

The initial *Gaia* source list[★]

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Received 20 May 2014 / Accepted 25 June 2014

ABSTRACT

Aims. We describe the production of the Initial *Gaia* Source List (IGSL) used both as the starting point for observation-matching in the *Gaia* data processing and as a comparison catalog to trigger early science alerts.

Methods. The IGSL was compiled from large scale public catalogs and a few specific catalogs provided by the *Gaia* Consortium. For all entries, a *Gaia* G magnitude is estimated and all objects with a $G < 21.0$ were included.

Results. The catalog has 1222598530 entries with the J2000 ICRF positions, proper motions, classification (star/non-star), and estimates of the *Gaia* G , *Gaia* G_{rvs} , Guide Star Catalog red (R_F) and blue (B_J) magnitudes. It is available from the Centre de Données astronomiques de Strasbourg.

Key words. catalogs – surveys – astrometry

1. Introduction

The Initial *Gaia* Source List (IGSL) was commissioned by the *Gaia* Data Processing and Analysis Consortium (DPAC) in 2006 to be a combination of the best optical astrometry and photometry information on celestial objects available at the *Gaia* Launch. A snapshot of the sky as we know it before *Gaia*. The method adopted was to cross match large area catalogs into one database then select the best parameters based on the typical precisions for each contributing catalogs.

Originally the main purposes of the IGSL were three fold: (i) to provide a comparison for science alerts for the first year before the first release of the *Gaia* results were available; (ii) to simplify the interconnection of the numerous *Gaia* auxiliary catalogs; (iii) to provide a list of objects fainter than the *Gaia* limit for calibration of the charge transfer efficiency. To these ends the first versions of the IGSL delivered in 2007 (IGSL1) and 2010 (IGSL2) included all entries from the input catalogs even if there was a chance they were not real.

In 2011 a decision was taken to make the IGSL the starting point for the initial data treatment cross-matching routines to simplify the operational procedures. As a result of this decision, it was decided to reduce the size of the IGSL by removing objects fainter than the *Gaia* limit. The result is a smaller, cleaner catalog that, for operational reasons, was frozen before the launch that is considered the IGSL3, hereafter simply IGSL.

The formal DPAC mandate for the IGSL is to fulfill the following broad requirements: all-sky positions, proper motions, and magnitudes for objects to a limit of *Gaia* magnitude $G = 21$ where possible, e.g., where there are large ($>10\,000$ square degrees) catalogs that reach that limit. The proper motions and magnitudes will be provided on a best effort basis, nominally

with precisions of 10 mas/yr and 0.3 mag, respectively, but obviously limited by the currently available large catalogs. The DPAC Core Processing Coordination Unit (CU3) catalogs of the Quasi Stellar Objects and the Ecliptic Pole Catalog should be included with no selection on magnitudes to directly support the CU3 processes that require those resources. The HIPPARCOS objects will be included with no selection on magnitudes to aid in the production of the Hundred Thousand Proper Motion catalog (de Bruijne & Eilers 2012).

2. Source catalogs

A quick perusal of compilation catalogs available in 2007 would suggest that the Naval Observatory Merged Astrometric Dataset (NOMAD, Zacharias et al. 2005) would have been a good choice for an IGSL. The adoption of NOMAD does not, however, diminish the work required to fulfill the goals of the IGSL. Nearly all the astrometric and photometric parameters would have needed updating, often returning to the original sources. It was decided that it was easier to construct the IGSL from scratch.

The main driving requirement was to find all objects all sky brighter than magnitude 21 in the expected *Gaia* G band. We have included publicly available large (e.g., $>10\,000$ square degrees) catalogs and some smaller special-area catalogs. To obtain an estimate of the G magnitude, we require an optical color (i.e., $B - V$, $V - I$, $g - r$ etc.) and apply the transformations in Jordi (2012). Many public catalogs were included in the original database, and the final decision on which ones would actually be used to construct the IGSL was taken only after various beta versions were produced.

The procedure we adopted was to start with the Guide Star Catalog (GSC) as a master list and add the entries from large catalogs to this list with a large matching radius of $5''$ with positions at J2000. This epoch was chosen because it is close to the epoch of the large catalogs that do not have proper motions, and

[★] The catalog is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/570/A87>

the option to use the epoch of observation was considered too complicated (for example the GSC23 has observations at over 8000 epochs) for any possible gain in matching precision. If more than one of the added entries matched one of the master list, the closest was considered the correct match, and a new entry was generated from the other entries. In this way the master list grew with each new catalog. The source catalogs and their order of inclusion for producing the IGSL version 3 were:

- GSC2.3 – The Second Guide Star Catalog version 2.3 (Lasker et al. 2008): this catalog forms the bulk of the photometry and defines the red and blue magnitudes (B_J and R_F) because this is the sky survey with the largest coverage in a homogenous photometric system. The only variation with the public version is that we removed the duplicate entries discussed in Sect. 4.2 of Lasker et al. (2008). This was done by insisting that only the Tycho-2 or first occurrence of entries within 10 mas were kept. As described in Sect. 4.3 of Lasker et al. (2008), the errors are not formal errors and cannot be used to set confidence limits, so we set the position errors to 400 mas.
- Tycho-2 (Høg et al. 2000): this catalog forms the backbone of all the major ground based catalogs currently available. It was made from a combination of the Tycho star mapper observations on the HIPPARCOS satellite (Hoeg et al. 1997), the Astrographic Catalogue, and 143 other ground-based catalogs.
- UCAC4 – USNO CCD Astrograph Catalog version 4 (Zacharias et al. 2013): this is the most precise all-sky astrometric catalog in the range $V = 10\text{--}16$ currently available. This catalog provides a red magnitude but is not in a standard bandpass.
- SDSS – Sloan Digital Sky Survey data release 9¹: we used the positions, magnitudes, and epoch of observation for all entries with $r < 24$ from the PhotoPrimary catalog of the ninth data release. This amounted to 4.7×10^8 entries in the SDSS footprint. We prioritized the astrometric and photometric data from this dataset for all the objects fainter than UCAC4. Since there were no proper motions in the SDSS when we used these positions, we propagated from the epoch of observation to 2000 using PPMXL proper motions. Owing to an error interpreting this catalog, the classifications are inverted; e.g., stars are classed 1 and non-stars 0.
- 2MASS – Two Micron All-Sky Survey Point Source Catalog (Skrutskie et al. 2006): this catalog is mainly a subset of the large Schmidt catalogs except for the red stars that were too faint. Magnitudes were calculated from a very rough extrapolation of the J and K infrared magnitudes to the B_J and R_F listed in Appendix A. The photometric errors of the extrapolated estimates were assumed to be 0.5 mag, and the positional errors were set to 300 mas. This positional error is higher than the quoted one in the 2MASS catalog, but because these objects do not have proper motions and the IGSL will be used now, e.g. 2014/2015, we have set the error high to be conservative, also considering that the 2MASS positions that enter are only for the faintest red objects. Since we only considered the PSC, all objects in this catalog were classified as stellar.
- PPMXL – Positions and Proper Motions “Extra Large” Catalog, (Roeser et al. 2010). Produced as a combination of the USNO-B (Monet et al. 2003) and the Two Micron Sky Survey point source catalog (Epchtein et al. 1999). The positions and proper motions should be ones that are the

most precise available for the objects fainter than the UCAC4 limit.

The order of this list follows the evolution of the production of the IGSL. As we are compiling catalogs, we naturally include false and erroneous entries and for some objects this leads to confusion. For example a bright star may get matched to noise rather than its true bright counterpart. The order of the inclusion can be optimized to minimize confusion at, for example, the bright end of the IGSL. The faint end, being dominated by the GSC23 and PPMXL where most of the false entries originated, will suffer the same confusion regardless of the order of inclusion. This is discussed below in the conclusions. The original IGSL deliveries used the GSC23 as the primary Schmidt-plate-based all-sky catalog, where the IGSL version 3 used the PPMXL because the former did not provide proper motions.

For operational reasons a number of smaller mission specific catalogs were also included. These were:

- GEPC – The *Gaia* Ecliptic Pole Catalog, version 3.0 (Altmann 2013): an approximately one-square-degree catalog around the northern and southern ecliptic poles produced specifically for calibrating *Gaia*. The two regions were defined as $62'$ squares centered on RA, Dec 06:00:00, $-66:33:41$ and 18:00:00, $+66:33:41$. The observations were done with the MEGACAM on the Canadian French Hawaii Telescope for the northern ecliptic pole and with WFI on the ESO 2.2 m telescope for the southern ecliptic pole. In this catalog there is a “stellarity” parameter that goes from 0 to 1, all objects that have a stellarity greater than 0.7 were considered a star and the rest non-star. An error in the translation meant that the IGSL galaxy classification for the non-stars is sometimes larger than 1, the stellar sources are all correctly classified as 0. Since the GEPC did not include all bright objects, all entries in the IGSL in this region of the sky are indicated as GEPC objects. The extra objects will therefore have aux EPC = 1 but idEPC = 0 as a source identification in the part of the IGSL.
- LQRF – The CU3 early version of Large Quasar Reference Frame (Andrei et al. 2009): this is a compilation of QSOs with precise positions produced as part of the *Gaia* auxiliary catalog development. For these objects we have defaulted to the LQRF positions and set the proper motions to zero because they are all confirmed QSOs.
- OGLE – Optical Gravitational Lensing Experiment version III: on the request of the *Gaia* science alerts team, we included objects in the OGLE bulge, LMC, SMC and Southern-EPC catalogs to improve the incompleteness of the IGSL in very crowded regions. The OGLE data are provided as catalogs of overlapping observations so many objects on the borders of chips were repeated and ended up as duplicates. To remove any duplicates, if a detection was within an arcsecond of another detection, we only kept the first entry.

There were also ~ 100 objects in the following catalogs that were not found in the above source catalogs mostly bright objects and they were forced to be included in the IGSL regardless of magnitude:

- HIP the HIPPARCOS catalog combined from Perryman et al. (1997) and van Leeuwen & Fantino (2005);
- Sky2000 (Myers et al. 2001) the SKYMAP Master Catalog of bright stars, Version 4;
- SPSS the *Gaia* spectrophotometric standard star catalog (Pancino et al. 2012).

¹ <http://www.sdss.org>

3. Production of the IGSL

There is no “correct” way to match large catalogs. All procedures will in certain cases fail, and the goal of any adopted procedure is to minimize the failures in the sense that is most beneficial to the purpose of the result. A very small matching radius will miss some real matches and result in some double entries, while a large one will have erroneous matches – especially when matching observations or catalogs from different epochs. In the case of the IGSL we adopt a large matching radius to minimize the number of double entries at the risk of making erroneous matches. In a compilation catalog such as the IGSL, the result is also a “compilation” of the individual catalog errors. The requirement that objects have at least two magnitudes from which to calculate a G magnitude cleans slightly the final result, and overall statistically the IGSL is reliable; however individual objects will have mismatches.

All the source catalogs were included in a MySQL database, indexed using the DIF facility (Nicastro & Calderone 2010), and each catalog matched to a master list using a nearest-neighbor approach with a limit of $5''$. The large matching radius was adopted to minimize the number of duplicate entries and to match the resolution limit of the GSC23, which was the original starting catalog. If, from a new catalog, two entries are matched to the same master-list object, a new entry is generated, and only the closest of the two is listed as a match. Once the master list is generated and all the catalogs have been matched to it, the production of the IGSL is just a combination of a few SQL scripts.

Initially all entries are included. Positions are assigned following the priority order: LQRF, UCAC4, Tycho-2, SDSS, PPMXL, GEPC, OGLE, GSC23. Proper motions are assigned following the priority order: UCAC4, Tycho-2, PPMXL, GSC23 and the LQRF objects have proper motions set to zero.

The classification is set to star for all UCAC/Tycho-2/OGLE as they have no classification indicator. The QSOs in the LQRF are also classified as stellar. The classification is then assigned in the following priority order: SDSS, GSC23, GEPC. We note that the classification as discussed earlier is inverted for the SDSS and sometimes more than one for the GEPC non-stars. In summary if a object is classed as zero it is a star, if not it is a non-star, except for classifications from the SDSS, e.g., where sourceClassification = 2, where the rule is inverted.

The magnitudes are assigned following the equations in Appendix A. The red and blue magnitudes are taken from magnitudes in the published catalogs following the priority order: Tycho, GSC23, PPMXL, SDSS, GEPC, OGLE, sky2000, 2MASS. The *Gaia* magnitudes follow this priority order: SDSS, Tycho-2, GEPC, OGLE, or transforms of the red and blue magnitudes as derived previously. The priorities for assignment are summarized in Table 1.

Once a *Gaia* G magnitude has been calculated, all objects with $G < 21$ are included into the IGSL. There are many objects that do not have a G magnitude because the source catalogs do not provide a red and blue magnitude from which to calculate G . There are for example many entries with magnitudes brighter than $R_F = 20$ or $B_J = 21$ that could be reasonably assumed to have $G < 21$, however, they may also be defects, unmatched entries or have unreliable magnitudes, so we have not included them. The exception to this rule are the objects in the LQRF, GEPC, HIP, SKY2000, and SPSS catalogs that are included with no constraint on magnitudes.

All entries are provided with a sourceID as described in De Angeli et al. (2007) and further developed in Bastian (2013). The running number and position for the heal-pixel

Table 1. Summary of the different catalog contributions in the IGSL.

Catalog	Code	IGSL matches	Priorities ¹				
			$\alpha/\delta, \mu, R_F/B_J, G/G_{\text{rvs}}, C$				
GEPC	67	608022	6,	–,	5,	3,	5
GSC23	1	777680797	7,	5,	2,	5,	4
LQRF	4	174715	1,	1,	–,	–,	1
OGLE	66	182451526	9,	–,	6,	4,	6
PPMXL	49	825467433	5,	4,	3,	6,	–
SDSS	2	172398260	4,	–,	4,	1,	3
2MASS	18	470005483	8,	–,	7,	7,	7
TYCHO2	5	2548506	3,	3,	1,	2,	2
UCAC	3	107701585	2,	2,	–,	–,	8

Notes. ⁽¹⁾ The priority for assignment of a given parameter; i.e., the positions are first taken from the LQRF, if the object is not there it is taken from UCAC, then TYCHO2, and so on. – Not provided by the contributing catalog.

(Górski et al. 2005) identification is provided at the first match of the contributing catalog to the master list. The sourceID is a combination of the source heal-pixel level 12 ID ($healpix12ID^2$) and the running number in the heal-pixel level 6 ($runningnumber$) bit combined via the MySQL relation $SourceID = (healpix12ID \ll 35) + (runningnumber \ll 7)$. This intrinsically indicates that the objects are entered in the main data base by the Data Processing Center Torino which has a DPAC center identification of 0. This SourceID will remain the identification of the *Gaia* objects unless the object is found to be multiple in which case new SourceIDs are generated for all components. We do not indicate components since we did not try to identify binary systems. Since the position in the IGSL is very rarely from the first catalog, the heal-pixel corresponding to the published IGSL position is not always consistent with the one used in the sourceID.

4. The Catalog

4.1. The main catalog

The IGSL has 1 222 598 530 entries and is currently included in the *Gaia* main database and at the CDS Strasbourg³ and is available for bulk download⁴. It is composed of two tables:

- 1) IgsSource: the main data with positional, photometric, and classification information as listed in Appendix A. Each entry is 147 bytes.
- 2) SourceCatalogIDs: a list of the identifiers in the various input catalogs, as well as the HIPPARCOS catalog on request from the *Gaia* team. Each entry is 98 bytes. We note that the identifiers are sometimes reported verbatim and are sometimes simplified as shown in Appendix A.

Due to differing precision and completeness in the source catalogs the distribution of the IGSL is biased. This is shown visibly by the outline of the SDSS footprint and the Schmidt plate boundaries in the distribution of object densities per region of the IGSL in Fig. 1. The checkered pattern is already noted in the

² $N_{\text{pix}} = 12 \times N_{\text{side}}^2$ and $N_{\text{side}} = 2^k$, where k is the map level (or order). Pixel area is $\Omega_{\text{pix}} = \pi/(3 \times N_{\text{side}}^2)$. For level 6 (12), it is $N_{\text{pix}} = 49152(201, 326, 592)$ and $\Omega_{\text{pix}} = 0.84 \text{ deg}^2 (0.74 \text{ arcmin}^2)$.

³ <http://vizier.u-strasbg.fr/viz-bin/VizieR?source=I/324>

⁴ <http://igsl.oato.inaf.it>

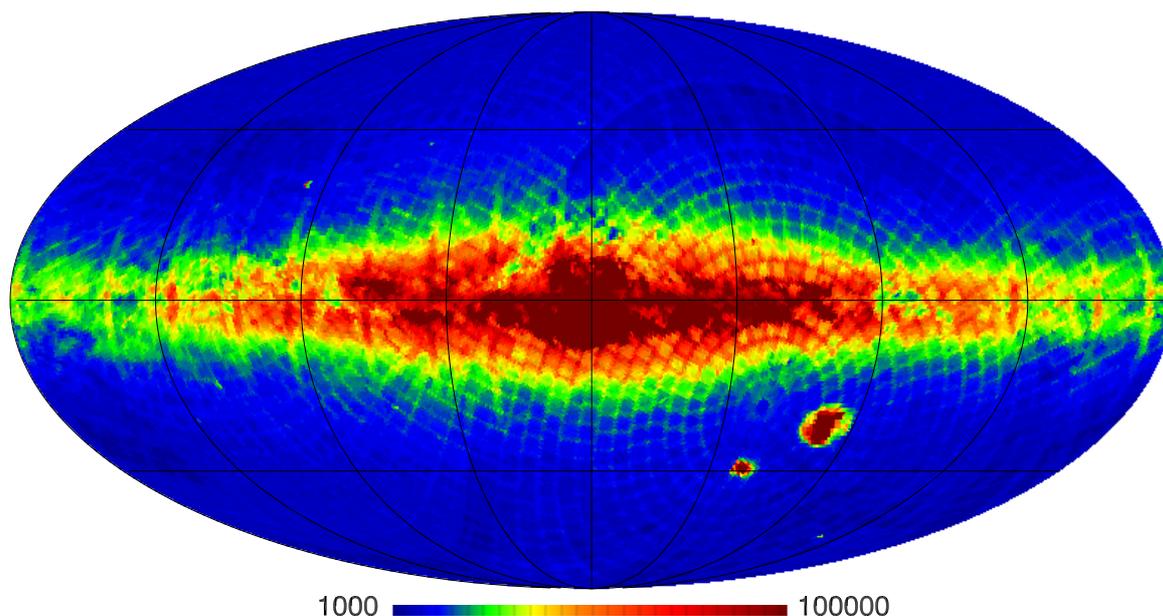


Fig. 1. Distribution of object density per heal-pixel 6th-level region of the Initial *Gaia* Source List. The stripes across the galactic plane are due to the SDSS Segue scans that are more complete and have a higher resolution than the other large catalogs based on Schmidt photographic plates that are also visible.

PPMXL⁵ and a similar pattern in the GSC23⁶, which are due to extra photometric information on multiple plates, better object detection on multiple plates, or multiple entries of objects at the plate boundaries.

4.2. Known problems

After the IGSL was frozen and delivered to the DPAC a number of problems were found. Some are trivial for example the ecliptic coordinates were calculated with a 1950B rather than J2000 transformation or the inversion of the SDSS classifications. Others were more complicated, for example the inclusion of the Tycho-2 used the catalog “mean right ascension” and “mean declination”; however, for some systems found to be binary in the Tycho catalog, these positions are identical (Hoeg et al. 1997). The software that generated the IGSL did not foresee the possibility of objects with identical positions, and the first entry of each system was overwritten by the second entry. If the first entry was in one of the other input catalogs, it was included later without the link to the Tycho-2, if the entry was only in the Tycho-2, it was not included in the IGSL⁷.

4.3. The Attitude Star Catalog toggle

The IGSL when delivered also included a binary toggle “toggleASC” that indicated that entry was considered sufficiently isolated and bright enough to be used in the on-ground attitude reconstruction of *Gaia*. Recent use found that the subset included many repeated entries from the source catalogs, and

⁵ http://alasky.u-strasbg.fr/footprints/tables/vizier/I_317_sample

⁶ http://alasky.u-strasbg.fr/footprints/tables/vizier/I_305_out

⁷ As problems are indicated they are compiled on the web page <http://igsl.oato.inaf.it> and accounted for in the *Gaia* processing downstream when possible.

also many entries violated the isolation criteria. This subset was regenerated and will be the subject of a future article.

5. IGSL4

The IGSL was developed to satisfy the operational requirements of the *Gaia* mission until the *Gaia* observations themselves produced an improved all sky catalog of celestial objects. It is, however, also being employed in various other scientific uses, and as such we have produced a version of the IGSL that corrected any known problems when possible. In particular for the bright objects starting from the faint catalogs before, the bright catalogs lead to the mismatch of many bright objects to faint noise in the denser catalogs. A better procedure, and one that has been adopted for the IGSL4, is to build the master list starting with the bright sparse catalogs. The IGSL4 has been built by combining the catalogs in the following order: HIPPARCOS, Tycho-2, SKY2000, UCAC4, GSC23, PPMXL, LQRF, TMASS, SDSS, GEPC, OGLE. It has also been delivered to the CDS Strasbourg and is linked as an update of the DPAC version.

Since the matching of the contributing catalogs in the IGSL4 is different from that of the IGSL, the running numbers and sometimes the heal-pixel changed. The sourceIDs therefore changed from the IGSL3 to IGSL4. For consistency we matched the IGSL4 objects to the IGSL3 and assigned the sourceIDs of the best matched from the DPAC version to the new version. There will be ambiguous matches where the new matching produced a different combination, and in the IGSL4, there are entries that were not in the IGSL3 – these were assigned new sourceIDs. In addition we have added estimates of the *Gaia* red and blue magnitudes based on the transformations provided in Jordi (2012) and included in Appendix A.

The IGSL3 has been made public to allow preparation for the results of *Gaia*. The SourceIDs used by *Gaia* will be those of the IGSL unless the object is found to be multiple, in which case new SourceIDs are generated. The IGSL4 has been made public to allow pre-*Gaia* simulations and astrometric usage with

a catalog free of the problems in the version delivered to the DPAC⁸.

Acknowledgements. We would like to thank Mario G. Lattanzi, Alessandro Spagna, Roberto Morbidelli, Rosario Messineo, Ulrich Bastian, Jose Hernandez, Uwe Lammers, Claus Fabricius, and Thomas Boch for constructive comments and feedback during the construction of the IGSL. The authors acknowledge the support of ASI under contract I/058/10/0 (*Gaia* Mission – The Italian Participation to DPAC); INAF through the TECNO- INAF CRA 1.05.01.15.04 (Customizable Instrument Workstation Software); the Marie Curie 7th European Community Framework Program grant No. 247593 Interpretation and Parameterization of Extremely Red COOL dwarfs (IPERCOOL) International Research Staff Exchange Scheme. This research has made use of: the Centre de Données astronomiques de Strasbourg; the Second Guide Star Catalog developed as a collaboration between the Space Telescope Science Institute and the Osservatorio Astrofisico di Torino; the Two Micron All Sky Survey which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology; and the Sloan Digital Sky Survey funded by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the US Department of Energy Office of Science.

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⁸ Future updates and identification of problems will be provided at <http://igsl.oato.inaf.it>

Appendix A: The IGSL parameters, cross identifications, and photometric transformations

Table A.1. IGSL parameters.

Parameter	Description	Units	Type
solutionId	Solution identifier		long
sourceId	Source identifier		long
alpha	Right ascension at J2000	radian	double
delta	Declination at J2000	radian	double
alphaError	Error in right ascension	radian	float
deltaError	Error in declination	radian	float
alphaEpoch	Mean epoch of right ascension	<i>Gaia</i> Time	float
deltaEpoch	Mean epoch of declination	<i>Gaia</i> Time	float
sourcePosition	Source of the positions ¹		byte
muAlpha	Proper motion in RA * cos(declination)	mas/yr	float
muDelta	Proper motion in Dec	mas/yr	float
muAlphaError	Error in muAlpha	mas/yr	float
muDeltaError	Error in muDelta	mas/yr	float
sourceMu	Proper motion source ¹		byte
galacticLon	Galactic longitude	degree	float
galacticLat	Galactic latitude	degree	float
eclipticLon	Ecliptic longitude	degree	float
eclipticLat	Ecliptic attitude	degree	float
magBJ	Magnitude estimated in GSC23 <i>B</i> band	mag.	float
magBJError	Error in magBJ	mag.	float
sourceMagBJ	source magBJ ²		byte
magRF	Magnitude estimated in GSC23 <i>R</i> band	mag.	float
magRFError	Error in magRF	mag.	float
sourceMagRF	source magRF ²		byte
magG	<i>Gaia</i> <i>G</i> magnitude estimate	mag.	float
magGError	Error in magG estimate	mag.	float
sourceMagG	Source magG ²		byte
magGrvs	<i>Gaia</i> <i>G</i> RVS magnitude estimate	mag.	float
magGrvsError	Error magGrvs estimate	mag.	float
sourceMagGrvs	Source magGrvs mag ²		byte
classification	Classification 0 = star, 1 = nonstar		boolean
sourceClassification	source of classification ¹		boolean
toggleASC	Attitude Star Catalog Tog ³		boolean
auxGSC23	In GSC2.3 catalog ⁴		boolean
auxSDSS	In SDSS DR9 dataset ⁴		boolean
auxUCAC	In UCAC4 catalog ⁴		boolean
auxLQRF	In CU3 LQRF ⁴		boolean
auxTYCHO	In TYCHO2 catalog ⁴		boolean
auxHIP	In HIPPARCOS catalog ⁴		boolean
auxPPMXL	In PPMXL catalog ⁴		boolean
auxOGLE	In OGLE III catalog ⁴		boolean
auxTMASS	In Two MASS PSC ⁴		boolean
auxEPC	In <i>Gaia</i> Ecliptic Poles Catalog ⁴		boolean

Notes. ⁽¹⁾ Position, proper motion, and classification source catalogs are identified by a number following the Codes in Table 1. ⁽²⁾ The source of the magnitudes are the relations given below. ⁽³⁾ The Attitude Star Catalog Toggle is 1 if it was considered a reliable ASC object or 0 if not. These are no longer used because the Attitude Star Catalog is now supplied separately. ⁽⁴⁾ The auxXXXX toggles are 1 if the entry was matched in the indicated catalog XXXX, 0 if not.

Table A.2. IGSL cross catalog identifiers.

Parameter	Short description	Notes
solutionId	Solution identifier	
sourceId	From the IGSL	
idGSC23	Identifier GSC23	Numerical value of the htm region plus running number
idSDSS	Identifier SDSS DR9	
idUCAC	Identifier UCAC 4	Running star number in UCAC4
idLQRF	Identifier LQRF	Running number in CU3 version of the LQRF
idTYCHO	Identifier Tycho-2	The combination of the Tycho-2 identifiers into one number = (TYC1*1000000)+(TYC2*10)+TYC3
idHIP	HIPPARCOS number	
idPPMXL	PPMXL identifier	The <i>ipix</i> identifier of the PPMXL
idOGLE	OGLE identifier	Combination of region number (<i>RI</i>) 10/11/12/13/14 corresponding to blg/car/cen/lmc/mus regions; file running number (<i>NNN.N</i>); running number in the file (<i>RN</i>). The idOGLE is then a concatenation of <i>RI</i> , <i>NNN.N * 10000</i> and <i>RN</i> .
idTMASS	Identifier 2MASS	the 2MASS IDs <i>2MASS JHHMMSS.S sDDMMSS.S</i> codified as sHHMMSSSSDDMMSSS a long integer.
idEPC	Identifier EPC	given as JHHMMSS.SS+DDMMSS.S

Table A.3. Photometric transformations blue / red magnitudes (B_J / R_F) to *Gaia* G / RVS / red / blue magnitudes ($G / G_{\text{RVS}} / G_{\text{RP}} / G_{\text{BP}}$).

01	$R_F/B_J = \text{value GSC23}; \sigma = 0.3$
02	$R_F/B_J = \text{value PPMXL}; \sigma = 0.4$
10	$R_F^a = V - 0.0478 - 0.5739(B - V) - 0.0938(B - V)^2 - 0.4606(B - V)^3 + 0.8419(B - V)^4 - 0.3472(B - V)^5; \sigma = \sigma_B$
11	$R_F = R - 0.0066 - 0.0563(V - R) - 0.2505(V - R)^2 + 0.3912(V - R)^3 - 0.0707(V - R)^4; \sigma = \sigma_V$
12	$R_F = V - 0.0137 - 0.5573(V - I); \sigma = (\sigma_V^2 + \sigma_I^2)^{1/2}$
13	$B_J^a = V + 0.0036 + 0.8768(B - V) - 0.0594(B - V)^2; \sigma_B = \sigma_B$
14	$B_J = R - 0.0480 + 2.4850(V - R) - 0.8760(V - R)^2 + 2.9117(V - R)^3 - 3.4144(V - R)^4 + 1.11850(V - R)^5; \sigma = \sigma_V$
15	$B_J = V + 0.0442 + 0.7851(V - I); \sigma = (\sigma_V^2 + \sigma_I^2)^{1/2}$
16	$R_F^b = V_T - 0.0478 - 0.578(B_T - V_T) - 0.0677(B_T - V_T)^2 - 0.2828(B_T - V_T)^3 + 0.4395(B_T - V_T)^4 + 0.1541(B_T - V_T)^5; \sigma = \sigma_{V_T}$
17	$B_J^b = V_T - 0.0036 + 0.655(B_T - V_T) - 0.0429(B_T - V_T)^2; \sigma = \sigma_{B_T}$
18	$R_F = r + 0.1784 + 0.1187(g - r + 0.259) + 0.0195(g - r + 0.259); \sigma = (0.04 + \sigma_r^2)^{0.5}$
19	$B_J = g + 0.0880 + 0.2434(g - r + 0.259) + 0.0439(g - r + 0.259); \sigma = (0.04 + \sigma_g^2)^{0.5}$
20	$B_J = V_p + 0.3608 + 1.40985(V_p - R_F); \sigma = 0.5$
21	$B_J = R_F + 0.3841 + 1.97440(R_F - I_N); \sigma = 0.5$
28	$G = V_T - 0.0246 - 0.3354(B_T - V_T) - 0.02558(B_T - V_T)^2 - 0.05153(B_T - V_T)^3; \sigma = (0.2916 + \sigma_{V_T}^2 + \sigma_{B_T}^2)^{1/2}$
29	$G_{\text{RVS}} = V_T - 0.1313 - 1.3422(B_T - V_T) - 0.09316(B_T - V_T)^2 - 0.0663(B_T - V_T)^3; \sigma = (0.2916 + \sigma_{V_T}^2 + \sigma_{B_T}^2)^{1/2}$
30	$G = g - 0.1128 - 0.5264(g - i) - 0.0869(g - i)^2 + 0.0025(g - i)^3; \sigma = (0.08^2 + \sigma_g^2 + \sigma_i^2)^{1/2}$
31	$G_{\text{RVS}} = g - 0.4994 - 1.2026(g - i) - 0.0202(g - i)^2 + 0.0021(g - i)^3; \sigma = (0.11^2 + \sigma_g^2 + \sigma_i^2)^{1/2}$
32	$G = g - 0.089 - 0.8543(g - r) - 0.1281(g - r)^2 + 0.0471(g - r)^3; \sigma = (0.1681 + \sigma_g^2 + \sigma_r^2)^{1/2}$
33	$G_{\text{RVS}} = g - 0.4332 - 1.8906(g - r) - 0.0231(g - r)^2 - 0.0329(g - r)^3; \sigma = (0.2401 + \sigma_g^2 + \sigma_r^2)^{1/2}$
41	$B_J = J + 4.9816 - 0.38945670(J - K); \sigma = 0.5$
42	$R_F = J + 2.6997 - 0.46257863(J - K); \sigma = 0.5$
50	$G^d = R_F - 0.0158 + 0.2915(B_J - R_F) - 0.0347(B_J - R_F)^2 - 0.0301(B_J - R_F)^3; \sigma = (0.1089 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
51	$G_{\text{RVS}}^d = R_F - 0.0974 - 0.4830(B_J - R_F) - 0.0184(B_J - R_F)^2 - 0.0178(B_J - R_F)^3; \sigma = (0.16 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
52	$G^c = V - 0.0247 - 0.2888(B - V) - 0.0353(B - V)^2 - 0.0839(B - V)^3; \sigma = 0.6$
54	$G = V - 0.0208 - 0.1004(V - I) - 0.1593(V - I)^2 + 0.0083(V - I)^3; \sigma = (\sigma_V^2 + \sigma_I^2)^{1/2}$
55	$G_{\text{RVS}}^c = V - 0.1333 - 1.4654(B - V) - 0.1075(B - V)^2 - 0.0768(B - V)^3; \sigma = 0.6$
57	$G_{\text{RVS}} = V - 0.0501 - 1.1667(V - I) - 0.0052(V - I)^2 + 0.0011(V - I)^3; \sigma = (\sigma_V^2 + \sigma_I^2)^{1/2}$
58	$G^e = R_F - 0.0201 + 0.2829(B_J - R_F) - 0.0526(B_J - R_F)^2 - 0.0339(B_J - R_F)^3; \sigma = (0.1225 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
59	$G_{\text{RVS}}^e = R_F - 0.1040 - 0.5590(B_J - R_F) - 0.0269(B_J - R_F)^2 - 0.0197(B_J - R_F)^3; \sigma = (0.1764 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
60	$G_{\text{RP}}^d = R_F - 0.0321 - 0.3607(B_J - R_F) + 0.0482(B_J - R_F)^2 - 0.0347(B_J - R_F)^3; \sigma = (0.1170 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
61	$G_{\text{BP}}^d = R_F - 0.0377 + 0.7373(B_J - R_F) - 0.0836(B_J - R_F)^2 + 0.0072(B_J - R_F)^3; \sigma = (0.2464 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
62	$G_{\text{RP}}^e = R_F - 0.0382 - 0.4238(B_J - R_F) + 0.0466(B_J - R_F)^2 - 0.0399(B_J - R_F)^3; \sigma = (0.1306 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
63	$G_{\text{BP}}^e = R_F - 0.0420 + 0.7627(B_J - R_F) - 0.1001(B_J - R_F)^2 + 0.0088(B_J - R_F)^3; \sigma = (0.2669 + \sigma_{B_J}^2 + \sigma_{R_F}^2)^{1/2}$
64	$G_{\text{RP}} = V - 0.0136 - 0.8963(V - I) - 0.0166(V - I)^2 - 0.0012(V - I)^3; \sigma = (.0016 + \sigma_V^2 + \sigma_I^2)^{1/2}$
65	$G_{\text{BP}} = V - 0.0506 - 0.3441(V - I) - 0.1038(V - I)^2 - 0.0076(V - I)^3; \sigma = (.0016 + \sigma_V^2 + \sigma_I^2)^{1/2}$
66	$G_{\text{RP}}^c = V - 0.0629 - 1.2352(B - V) + 0.1614(B - V)^2 - 0.1016(B - V)^3; \sigma = 0.6$
67	$G_{\text{RP}}^c = V - 0.0442 + 0.4419(B - V) - 0.1637(B - V)^2 + 0.0077(B - V)^3; \sigma = 0.6$
68	$G_{\text{RP}} = g - 0.3691 - 1.0344(g - i) - 0.0194(g - i)^2 - 0.0011(g - i)^3; \sigma = (0.0121 + \sigma_g^2 + \sigma_i^2)^{1/2}$
69	$G_{\text{BP}} = g + 0.0171 - 0.2154(g - i) - 0.0358(g - i)^2 + 0.0039(g - i)^3; \sigma = (0.0144 + \sigma_g^2 + \sigma_i^2)^{1/2}$
70	$G_{\text{RP}} = g - 0.3155 - 1.6703(g - r) + 0.0390(g - r)^2 - 0.0624(g - r)^3; \sigma = (0.25 + \sigma_g^2 + \sigma_r^2)^{1/2}$
71	$G_{\text{BP}} = g + 0.0333 - 0.2403(g - r) - 0.1558(g - r)^2 - 0.0149(g - r)^3; \sigma = (0.001 + \sigma_g^2 + \sigma_r^2)^{1/2}$
72	$G_{\text{RP}} = V_T - 0.0629 - 1.1399(B_T - V_T) + 0.1166(B_T - V_T)^2 - 0.0623(B_T - V_T)^3; \sigma = (.4225 + \sigma_{V_T}^2 + \sigma_{B_T}^2)^{1/2}$
73	$G_{\text{BP}} = V_T - 0.0442 + 0.2856(B_T - V_T) - 0.1182(B_T - V_T)^2 + 0.0047(B_T - V_T)^3; \sigma = (.0016 + \sigma_{V_T}^2 + \sigma_{B_T}^2)^{1/2}$
80	$G = \text{value and sigma from GEPC}$
81	$G_{\text{RVS}} = \text{value and sigma from GEPC}$
83	$G_{\text{BP}} = \text{value and sigma from GEPC}$
84	$G_{\text{RP}} = \text{value and sigma from GEPC}$

Notes. ^(a) Valid only for $(B - V) < 2.5$; ^(b) valid only for $(B_T - V_T) < 2.5$; ^(c) only used with SKY2000 magnitudes when others not available; ^(d) used for objects with declination ≥ 0 ; ^(e) used for objects with declination < 0 . B, V, R, I = published Johnson-Cousins magnitudes; g, r, i = SDSS magnitudes; V_T, B_T = Tycho magnitudes; J, K = 2MASS magnitudes; B_J, R_F are GSC23/PPMXL measured or estimated magnitudes. The σ represents the transformation error, and if significant, we add in quadrature the published errors. Equations (10)–(21) were determined from a combination of Johnson - GSC2 transformations derived internally and Tycho - Johnson transformations published in the “Guide to the Tycho-2 Catalog” (Hog et al. 2000, <http://www.astro.ku.dk/~erik/Tycho-2/>). Equations 41/42 were calculated internally from a GSC23 to 2MASS match. Other equations between 28–57 were taken from Jordi (2012) combined with Høg et al. (2000) and internal transformations where needed.