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The Gaia Attitude Star Catalog

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ABSTRACT

We describe the Attitude Star Catalog produced for the Gaia mission. This catalog is being used by Gaia for the first on-ground attitude reconstruction. Originally it was simply a subset of the Initial Gaia Source List but this subset did not meet the isolation requirements and it contained a significant number of double entries. As a result during the commissioning phase of Gaia a new generation of this catalog, that better fulfills the attitude reconstruction requirements, was requested. Here we describe the production and properties of this new Attitude Star Catalog.

The Attitude Star Catalog was made by combining 7 all sky catalogs and selecting entries based on magnitude, isolation and astrometric precision criteria. The catalog has 8173331 entries with estimates of the positions at 2000, proper motions and magnitudes (Gaia G, Gaia G_{rvs}, red R_F & blue B_J) in the magnitude range $7.0 < G < 13.4$. It is publically available from the CDS Strasbourg and the IGSL web-site.

1. Introduction

The Attitude Star Catalog (ASC) was commissioned by the Gaia Data Processing and Analysis Consortium (DPAC) in 2006 to allow a first reconstruction of the attitude of Gaia. Eventually it will be replaced by a catalog constructed from the Gaia observations but for at least the first two years a precompiled ground based catalog was needed. The ASC entries were required to be of a high astrometric precision, isolated from other bright $G > 13.7$ objects, and, brighter than the 2-d window threshold of the Gaia instrument.

The first version delivered to the DPAC in September 2013 was simply a subset of the Initial Gaia Source List (IGSL) described in Smart and Nicastro (2014, hereafter SMA14) identified by the parameter toggleASC $=$ 1. Early commissioning usage and an examination of the ASC subset revealed a number of repeat entries for the same object and entries that did not meet the isolation requirements. Since the reliability of the ASC was fundamental to the Gaia mission a new re-compilation was requested in January 2014. The new separate ASC was delivered to DPAC in April 2014. Here we describe the production and properties of the ASC, which are currently available from the CDS Strasbourg or the IGSL web-site.[1] The experience obtained in the production of the ASC will be useful for similar endeavors such as the production of supporting catalogs for future space missions.

2. Source catalogs

Combining catalogs inevitably leads to a combination of errors of the individual source catalogs. To minimize the errors in the production of the ASC the source catalogs were kept to only those necessary to be complete to the isolation criteria, provide the best astrometric precision available and allow a precise estimate of the Gaia G magnitude. The source catalogs used and their order of inclusion were:

- HIPPARCOS (Perryman et al., 1997): The results of the HIPPARCOS mission. We have included the photometry from the original HIPPARCOS Catalogue and the astrometric parameters from the update by van Leeuwen (van Leeuwen and Fantino, 2005) when published. Initially all entries were included regardless of the known errors,[2] e.g. also for entries that are considered erroneous. Since inclusion in the ASC requires an estimate of the G magnitude the unreal entries were excluded as part of the cleaning phase.
- Tycho-2 (Høg et al., 2000): This catalog forms the astrometric backbone of most 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.

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[1] http://igsl.oato.inaf.it.

[2] http://www.rssd.esa.int/index.php?project=HIPPARCOS&page=catalog-errors.

http://dx.doi.org/10.1016/j.ascom.2016.01.004
2213-1337/

- Sky2000 (Myers et al., 2001): The SKYMAP Star Catalog System is a list of all stars with either measured Johnson blue or visual magnitudes brighter than 9.0. The version used here had 299 167 entries of which 212 were not in the combined HIPPARCOS + Tycho-2 catalogs. Sky2000 provides positions at 2000, proper motions and a blue and visual magnitude. We assumed the positions to have an error of 100 mas, the proper motions an error of 10 mas/yr, and an error of 0.6 in the ASC magnitudes derived from the Sky2000 values.
- UCAC4 (Zacharias et al., 2013): The USNO CCD Astrograph Catalog version 4 is the most precise all-sky astrometric catalog in the range $V = 10$–16 currently available. There are no original standard magnitudes in this catalog.
- GSC2.3 (Lasker et al., 2008): The Second Guide Star Catalog version 2.3 forms the bulk of the photometry and defines the red and blue magnitudes (B_J and R_F) as this is the sky survey with the largest coverage on a precise homogeneous photometric system. The only variation with the public version is that we removed the multiple entries discussed in Section 4.2 of Lasker et al. (2008). This was done by insisting that only one entry from any objects with position differences of less than 10 mas was kept selecting Tycho-2 or Sky2000 over other entries.
- PPMXL (Roeser et al., 2010): The Positions and Proper Motions "Extra Large" Catalog, produced from a combination of the USNO-B (Monet et al., 2003) and the Two Micron Sky Survey point source catalog (Epchtein et al., 1999). This catalog was included to provide magnitudes for those entries that did not have them in the previous catalogs.

In addition any objects in the Washington Double Star catalog (Mason et al., 2010) or the Tycho Double Star catalogue (Fabricius et al., 2002) were indicated as probable members of a binary system.

The last two Schmidt plate based catalogs were included just to provide color information when it was not provided by Tycho-2/Sky2000 for the estimation of the Gaia G magnitude. Since the source catalogs are not identical the same object in the IGSL and the ASC will have different estimates of the Gaia magnitudes. Indeed some of the sources in the ASC are not in the IGSL as in the selection process for the IGSL they were removed, this occurred for 54 932 of the ASC entries.

3. Production of the ASC

The first version of the ASC was a subset of the IGSL and consequently was derived using the procedure in SMA14. In summary we produced a master list of objects starting with the large faint catalogs, progressively adding other catalogs and increasing the master list as entries from new catalogs were unmatched. The catalogs of bright objects were then matched to a large master list which resulted in mismatches of the bright objects to noise or faint objects near the true bright objects. Also it was found that the large Schmidt catalogs in the overlap region between plates often had many multiple entries of the same objects, this can be seen in the sky plot of the PPMXL.[3] These multiple entries, if they were bright enough, were included as ASC sources.

The first on-ground attitude reconstruction of Gaia is described in detail in Padeletti and Bastian (2009). The goal of this attitude reconstruction is to provide the attitude with an accuracy of 50 mas for the first year when the ASC will be the primary source of reference objects. Later in the mission it is planned to replace this catalog with one produced by Gaia with an expected accuracy of a few mas. This reconstruction requires at least one 2-d measurement per second and per field of view which equates into a minimum density of 75 stars per square degree.

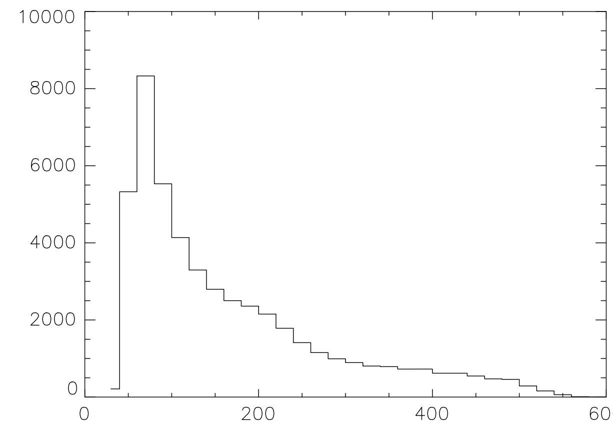

Fig. 1. Histogram of object density per HEALPix 6th level region of the Attitude Star Catalog.

To be automatically assigned a 2-d window the star must have a $G < 13$ but this does not provide enough calibration sources especially near the galactic poles. The compromise was to provide a list of faint calibration stars to a $G = 13.4$ which sets the limiting magnitude of the ASC.[4]

The cross-matching radius in the first on-ground attitude reconstruction will be between 20 and 30", the precise value to be optimized during the commissioning phase. Hence we conservatively require that all ASC sources are isolated at the level of 40". Using this criterion there should be only one bright star in a window for the on-ground cross-matching to match thus reducing the possibility of failures. This isolation requirement would potentially allow up to 8000 ASC entries per square degree and not violate the isolation criteria. Following this consideration, in the original subset of the IGSL that constituted the ASC, we just lowered the magnitude limit to reduce the number of stars to less than 1000/square degree. We then assumed the isolation criteria would always be met when there were this many objects/square degree. However, because of the multiple entries, uncataloged binary systems and general non uniform distribution it was found that the isolation requirement of the ASC subset was violated for over 25% of the entries.

To address the isolation and duplicate entry issues the ASC was reproduced from scratch using the catalogs listed in Section 2 in the order given. The production of the ASC starts with all objects in the HIPPARCOS catalog as a master list, the other catalogs are inputted and matched to this master list with a matching radius of 5″. All entries from the input catalog not matched are included as new master list objects. If more than one entry from the input catalog matches the master list only the closest is considered matched and a new entry is generated for the others.

In this way the master list grows with each included catalog. Since the first catalogs are composed of bright objects they are sparse and the chances of a mismatch between the input catalogs and the master list were reduced. The confusion at the bright end of the master list was in this way minimized. When the large, dense Schmidt plate based catalogs are included there is still the possibility that non-real entries are matched to bright objects and the real bright objects in the GSC23/PPMXL enter as new entries. However, the Schmidt data is only used to provide photometric information and to clean up the ASC list we drop any objects

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

4 In Padeletti and Bastian (2009) the limit of the ASC was set to $G = 14.0$ however a change of the procedure allowed a relaxation of that requirement to $G = 13.4$, Ulrich Bastian private communication.

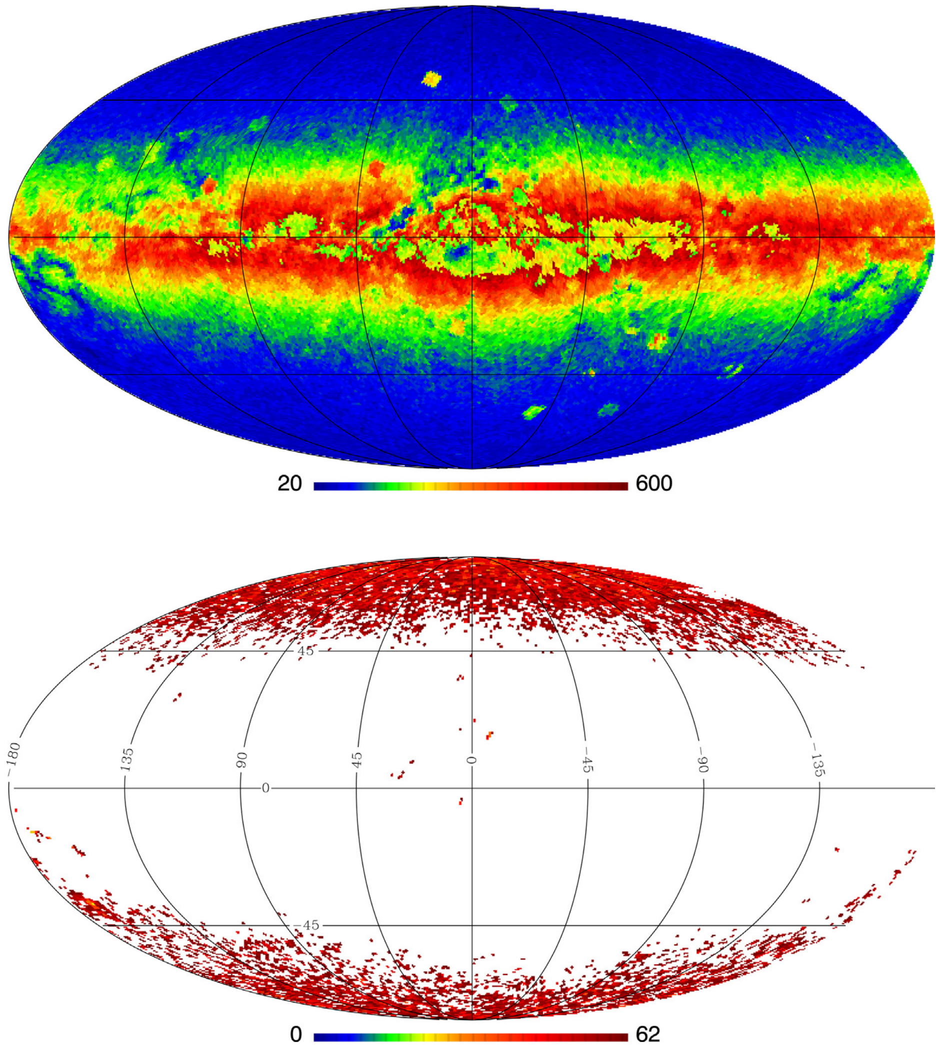

Fig. 2. The distribution of object density per HEALPix 6th level region of the Attitude Star Catalog. Top panel all cells, bottom panel just cells with a density of less than 63.

that are not in either UCAC4, Tycho-2, sky2000 or the HIPPARCOS catalogs under the assumption that the union of these catalogs is complete to fainter than the Gaia isolation limit of $G = 13.7$.

Once the master list was completed with the compilation of all the catalogs we estimated the red R_F, blue B_J, Gaia G and Gaia G_{RVS} using the relations and priorities in SMA14 with the photometry from the contributing catalogs. We then dropped any objects fainter than $G = 13.7$. This compilation and selection criterion results in 15 million objects. We assume all objects are stellar and then examine each object one-by-one and indicate for each object the number of neighbors within 40″.

From this list we drop any star with a (i) neighbor, (ii) $G < 7.0$ or $G > 13.4$ or (iii) in the Washington Double Star or Tycho Double Star catalogs. The result is a catalog of 8 million objects that constitutes the ASC.

4. Properties of the ASC

The production of the catalog was carried out using tables with the level 6 HEALPix spatial division (Górski et al., 2005). We therefore examine the ASC using this division of the sky which has the advantage that all cells cover the same area of sky equal to $41\,253/49\,152 = 0.84$ degree^2/cell. In this pixelization the minimum star density of 75 per square degree equates to 63 stars/cell. In Table 1 we list the per cell properties of the ASC and the number of cells with less than 63 stars.

Table 1
ASC properties per 6th level HEALPix, ∼0.84 degree cells.

Number of entries	8 173 331
Average density per cell	166
Minimum density per cell	23
Maximum density per cell	583
Number of cells with at least 63 stars	42 248
Number of cells with less than 63 stars	6 904

In Fig. 1 we plot a histogram of the per cell density of ASC stars. The minimum number of stars/cell is 23, the peak is around 80 and the maximum is 583. Over 85% of the sky has at least 63 stars/cell. In Fig. 2 we plot the on sky density of the ASC in HEALPix level 6. The top panel is all values and the bottom panel shows the 6904 (15%) of the cells that do not have 63 stars.

In Fig. 3 we plot the distribution of the G, G_{RVS}, R_F and B_J magnitudes. The G is confined by the selection criteria to the range 7–13.4, the other magnitudes are estimated from the input catalogs and are not restricted. We find that of the 8 million entries 7411, 457 563 and 17 763 in G_{RVS}, R_F and B_J respectively are outside a reasonable range of 5 to 15.4 which is plotted in Fig. 3. Some of these will be mismatches between the input catalogs providing a false color that when transformed leads to an unrealistic magnitude. There will also be objects with extreme colors that are not well represented by the transformations. We therefore note that any use of these magnitudes for individual objects should be done with caution. Finally the slight dip in the

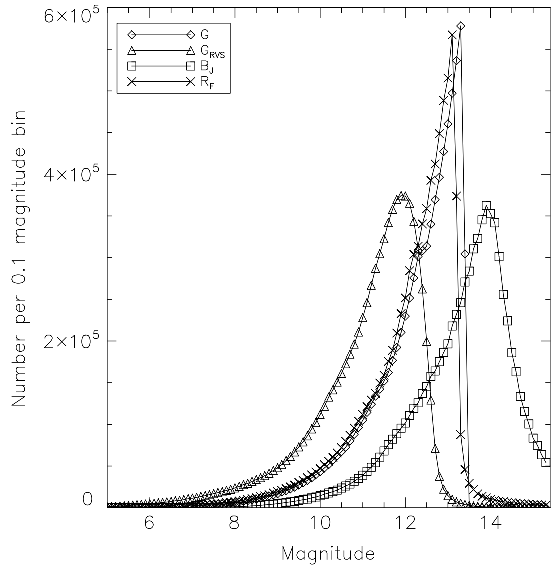

Fig. 3. Number of entries per 0.1 magnitude bin in the G, G_{RVS}, R_F and B_J pass bands as shown in the legend.

distribution $G \sim 12.5$ magnitudes is either due to the change from Tycho-2 to UCAC4 as the main source of stars or the change of magnitude transformations which no longer start from Tycho V_T, B_T magnitudes but from the GSC2/PPMXL R_F, B_J magnitudes.

The format of the ASC provided to the DPAC and the CDS is identical to the IGSL as detailed in SMA14. The ASC will remain the reference catalog for the first on-ground attitude reconstruction until 2016 when the first full Gaia data solutions are run and the ASC positions will be replaced by Gaia ones. For bulk download of the ASC and a list of known problems see the web-site http://igsl.oato.inaf.it.

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