# DoD Guidance, Navigation and Control Standard Reference Catalog v1.1 (GNC)

## Technical Report 23-002

**US Naval Observatory**

Celestial Reference Frame Department

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# Contents.

# I. Introduction.

The DoD Guidance, Navigation and Control Standard Reference Catalog v1.1 (hereafter GNC) is a bright star catalog with the aim of meeting the demands required by projects using relatively "modest aperture" instruments such as star trackers. Thus, the GNC is essentially a "bright star" catalog covering astrometry and photometry in the visible and short wave infrared (SWIR)[1]. This document presents the GNC, and reviews the different steps of the construction of the catalog, which took place in the period July-December 2022.
The catalog was developed entirely in a Postgres database, using the DoD Celestial Database (DCDB) operated by the US Naval Observatory (USNO).

# II. Catalog requirements.

These are the requirements of the catalog.

1. The GNC shall contain all stars brighter than G = 11 mag.
2. The epoch of the GNC catalog shall be 2016 (epoch of the Gaia DR3 catalog).
3. The GNC shall include a GNC ID, and the Hipparcos and Gaia DR3 IDs when available.
4. The GNC shall contain the following astrometric and photometric fields, with their corresponding uncertainties:

| **Astrometry** | **Photometry** |
|---|---|
| RA | Optical: Gaia DR3's G, Bp, Rp |
| Dec | Near-infrared: $JHK_s$ |
| Proper motion in RA | |
| Proper motion in Dec | |
| Parallax | |

   Note: the covariance of the astrometric parameters is omitted in this catalog, but might be considered in a future release.
5. The GNC shall contain a variability flag.
6. The GNC shall contain a multiplicity flag.
7. The GNC shall contain the distance to the nearest catalog neighbor.
8. The GNC shall include an estimate of the astrometric shift of the photocenter caused by a close neighbor.
9. The GNC shall flag all stars with greater than 50 mas photocenter shift.
10. The GNC shall flag all stars with position uncertainty greater than 100 mas.
11. The GNC shall flag all stars with proper motion uncertainties greater than 10 mas/year.
12. The GNC shall flag all stars with parallax uncertainties great than 100 mas.
13. The GNC shall flag all stars with nearest catalog neighbor less than 4.6 arcseconds.

[1] Also referred to as the "near infrared", i.e., wavelengths in J, H, and K bands, or wavelengths of 1.1-2.4 microns.

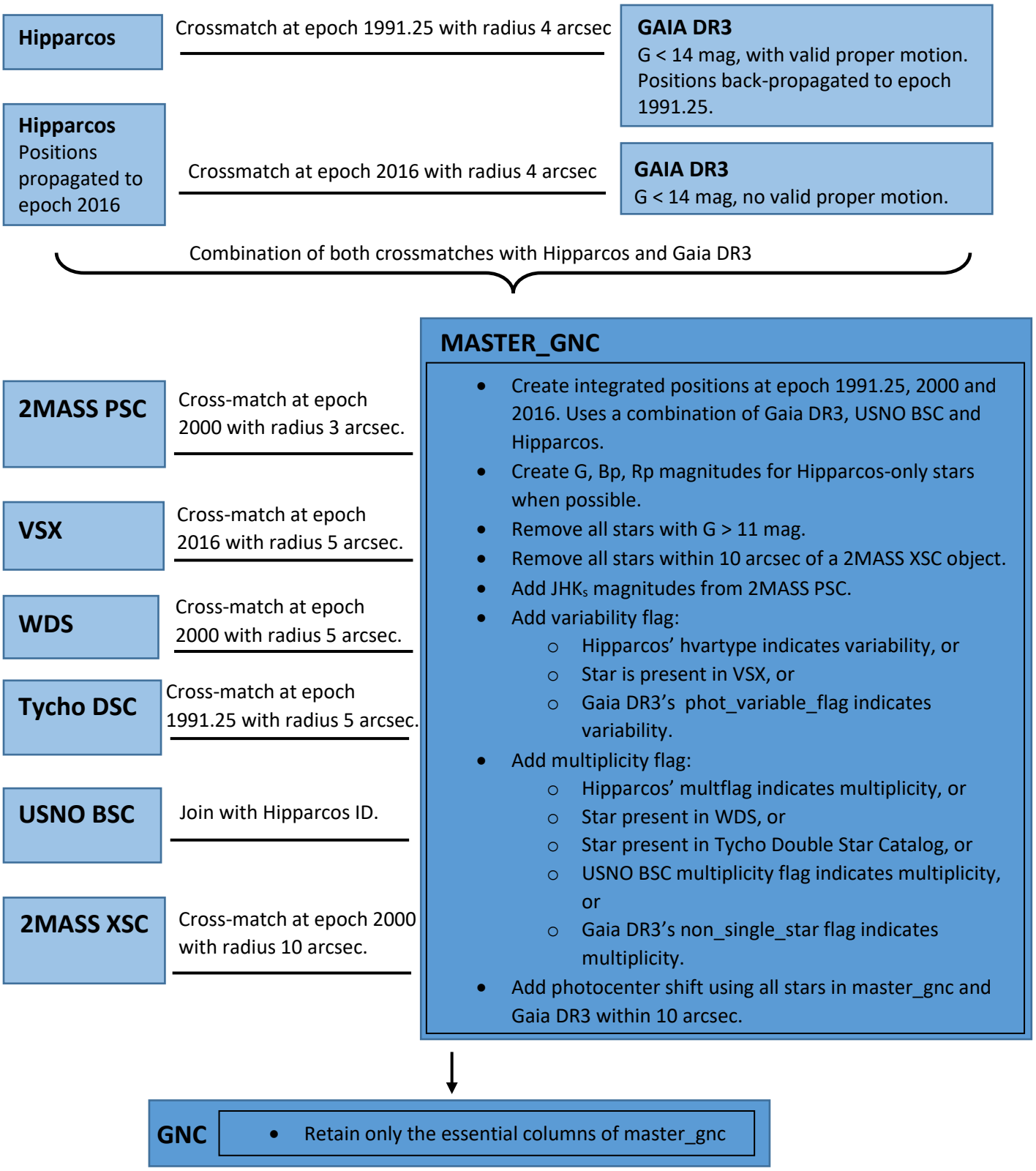
## III. Original data used in the catalog.

The following table lists the original catalogs used to create the GNC. The references for those catalogs are found in the references section. The USNO BSC catalog is a bright star astrometric catalog developed at USNO and based in part on internal astronomical observations.

| **Feature** | **Original source of data** |
|---|---|
| Astrometry | Gaia DR3, Hipparcos, USNO BSC |
| Optical photometry G, Bp, Rp | Gaia DR3, Hipparcos (converted magnitudes) |
| Near-Infrared photometry $JHK_s$ | 2MASS PSC |
| Variability information | VSX (version 2021 02 22), Hipparcos, Gaia DR3 |
| Multiplicity information | Tycho Double Star, Gaia DR3,<br>Washington Double Star (version 14 dec 2020) |

## IV. Construction of the catalog.

### IV.1. Schematic view.



## IV.2. Building the astrometric part using Gaia DR3, Hipparcos and USNO BSC.

### Crossmatch between Hipparcos and Gaia DR3:

A bright subset of the Gaia DR3 catalog was created with a magnitude limit of G < 14 mag. The rationale being that this limited catalog is easier to manipulate than the full Gaia DR3 catalog, while still containing all the Hipparcos counterparts. We thus have three astrometric catalogs to crossmatch and combine:

| | | |
|---|---|---|
| Gaia DR3 with G < 14 mag, with proper motions, called Gaia_PM | 16,844,053 objects | Epoch 2016.<br>Positions were created at epoch 1991.25 and 2000. |
| Gaia DR3 with G < 14 mag, no proper motions available, called Gaia_noPM | 128,089 objects | Epoch 2016. |
| Hipparcos (original catalog) | 117,955 objects | Epoch 1991.25.<br>Positions were created at epoch 2000 and 2016. |

Hipparcos was matched with Gaia_PM at epoch 1991.25, and independently with Gaia_noPM at epoch 2016. Both crossmatches used a 4 arcsec radius. As a result, Hipparcos stars were found to be matched with several Gaia stars, and vice-versa. In those cases, only the closest match was kept, and the other matches were considered to be independent stars. Some Hipparcos stars were matched to both Gaia_PM and Gaia_noPM stars. Again, the closest match was preferred by comparing the distance of the matches at their respective epochs. Leveraging the stellar magnitude information in the crossmatch might be considered in a future version of the catalog.

100 Hipparcos stars could not be matched with Gaia. Most of them were too bright for Gaia (72 have their Hp < 5 mag). The 28 remaining stars, with 5 < Hp < 13.8 were not thoroughly investigated, but these are some possibilities for why they are missing in Gaia:

1. Gaia DR3 might still not be complete for Hp > 5 mag,
2. Point checks showed that some of those Hipparcos stars are located in nebulas, causing problems with the Gaia point-source data processing,
3. The 4 arcsec crossmatch radius was not large enough when matching stars which were propagated with inaccurate proper motion,
4. The Gaia subset, with G < 14 mag, was not faint enough for the faintest Hipparcos stars.

The last step was to integrate in one single table:

1. the crossmatched stars,
2. the 100 Hipparcos stars not matched in Gaia,
3. the Gaia stars not matched with Hipparcos (those were either not matched with Hipparcos, or were matched, but were not the closest counterpart).

The USNO BSC astrometry data was added to the table by using the Hipparcos ID available in the BSC catalog.

## IV.3. Adding additional information to the GNC table

### Adding a synthetic G magnitude to all stars:

A synthetic Gaia magnitude was computed for the 100 Hipparcos stars using the conversion formulas found in Riello et al. (2021). These formulas are (Hp, B-V) → G and (Hp, V-I) → G. The formulas were applied within their valid color range. This color range can be extended for M stars, so the formula was applied for stars that were listed as having a M spectral type from the SIMBAD online database. The formula using the Tycho-2 magnitudes (Bt,Vt) → G was checked for usefulness but did not provide additional information.

16 Hipparcos-only stars were left without synthetic G magnitude, either because they do not have B-V or V-I colors, or because their B-V, V-I are not in the range of the conversion formulas. The brightest of those stars has Hp = 8.8685 mag. Those 16 stars were left out of the GNC catalog.

A cut was then applied, where only the stars with G ≤ 11 mag were kept, giving a total of 1247322 stars, of which 82 are found only in Hipparcos.

### Adding a synthetic Bp, Rp, and $JHK_s$ magnitudes to all stars:

Similarly, the formulas from Riello et al. (2021) were used to provide Gaia's Bp and Rp magnitudes to the 82 Hipparcos-only stars.

To obtain JHK photometry, a crossmatch between GNC and 2MASS PSC is needed. In preparation for this task, positions at epoch 2000 were created by using the astrometry of the parent catalogs and the following hierarchy:

1. Gaia with proper motion (back –propagated from 2016 to 2000).
2. If not available, USNO BSC.
3. If not available, Hipparcos.
4. The remainder of the stars are Gaia stars without proper motion. Their positions at epoch 2000 were assumed to be identical to the positions at the original epoch 2016.

The GNC positions at epoch 2000 were crossmatched with 2MASS PSC with a 3 arcsec radius. When a GNC or 2MASS star had more than one match, a cleaning process was done, in which the closest match was preferred, and the other counterparts were considered to be independent stars. Sanity checks were performed and showed that each GNC and 2MASS stars were unique in that cleaned crossmatch. The JHK magnitudes were then copied to the GNC table by using the crossmatch table. Following the 2MASS documentation, the $JHK_s$ magnitudes with null uncertainties were not considered.

**Note on the propagated positions:**
The positions were propagated following the method of Eichhorn & Rust (1970, Astron.Nachr., Bd 292, H.I). The computation is using rectangular coordinates, and assumes a null radial velocity. The rigorous propagation of the position uncertainties is more complex, and here we used the classic simple formula:

$$\sigma^2_{\delta,t_1} = \sigma^2_{\delta,t_0} + (t_1 - t_0)^2\, \sigma^2_{\mu_\delta} + 2\,(t_1 - t_0)\, \sigma_{\delta,t_0}\, \sigma_{\mu_\delta}\, \rho_{\delta,\mu_\delta}$$

and similarly for the Right Ascension. We used the correlations (last term in the formula above) in order to compute more accurate position uncertainties at epoch 2016. As mentioned above, these covariant parameters are not present in the catalog, but might be added in a future release.

## Adding the variability flag:

A cross-match of the GNC positions at epoch 2016 with the VSX catalog (version 2021_02_22) was performed with a 5 arcsec radius. The GNC positions at epoch 2016 were determined from the following hierarchy:

1. Gaia with or without proper motion.
2. If not available, USNO BSC (propagated from 1991.25 to 2016).
3. If not available, Hipparcos (propagated from 1991.25 to 2016).

Multiple matches were removed based on their distance, until each GNC star has only one VSX counterpart, and vice-versa.

The variability flag has three characters, as follows:

- The first character, "H", indicates if Hipparcos' 'hvartype' is not null and different from 'C'.
- The second character, "V", indicates if the GNC star has a counterpart in the GNC and VSX cross-match.
- The third character, "G", indicates if the Gaia DR3's 'phot_variable_flag' is set to 'VARIABLE'.

Those characters are set to "_" when no variability is detected. This is the count of all the different instances of the variability flag in the GNC:

| flag_var | count |
|---|---|
| ___ | 1102158 |
| _VG | 45226 |
| __G | 44198 |
| _V_ | 31310 |
| H__ | 13212 |
| HV_ | 5094 |
| HVG | 4510 |
| H_G | 1386 |

The flag has 8 different combinations.

## Adding the multiplicity flag:

A cross-match of the GNC positions at epoch 1991.25 with the Tycho Double Star catalog was performed with a 5 arcsec radius. The GNC positions at epoch 1991.25 were determined from the following hierarchy:

1. USNO BSC.
2. If not available, Hipparcos.
3. If not available, Gaia with proper motion (back –propagated from 2016 to 1991.25).
4. The remainder of the stars are Gaia stars without proper motion. Their positions at epoch 1991.25 were assumed to be identical to the positions at the original epoch 2016.

Multiple matches were removed based on their distance, until each GNC star has only one Tycho-DSC counterpart, and vice-versa.

A cross-match of the GNC positions at epoch 2000 with the Washington Double Star catalog (version 14 December 2020) was performed with a 5 arcsec radius. Multiple matches were removed based on their distance, until each GNC star has only one WDS counterpart, and vice-versa.

The multiplicity flag has seven characters, as follows:

- The first character, “H”, indicates if Hipparcos’ ‘mult_flag’ is not null.
- The second character, “U”, indicates if USNO BCS’s multiplicity flag is not null and different from 0.
- The third character, “T”, indicates if the GNC star has a counterpart in the GNC and Tycho-DSC cross-match.
- The fourth character, “W”, indicates if the GNC star has a counterpart in the GNC and WDS cross-match.
- The fifth character, “E”, indicates if the Gaia DR3’s multiplicity flag specifies an eclipsing binary.
- The sixth character, “S”, indicates if the Gaia DR3’s multiplicity flag specifies a spectroscopic binary.
- The seventh character, “A”, indicates if the Gaia DR3’s multiplicity flag specifies an astrometric binary.

Those characters are set to “_” when no multiplicity is detected. This is a partial list counting the different instances of the multiplicity flag in the GNC:

```
flag_mult |  count
-----------+---------
 _______   | 1078778
 _____S_   |   44963
 __TW___   |   28945
 ______A   |   27483
 _____SA   |   19697
 ___W___   |   15925
 __T____   |    8739
 H_TW___   |    7532
 H______   |    3236
 H_T____   |    2467
 H__W___   |    2023
Etc…
```

The flag has 65 different combinations.

## Removal of extended objects:

The GNC was crossmatched with the 2MASS Extended Object Catalog (XSC) using positions at epoch 2000 in order to remove problematic stars, like nebulae, which could cause astrometric and photometric calibration issues. A crossmatch radius of 10 arcsec was used, and 228 stars were removed from the GNC catalog.

## Closest neighbor:

The GNC was crossmatched with itself using its positions at epoch 2016, and a 1 degree radius. The GNC ID of the closest neighbor was noted for each star, as well as its angular separation. A sanity check showed that the cross-match radius was large enough to find the closest neighbor for every star.

## Photocenter shift:

Because the GNC is a star catalog aimed at projects using star trackers, we consider that the PSF of the instruments used are large, and we compute the photocenter shift for every star in the catalog caused by all its companions located at a maximum separation of 10 arcsec. In case there are multiple companions located within that range, only the maximum photocenter shift is considered.
Note that considering only the largest photocenter shift is a technical simplification. We expect that computing the average photocenter shift based on all neighbors will only produce a small difference, because a non-negligible shift can only be caused by a bright companion, and a given star has very rarely more than one bright neighbor. This might be taken into account in a future version of the catalog.
For a given star with Gaia magnitude G and its companion with magnitude $G_c$, the photocenter shift is computed as the center of mass of the fluxes of the two stars:

$$\text{Photocenter shift} = \text{Distance between the stars} \times \frac{10^{-0.4\,G_C}}{10^{-0.4\,G} + 10^{-0.4\,G_C}}$$

A first computation is done with all the companions located in the GNC catalog and within 10 arcsec. Those companions thus range from the brightest star in Hipparcos to stars with G=12. As a second step, a similar computation is done by considering all the companions present in Gaia DR3 and within 10 arcsec. This misses the companions too bright to be in Gaia (but those were found during the first step) and takes care of the companions down to the faint limit of Gaia DR3.

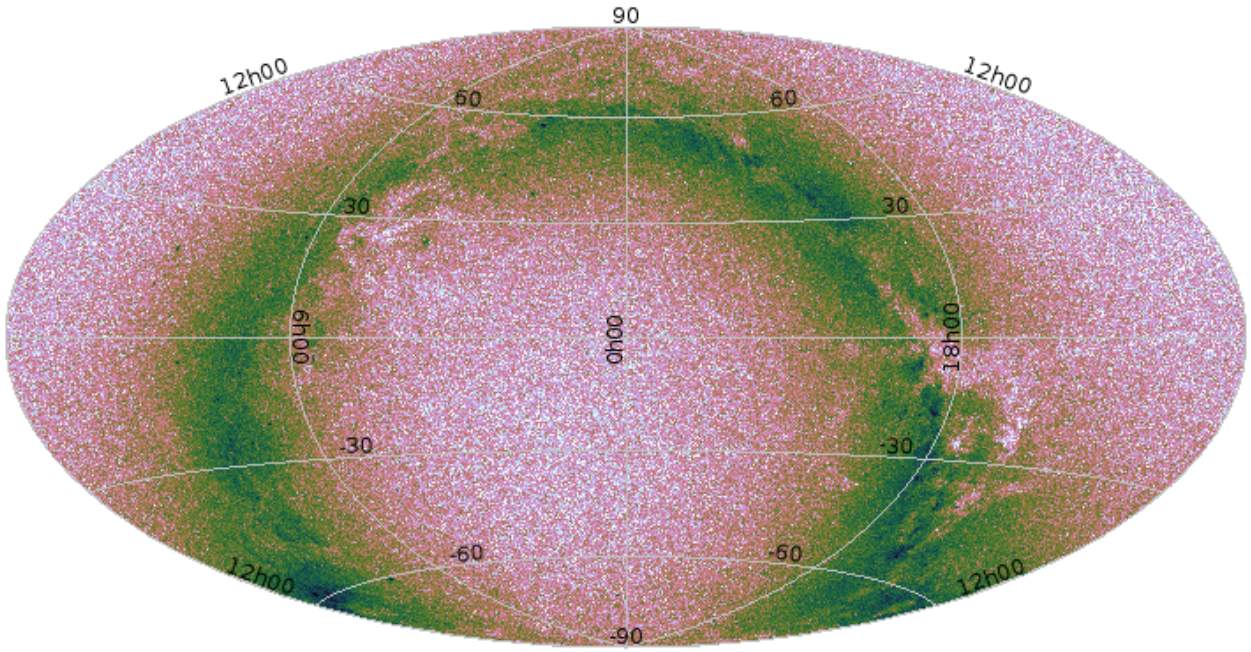
## Additional flags:

The Photocenter shift flag, Position uncertainty flag, Proper motion uncertainty flag and Closest neighbor flag are all marked with an ‘x’ in the catalog. The default value is null (no value).

No stars were found to have a parallax uncertainty greater than 100 mas; the corresponding required flag is thus not included in the catalog.

## V. Aitoff projection of the GNC catalog.

The map is in equatorial coordinates. All the stars in the catalog are indicated as individual dots. For regions of large density, the dots overlap and the color code represents the stellar density.



## VI. Statistics of the catalog fields.

The catalog has 1,247,094 entries. A few fields in the following table are omitted due to their limited interest.

| *Field* | *Minimum value* | *Median value* | *Maximum value* | *Number of null values* | *Format* |
|---|---|---|---|---|---|
| ***IDs*** | | | | | |
| GNC ID | 1 | | 1247094 | 0 | Integer |
| Hipparcos ID | 1 | | 120404 | 1,130,749 | Integer |
| Gaia DR3 ID | 7632157690368 | | 6917521541514092416 | 82 | Integer |
| ***Astrometry at epoch 2016*** | | | | | |
| RA, epoch 2016 [deg] | 0.0004348245428307492 | 195.73580382955254 | 359.99983250078253 | 0 | Binary64 |
| Dec, epoch 2016 [deg] | -89.88970656431687 | -5.615933937599731 | 89.83234830529616 | 0 | Binary64 |
| Uncertainty of RA, epoch 2016 [mas] | 0.0039426945 | 0.014 | 4904.5723 | 0 | Binary32 |
| Uncertainty of Dec, epoch 2016 [mas] | 0.004813559 | 0.012 | 2430.3206 | 0 | Binary32 |
| PM_RA*cos(Dec) [mas/yr] | -4406.469 | -1.59 | 6765.995 | 8,945 | Binary32 |
| PM Dec [mas/yr] | -5817.8003 | -3.32 | 10362.395 | 8,945 | Binary32 |
| Uncertainty of PM_RA*cos(Dec) [mas/yr] | 0.0044725607 | 0.018 | 199.55 | 8,945 | Binary32 |
| Uncertainty of PM_Dec [mas/yr] | 0.0057531884 | 0.016 | 98.13 | 8,945 | Binary32 |
| Parallax [mas] | -16.55 | 1.72 | 768.0665 | 8,945 | Binary32 |
| Uncertainty of parallax [mas] | 0.0071899574 | 0.017 | 3.56 | 8,945 | Binary32 |
| Catalog providing the astrometry at epoch 2016 | GAIADR3: 1,247,012<br>HIPPARCOS: 68<br>USNO BSC: 14 | | | 0 | Text |
| ***Photometry*** | | | | | |
| G magnitude [mag] | -1.1151785 | 10.26 | 10.999999 | 0 | Binary32 |
| Uncertainty of G magnitude [mag] | 0.00012689612 | 0.00052 | 0.362092 | 0 | Binary32 |
| Bp magnitude [mag] | -1.1167357 | 10.74 | 16.982798 | 933 | Binary32 |
| Uncertainty of Bp magnitude [mag] | 6.583969e-08 | 0.0012 | 2.9270496 | 933 | Binary32 |
| Rp magnitude [mag] | -1.7406223 | 9.59 | 11.196614 | 926 | Binary32 |
| Uncertainty of Rp magnitude [mag] | 5.9853232e-06 | 0.00080 | 3.206757 | 926 | Binary32 |
| J magnitude [mag] | -2.989 | 8.72 | 12.085 | 13,229 | Binary32 |

| | | | | | |
|---|---|---|---|---|---|
| Uncertainty of J magnitude [mag] | 0.013 | 0.023 | 9.998 | 13,229 | Binary32 |
| H magnitude [mag] | -4.007 | 8.26 | 11.926 | 13,229 | Binary32 |
| Uncertainty of H magnitude [mag] | 0.013 | 0.028 | 9.998 | 13,229 | Binary32 |
| K magnitude [mag] | -4.378 | 8.15 | 11.771 | 13,229 | Binary32 |
| Uncertainty of K magnitude [mag] | 0.011 | 0.020 | 9.998 | 13,229 | Binary32 |
| ***Additional information*** | | | | | |
| Variability flag | Flag is indicating variability: 144,936<br>Flag is not indicating variability: 1,102,158 | | | 0 | Text |
| Multiplicity flag | Flag is indicating multiplicity: 168,316<br>Flag is not indicating multiplicity: 1,078,778 | | | 0 | Text |
| Closest neighbor ID | 1 | | 1247094 | 0 | Integer |
| Distance to closest neighbor [arcsec] | 0.18117699 | 264.11 | 2077.6003 | 0 | Binary32 |
| Photocenter shift [arcsec] | 4.813232e-06 | 0.0051 | 9.8153715 | 550,242 (696,852 are non-null) | Binary32 |
| Photocenter shift flag | 123,097 stars have a photocenter shift > 50 mas | | | 1,123,997 | Text |
| Position uncertainty flag | 10 stars have a position uncertainty in either coordinates > 100 mas | | | 1,247,084 | Text |
| Proper motion uncertainty flag | 27 stars have a proper motion uncertainty in either coordinates > 10 mas/yr | | | 1,247,067 | Text |
| Closest neighbor flag | 18,522 have a GNC neighbor closer than 4.6 arcsec | | | 1,228,572 | Text |

## VII. Important note concerning the propagation of the position uncertainty to future epochs.

The epoch of the GNC catalog is 2016. The position uncertainties at epoch 2016 ($\sigma_{\alpha^*_{2016}}$ and $\sigma_{\delta_{2016}}$) and the proper motion uncertainties ($\sigma_{\mu_{\alpha^*}}$ and $\sigma_{\mu_\delta}$) are given in the catalog.
The usual method for the computation of the position uncertainty of a star at a future epoch (denoted *t*) is to use the linear formulas

$$\sigma_{\alpha^*_t} = [\sigma^2_{\alpha^*_{2016}} + \sigma^2_{\mu_{\alpha^*}} (t - 2016)^2 ]^{1/2} \quad (1)$$

$$\sigma_{\delta_t} = [\sigma^2_{\delta_{2016}} + \sigma^2_{\mu_\delta} (t - 2016)^2 ]^{1/2} \quad (2)$$

These formulas are correct for the majority of the stars in the GNC catalog. The original catalog of those stars is Gaia DR3 (found with the condition `cat_2016 = 'GAIADR3'`) with original epoch 2016. On the other hand, 82 stars in the GNC catalog have their astrometry taken from the Hipparcos and USNO BSC catalogs; the original epoch of both of these catalogs is 1991.25. For those stars (easily found with the condition `cat_2016 != 'GAIADR3'`), the correct formulas for the propagation of the position uncertainty are slightly different:

$$\sigma_{\alpha^*_t} = \left\{\sigma^2_{\alpha^*_{2016}} + \sigma^2_{\mu_{\alpha^*}} [(t - 1991.25)^2 - (2016 - 1991.25)^2]\right\}^{1/2} \quad (3)$$

$$\sigma_{\delta_t} = \left\{\sigma^2_{\delta_{2016}} + \sigma^2_{\mu_\delta} [(t - 1991.25)^2 - (2016 - 1991.25)^2]\right\}^{1/2} \quad (4)$$

Using formulas (1-2) for the Hipparcos and USNO BSC stars would underestimate the true values by as much as 50% to 100%.

## VII. References.


Gaia DR3: see Brown, Anthony GA, et al. "Gaia Early Data Release 3-Summary of the contents and survey properties." *Astronomy & Astrophysics* 649 (2021): A1.
The catalog is available online at https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=I/355

Hipparcos: see Perryman, M. A. C., et al. "The HIPPARCOS Catalogue." *Astronomy and Astrophysics* 323 (1997): L49-L52.
The catalog is available online at https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/239

USNO Bright Star Catalog (BSC): see Zacharias et al. "USNO Bright Star Catalog, Version 1." *The Astronomical Journal* 164.2 (2022): 36.
The catalog is available online at https://crf.usno.navy.mil/icrs
And http://vizier.cds.unistra.fr/viz-bin/VizieR?-source=J/AJ/164/36

2MASS Point Source Catalog (PSC) and Extended Source Catalog (XSC): see Skrutskie, M. F., et al. "The two micron all sky survey (2MASS)." *The Astronomical Journal* 131.2 (2006): 1163.
The catalog is available online at https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=II/246

Tycho Double Star Catalog (Tycho-DSC): see Fabricius, Claus, et al. "The Tycho double star catalogue." *Astronomy & Astrophysics* 384.1 (2002): 180-189.
The catalog is available online at https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=I/276

Washington Double Star Catalog (WDS): see Mason, Brian D., et al. "The 2001 US naval observatory double star CD-ROM. I. The Washington double star catalog." *The Astronomical Journal* 122.6 (2001): 3466.
The catalog is available online at https://crf.usno.navy.mil/data-products
And https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=B/wds

VSX Catalog: see Watson, C., A. A. Henden, and A. Price. "VizieR Online Data Catalog: AAVSO International Variable Star Index VSX (Watson+, 2006-2014)." *VizieR Online Data Catalog* (2016): B-vsx.
The catalog is available online at https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=B/vsx

Riello, Marco, et al. "Gaia Early Data Release 3-Photometric content and validation." *Astronomy & Astrophysics* 649 (2021): A3.

## VIII. Contacts.

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