A Giant Step: from Milli- to Micro-arcsecond Astrometry
Proceedings IAU Symposium No. 248, 2007
W. J. Jin, I. Platais & M. A. C. Perryman, eds.
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doi:10.1017/S1743921308019443

The GSC-II catalog release GSC 2.3: description and properties

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Abstract. The GSC 2.3 is a current catalog release extracted from the Guide Star Catalog II database, which is maintained at the Space Telescope Science Institute in Baltimore, USA. The catalog contains astrometry, multi-band photometry (B_J, R_J, I_N) and star/non-star classification for 945,592,683 objects down to the magnitude limit of the survey plates. We review the performance of stellar parameters, anticipating the improvements in astrometric accuracy foreseen by its recalibration with the newly available catalog in the UCAC series.

Keywords. astrometry, catalogs, reference systems, surveys, techniques: miscellaneous

1. Overview and applications

The Guide Star Catalog II (GSC-II) - a joint effort of the Space Telescope Science Institute (ST ScI) and the Torino Astronomical Observatory (INAF-OATo), with additional resources from international institutions - is an all-sky astro-photometric catalog derived from the digitization of the Palomar and UK Schmidt surveys. Its latest release, GSC 2.3, (Lasker *et al.* 2007) is the operational catalog for HST starting from GO Cycle 15 and is one of the primary data sources for preparation of the Initial Source List of the Gaia reduction pipeline; it is also planned to be an input catalog for the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) of China.

Given its completeness, depth, and multi-color characteristics, GSC-II has also been used for investigations on Galactic structure and stellar populations through proper motions (see, e.g., Sciortino *et al.* 2000, Vallenari *et al.* 2006). The latter, which are not included in the current public version of the catalog, have been obtained from the GSC-II database by ad-hoc algorithms, developed at OATo, linking measured positions (x,y) of the same objects on overlapping plates from different epochs. While the intrinsically precise x,y measurements should allow to obtain the proper motion accuracies of the order of 3-5 mas yr^{-1}, the procedure cannot be automatized easily, and it resorts to the presence of field galaxies - not available in high-extinction regions - for the link to the absolute reference frame (Spagna *et al.* 1996). Alternatively, proper motions can be derived in a straightforward manner from multi-epoch plate-based sky positions relying on external reference catalogs. In this case, their accuracy reflects possible deficiencies of a single-plate astrometric model and therefore can suffer from the well known problems that have plagued the Schmidt plate astrometry.

Although the overall quality of GSC 2.3 astrometry is quite good, small systematics are still present. In the following sections we summarize the properties of the current

https://doi.org/10.1017/S1743921308019443 Published online by Cambridge University Press

catalog and outline the foreseen ways of improvements which will lead to the publication of a new release with the inclusion of proper motions.

2. Catalog description

The GSC-II is derived from the uncompressed Digitized Sky Survey (DSS) material scanned at the STScI with two heavily modified PDS machines, named the GAMMA. Image cutouts of all detected objects, and their associated features, are extracted from each digitized plate by pipelined tasks (*sky background determination, object identification, blend resolution, centroiding, classification*), and outputted for the subsequent plate calibration algorithms performing: a) star/non-star classification via an oblique-decision-tree algorithm (Murthy *et al.* 1994) trained by 5334 hand-classified objects; b) photometric calibrations; and c) astrometric calibrations.

Photometric reductions are based on Johnson-Kron-Cousins B,V,R standards from the GSPC-I (Lasker, Sturch *et al.* 1988) and GSPC-II (Bucciarelli *et al.* 2006), plus additional B_T and V_T phtometry from TYCHO stars needed to constrain the bright range of the density-to-intensity relation of the photographic emulsion. Magnitudes are computed in the natural passbands of the plates, defined by the emulsion/filter combination. The instrumental parameter of choice is the integrated density and its fit to standard magnitudes is performed via Chebyshev polynomials.
Stellar positions are directly tied to the International Celestial Reference System (ICRS) by the use of the ACT and TYCHO-2 as reference catalogs. A polynomial model is applied to map the measured x, y coordinates of reference stars (pre-corrected for refraction) onto their standard coordinates (ξ,η). Then, for each survey, the $\Delta\xi$, $\Delta\eta$ residuals are accumulated in a plate-based grid of 4.4×4.4 mm^2 bins to build the so-called astrometric masks. The resulting patterns in these masks are used to remove the systematic errors left out by the model.

All the calibrated plates are loaded into COMPASS, the GSC-II database built on *Objectivity* - an Object-Oriented Database Management System - (Greene *et al.* 1998), which sets a unique correspondence between the plate-based data and partitions of the celestial sphere. For every new plate which is loaded into COMPASS, a matching task identifies and labels unique objects on different plates.

After the GSC 2.2 release in July 2001, the production of a GSC 2.3 export catalog extracted from the GSC-II database was mainly motivated by the desire to release a large and valuable data set to the international astronomical community, and also by the needs to improve the planning of observations and operations of HST (McLean 2007). GSC 2.3 contains nearly all objects down to the magnitude limit of the plates (a total of 945,592,683 entries), so that it is expected to be complete to at least $R_F = 20$. This limit is confirmed at high galactic latitudes; however, in very crowded fields near the Galactic plane it may suffer incompleteness at magnitudes brighter than $R_F \approx 18$ (Drimmel *et al.* 2007) .

Extraction rules have been set to minimize the deficiencies of the calibration algorithms at the plate borders where highly non-linear effects are dominant. In particular: a) positions are measured on the red IIIaF plates, and multiple measurements are solved by selecting the closest solution to the plate center. If the object is not detected on any IIIaF plate, then its position from the blue IIIaJ, visual IIaD, and infrared IV-N plates is used, following this order of priority: b) photographic magnitudes (B_J, R_F, I_N,) are provided, if available, for all exported objects; additional V_{12} (Palomar Quick-V) and O (POSS-II) magnitudes are also given. When different plates of the same band overlap, the observation closest to the plate center is selected without applying any averaging procedure.

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Also, to improve the completeness and accuracy at the brightest magnitudes, GSC 2.3 has been supplemented with data from the TYCHO-2 and SKY2000 (Myers *et al.* 2002) catalogs, that substitute, when feasible, the GSC-II data for any given object.

3. Catalog properties

The main properties of GSC 2.3 are summarized in Table 1. Performance of the different stellar parameters has been assessed via comparisons to external reference catalogs; in particular, the astrometric and photometric errors reported in the table are global averages against the fifth data release of the Sloan Digital Sky Survey (SDSS DR5, Adelman-McCarthy 2007).

Photometric errors are only reported for stellar sources, as the GSC-II pipeline is not optimized for galaxy photometry. In GSC 2.3 extended objects appear systematically brighter than from the SDSS, although the effect decreases towards fainter objects until becoming negligible at around 18th magnitude.

In terms of astrometry, the point-like sources have lower errors. Larger errors are present for the extended objects (”non-stars”) – which may include galaxies and nebulae, as well as blends and unresolved binaries – mainly due to saturation and sampling problems for very bright and very faint objects, respectively.

Table 1. Overview of GSC 2.3 Global Properties

Total number of objects	945,592,683 (206,688,844 point-like; 738903839 extended)
Magnitude limit	$B_J = 22.5$, $R_F = 20.5$, $I_N = 19.5$
Mean epoch of positions	1992.5
Reference frame	ICRF
Astrometric reference catalogs	ACT + TYCHO2
Average positional accuracy:	
–stellar objects	0.″30
–extended objects	0.″40
Average positional precision:	
–stellar objects	0.″22
–extended objects	0.″35
Photometric reference catalogs	GSPC1 + GSPC2 + TYCHO
Average photometric accuracy(stellar sources)$^{(1)}$:	
at $B_J \approx 20$	0.18 mag
at $R_F \approx 19$	0.15 mag
at $I_N \approx 18$	0.20 mag
Stellar Classification reliability:	at least 90%$^{(2)}$
Completeness:	$> 98\%^{(3)}$

Notes:
$^{(1)}$ Photometry of non-stellar sources suffers from systematic errors which, for very bright objects, can be as high as ≈ 2 mag.
$^{(2)}$ Percentage of stars correctly classified as such; the success ratio decreases at magnitudes fainter than $R_F = 19.5$
$^{(3)}$ up to $R_F = 20$ and $l > 30°$; incompleteness at brighter magnitudes is strictly related to the object field density

4. Magnitude-dependent errors and future re-calibration

Further astrometric tests of GSC 2.3 have detected a magnitude-dependent systematic error reaching a level of the order of $\approx 0.''10$, also dependent on object's position on

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the plate. As shown in Fig. 1, which plots the right ascension differences against the UCAC 2 catalog for the bright and faint magnitude samples as a function of declination, the effect is more pronounced for faint stars, farthest from the magnitude range of the TYCHO 2 to which GSC 2.3 has been tied. Whatever the cause of this effect, we are confident that it can be cured by using fainter astrometric calibrators, such as those available from the UCAC catalog, whose CCD stellar images are are optimally exposed as they fall in the linear range of the photographic emulsion sensitivity. Preliminary tests have already showed the potential astrometric improvements (Tang *et al.* 2008), and we are in the process of setting up a fully operational procedure to perform a new astrometric calibration of the entire catalog, which will allow us to obtain scientifically valuable proper motions over the whole sky.

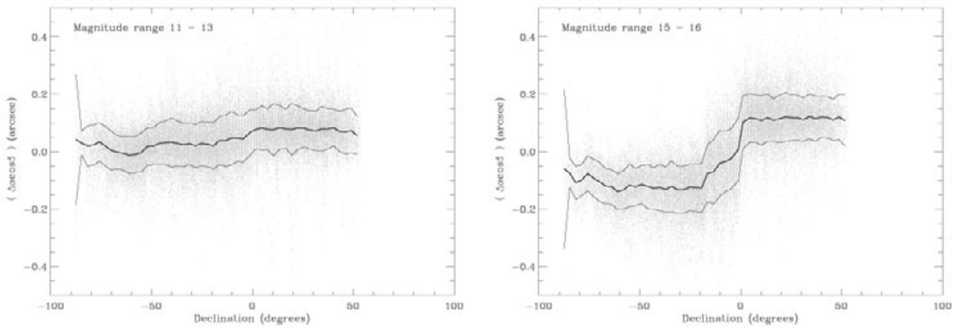

Figure 1. GSC 2.3 - UCAC2 RA differences as a function of declination for the magnitude ranges 11-13 (left panel) and 15-16 (right panel). The central solid line marks the median for the data binned in declination, while the external ones trace the RMS deviations about each median.

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