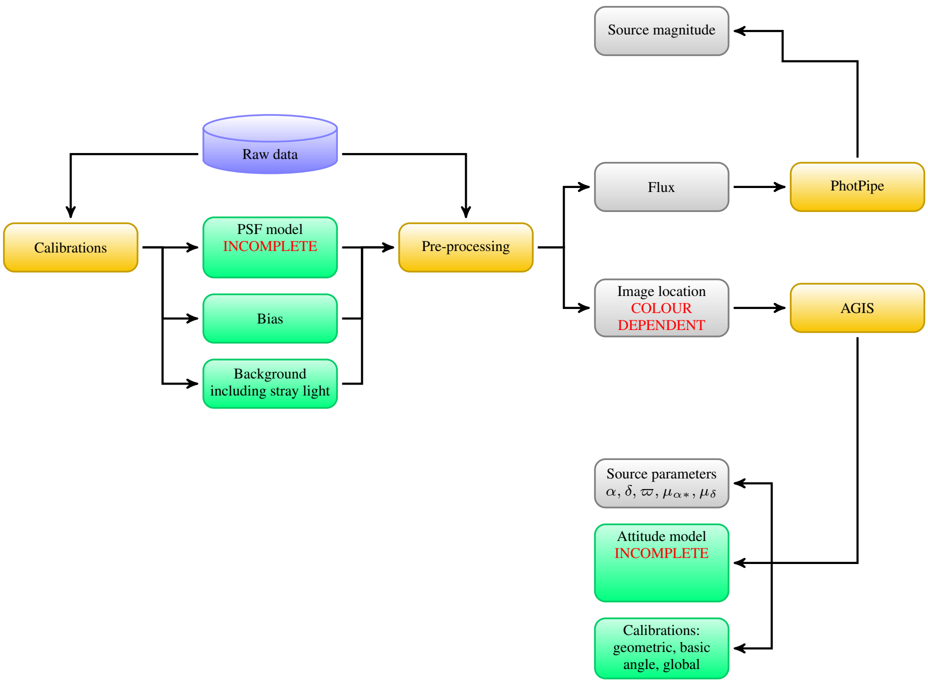

Figure 5: Simplified processing in *Gaia* DR1. Credit: A. Brown.

model is incomplete. So, the image location suffers from chromatic effects. The attitude reconstruction is also incomplete in the modelling of the micro-meteoroids and the micro-clanks. The iteration between astrometry and photometry has not been put in place either. In spite of this, the AGIS iterations show a good convergence from precisions at the level of 100 mas in IDT to 10 mas after calibrations.

An extensive validation process of the astrometry and photometry has been carried out. The validation includes internal statistical evaluations, comparisons with models and comparisons with external data [1]. As a result of this validation, some filtering as a function of uncertainties and a few other parameters have been decided and applied. The published *Gaia* DR1 is the result of such filtering [1] [7].

4 Content of Data Release 1

The first *Gaia* data release is accessible at `https://archives.esac.esa.int/gaia`. It has several components:

- J2015.0 positions (α,δ) and G mean magnitudes for 1,142,679,769 sources down to white light $G \sim 20.7$ mag,
- J2015.0 positions, proper motions and parallaxes (so, five astrometric parameters) for 2,057,050 stars in the Tycho-2 catalogue,
- 3194 light curves of Cepheids and RR Lyrae near the South Ecliptic Pole (at LMC),
- J2015.0 positions (α,δ) and G mean magnitudes for 2152 ICRF quasars, and
- cross-matches between *Gaia* sources and Hipparcos-2, Tycho-2, 2MASS PSC, GSC2.3, PPM-XL, UCAC-4, SDSS DR10 / DR12, AllWISE, and URAT-1 catalogues.

In the following subsections, we describe these components.

4.1 The billion sources

Those sources with acceptable formal standard errors on positions with a median uncertainty of $\sim$10 mas are included. The positions are aligned to ICRF to better than 0.1 mas with a rotation less than 0.03 mas yr^{-1}. Therefore, *Gaia* DR1 is the most accurate all sky map to date at HST-like resolution (Fig. 6).

The photometry uncertainty shows a dependence with magnitude in rather good agreement with expectations. The faint end shows slightly larger uncertainties perhaps due to inaccuracies on the background determination. On the bright end, the calibration error threshold is of about 3 mmag. *Gaia* DR1 includes the zeropoints in the Vega and AB systems, as well as transformations to other photometric systems.

The 14 months time span of the data in *Gaia* DR1 yields a rather inhomogeneous sky coverage with a number of CCD observations per source ranging from 40 to 400. In total,

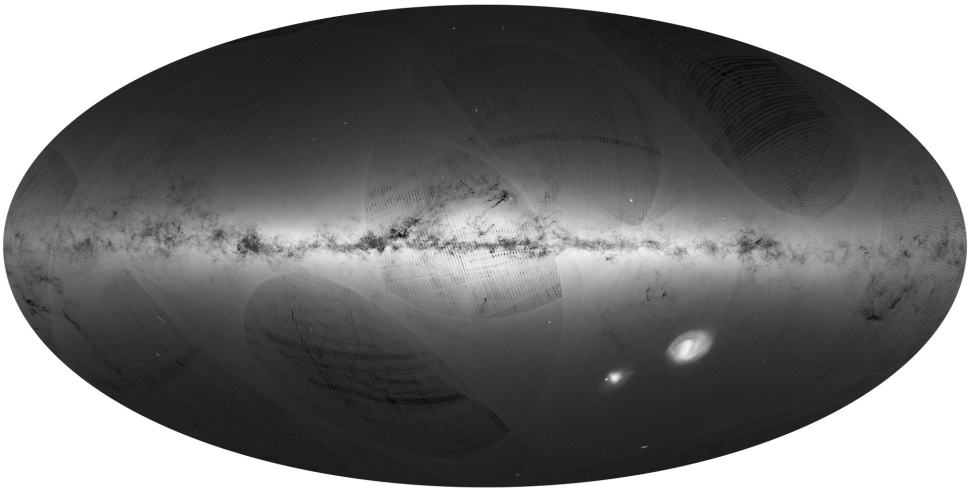

Figure 6: The first *Gaia* sky map. The brighter the area the higher stellar density. Easily recognizable are the Magellanic Clouds, the Milky Way disk and the many regions obscured by the interstellar dust. There are also artifacts due to incompleteness caused by the scanning law. Image credits: CENTRA - University of Lisbon (part of the DPAC-CU9).

there are $2.3 \cdot 10^{10}$ transits over the focal plane. The scan pattern can also be recognized in the dependence of errors with the sky position.

4.2 The TGAS component

The short time span of *Gaia* DR1 does not allow to break the degeneracy between the proper motion and parallax for a given star. The approach has been to combine current positions from *Gaia* with positions in J1991.25 from Hipparcos [15] and Tycho-2 [10] catalogues, which have similar accuracies as the current *Gaia* positions. The 24 yrs baseline has demonstrated to be the key for the determination of proper motions and parallaxes. The full description of how the Hipparcos and Tycho-2 positions are used as prior information and how the five astrometric parameters have been derived in *Gaia* DR1 can be found in [12] and [11].

The median uncertainty of the positions, proper motions and parallaxes is of $\sim$0.3 mas, $\sim$1.3 mas yr^{-1} (0.07 mas yr^{-1} for the Hipparcos subset) and $\sim$0.3 mas, respectively. The dependences of such uncertainties over the sky can be seen in Fig. 7. Error levels partly reflect early scan law coverage.

The comparison of TGAS proper motions with Hipparcos and Tycho-2 ones ([11] and [1]) has revealed systematic differences of 0 ± 0.004 mas yr^{-1} for TGAS–Hipparcos, -0.009 ± 0.005 mas yr^{-1} and 0.08 ± 0.002 mas yr^{-1} for TGAS–Tycho-2 for the Hipparcos and non-Hipparcos subsets, respectively. The detailed comparison with Tycho-2 proper motions shows systematic differences with declination, which are due to inaccuracies of Astrographic Catalogue in the several sky zones. The comparison with proper motions from VLBI for 36 stars in common yields a difference of 0.008 ± 006 mas yr^{-1}. Therefore, if there

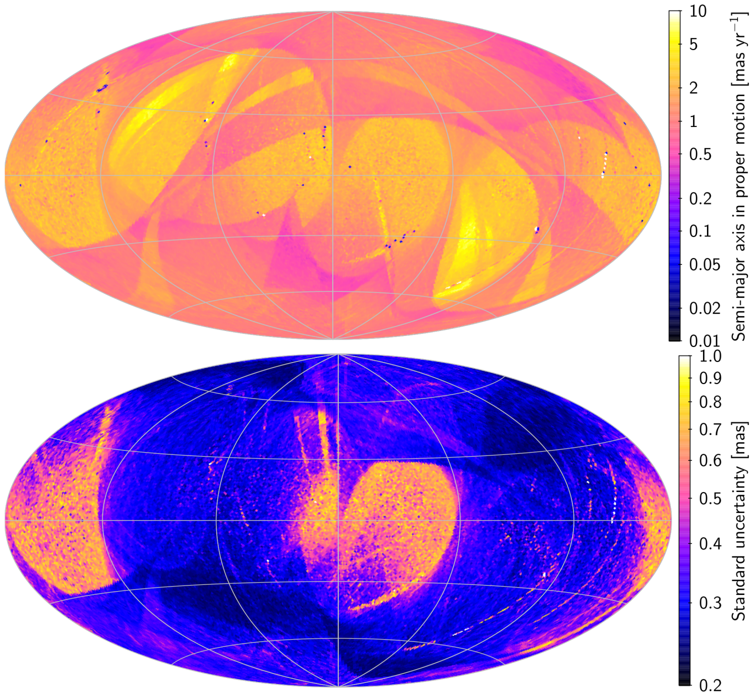

Figure 7: TGAS median proper motions (top) and parallaxes (bottom) uncertainties over cells of ~ 0.84 deg^2. The pattern of the scanning law is easily recognizable. Figure from [11].

is any problem in TGAS, this is of second order only.

Figure 8 shows the comparison of the parallaxes in Hipparcos catalogue and in TGAS, which are fully independent since only Hipparcos positions were used in the TGAS solution. The comparison shows a very good agreement and the detail of the negative parallaxes confirms the reliability of the *Gaia* DR1 uncertainties.

A special AGIS solution has been performed for the QSOs assuming null proper motions as prior information. The resulting parallaxes are used to validate the solution. There is a global zero point of -0.04 mas and large scale variations (10% of QSO has $|median(\varpi)| > 0.3$ mas, with some extreme regions in the sky where median values reach ± 1 mas, Fig. 9).

There are high correlations among the five parameters, due to the non-uniform coverage of the sky and the uneven distribution of scan directions for given positions in the sky. See details in [11].

4.3 Light curves of Cepheids and RR Lyrae

At the beginning of the routine phase and for a period of 4 weeks, a special scanning mode repeatedly covering the ecliptic poles on every spin was executed for calibration purposes. Data for 300,000 variable sources with more than 20 field-of-view transits were analyzed. From those, 9,000 were classified and 3194 RR Lyrae and Cepheid selected for publication. 300 are new discoveries. These high-cadence measurements (epoch photometry) are contained

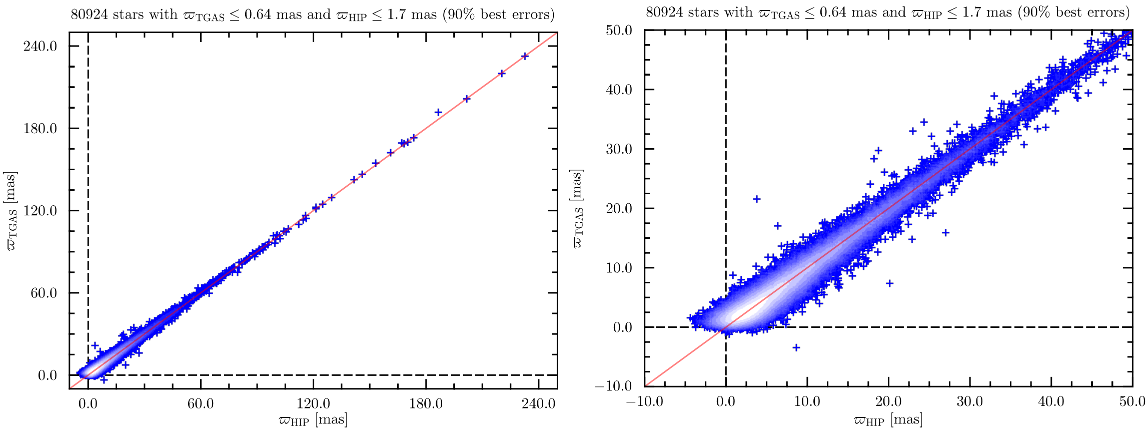

Figure 8: TGAS and Hipparcos parallaxes comparison (left) and a zoom (right). Credit DPAC/CU3/AGIS group.

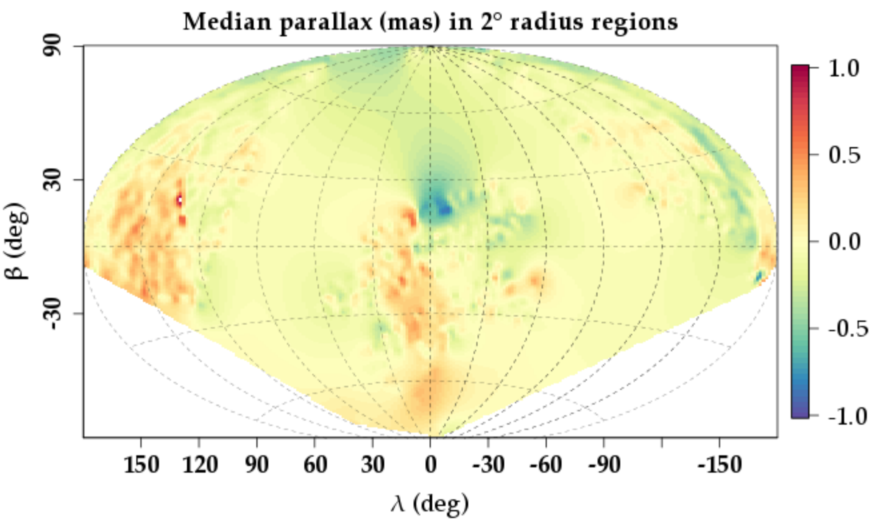

Figure 9: Median quasar parallaxes in 2 deg radius regions (mas), ecliptic coordinates. Local systematics with about 0.3 mas characteristic amplitude can be seen. Figure taken from [1].

in *Gaia* DR1. The full details can be found in [5] and [3], with examples of light curves there.

5 Use of *Gaia* DR1

By the incomplete data processing of *Gaia* DR1 and the short time span coverage, there are inherent known weaknesses that all users should be well aware of:

- *Gaia* DR1 has incompleteness for several reasons:
  - limited angular resolution because no deblending is performed of low-spectroscopy observations: few double stars below 2" (and 4" in dense areas),
  - there are no very bright stars $G < 3$ due to difficulties in the calibration,
  - because of IGSL construction, stars with proper motion higher than 3.5 arcsec yr^{-1} are missing [6], and
  - because of several filtering during the photometric processing, there is a deficit of sources with extreme colours.
- *Gaia* DR1 is based on only ~14 months of data, with a far from uniform scan of the sky, so the precisions and accuracies are limited in comparison with expectations at the mission end,
- *Gaia* DR1 processing is very simplified (chromaticity, PSF/LSF modelling, attitude modelling, basic angle variation, all sources treated as single stars, cyclic processing loop not closed, etc),
- cross-matching of individual transits suffers from Initial Gaia Source List (IGSL, [14] [6]) defects, spurious and duplicate source problems, and although duplicates are filtered out, some may remain,
- the TGAS subsample includes the brightest stars and they are the most difficult to calibrate (ghosts, saturation, etc),
- there are large spatially correlated systematics specially among the five parameters in TGAS,
- parallax systematics are at the 0.3 mas level over small regions, so that error contribution should be accounted for as $\varpi \pm \sigma_\varpi$ (random) $\pm$ 0.3 mas (systematic); this meaning that the 0.3 mas contribution cannot be statistically reduced by the factor $\sqrt{N}$ in small areas (for instance, in clusters).

6 Towards Data Release 2

Gaia DR1 will be improved in further releases, because of a more accurate data treatment together with a longer time coverage of observations.

Gaia Data Release 2 (DR2) will include observations acquired until 23 May 2016, so 22 months of data. Positions, proper motions and parallaxes will be derived for all well-behaved single-like sources to limiting magnitude of $G = 20.7$. Together with white light G magnitudes, *Gaia* DR2 will include integrated BP/RP photometry together with basic astrophysical parameter estimation ($T_{\rm eff}$, A_v), and mean radial velocities for bright objects ($G < 16$ mag) showing no radial-velocity variation and for which an adequate synthetic template could be selected.

Further releases (see the scenario in `http://www.cosmos.esa.int/web/gaia/release`) will be incremental in the kind of data included (orbital solutions, astrophysical parameters, spectrophotometry, and so on) together with the improvement of the astrometry and photometry.

7 Conclusions

The *Gaia* mission is in its current science operational phase. The first data release has been published on September 2016. It contains positions and G band photometry for more than one billion well-behaved sources. For a subset of 2 million stars, proper motions and parallaxes have been derived using the positions of Hipparcos and Tycho-2 catalogues as prior information. The release also includes the specific solution for 2152 ICRF quasars and light curves for 3194 Cepheids and RR Lyrae. Although there are several known weaknesses and large spatial correlations, this is the first all sky map at the angular resolution feasible from space (like HST) and the largest survey of parallaxes and proper motions at submas precision level.

Acknowledgments

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