

## Besançon Galaxy Model Simulation for CU9-WP943 (BGMBTG 2.0) I. First steps comparing Tycho-2 and Model.

| prepared by: | R. Mor, A. C. Robin, F.Figueras, E. Antiche, C. |
|--------------|---|
|              | Fabricius, M. Romero-Gómez                      |
| approved by: | F. Arenou                                       |
| reference:   | GAIA-C9-TN-UB-RMC-001-1                         |
| issue:       | 1   |
| revision:    | 6   |
| date:        | 2015-05-11                                      |
| status:      | Issued  |



## Abstract

This technical note describes the process followed to generate the catalogues BGMBTG 2.08 and 2.012 to be used in the CU9-WP943 to validate Gaia data. For that, the Czekaj et al. (2014) version of the Besançon Galaxy Model (BGM) has been used. These samples are limited in apparent G magnitude up to G=13 and contain both single stars and multiple systems. The simulated catalogues include true (not affected by errors) astrometric and photometric data as well as "observable" data obtained assuming that stars are affected by Tycho errors (Høg et al. (2000)), TGAS errors (Michalik et al. (2015)), and 6 month Gaia data errors (following the recipes published in September 2014 Gaia performance web). A first comparison between model and Tycho-2 data up to V=11 is presented and discussed. Star counts maps show a general good agreement but in the Galactic plane, where Marshall's extinction seems not adequate for short distances (1-2 kpc). Proper motions map reflect a shift probably due to the adopted solar motion and mean motion of the LSR. Work is in progress to diminish these discrepancies.



| Issue | Revision | Date       | Author | Comment   |
|-------|----------|------------|--------|---|
| 0     | 6        | 2015-04-08 | RMC    | Corrections from Annie Robin and redistribution of  |
|       |          |            |        | plots   |
| 0     | 5        | 2015-03-23 | RMC    | Corrections and minor changes                       |
| 0     | 4        | 2015-03-09 | RMC    | Corrections from Annie Robin, Claus Fabricius,      |
|       |          |            |        | Francesca Figueras, Erika Antiche and Merce Romero- |
|       |          |            |        | Gómez are added                                     |
| 0     | 3        | 2015-02-26 | RMC    | Add changes in Gaia Errors sections and some minors |
| 0     | 2        | 2015-02-16 | RMC    | First Draft   |
| 0     | 1        | 2015-01-26 | RMC    | Creation  |

## **Document History**

## Contents

| 1 | Intro                         | oduction  | 5  |  |
|---|-------------------------------|---|----|--|
| 2 | The BGM catalogues up to G=13 |   |    |  |
|   | 2.1                           | Main ingredients description  | 5  |  |
|   | 2.2                           | Computation of Tycho and Gaia photometry  | 6  |  |
|   | 2.3                           | Statistics  | 6  |  |
| 3 | The                           | generation of "observed" Tycho, TGAS, and Gaia mock catalogues.                                   | 9  |  |
|   | 3.1                           | Strategy for the generation of the "observed" parameters  | 9  |  |
|   |                               | 3.1.1 Astrometric and photometric errors  | 9  |  |
|   |                               | 3.1.2 Binary treatment according to the catalogue angular resolution                              | 10 |  |
|   | 3.2                           | Healpix and GAT tools for catalogue comparison  | 10 |  |
|   | 3.3                           | First statistics comparing simulated "true" with Tycho, TGAS and Gaia simulated "observed" values | 11 |  |



| 4 | Firs | t compar | ison of model and real Tycho-2 data                             | 12 |
|---|------|----------|---|----|
|   | 4.1  | Star Co  | ants  | 12 |
|   | 4.2  | Proper I | Motions   | 17 |
|   |      | 4.2.1    | Sky distribution of $\mu_{\alpha^*}$                            | 17 |
|   |      | 4.2.2    | Sky distribution of $\mu_{\delta}$                              | 21 |
| 5 | Con  | clusions | and next steps  | 23 |
| 6 | Ann  | exes     |   | 25 |
|   | 6.1  | Comput   | ation of proper motion accuracy for a mission length L $\ldots$ | 25 |
|   | 6.2  | Referen  | ces   | 26 |
|   | 6.3  | Acrony   | ns  | 27 |
|   | 6.4  | BGMB     | ΓG catalogue format   | 27 |



## 1 Introduction

Tests are being designed to validate Gaia data. For that work GOG and other BGM versions are needed. For this reason we build the catalogues BGMBTG 2.08 and 2.012, which are simulated with the Besançon Galaxy Model (Robin et al. (2003)) including a revision of the generation of the simulated binaries and single stars (Czekaj et al. (2014)). This catalogue contains the simulated stars up to magnitude G = 13.

Furthermore, the Tycho Gaia Astrometric Solution (Michalik et al. (2015)) is expected to be available in the coming months.

## 2 The BGM catalogues up to G=13

### 2.1 Main ingredients description

The catalogue has been generated using the new version of the Besançon Galaxy Model described in Czekaj et al. (2014). An important change when comparing to GUMS is a new star production philosophy for the thin disk populations. This new method allows us to turn the IMF, SFR and evolutionary tracks into free user specified parameters. Different ingredients have been evaluated looking for the best fit to Tycho data, Czekaj et al. (2014). The physical ingredients to generate BGMBTG 2.08 and 2.012 - IMF, SFH, evolutionary and atmosphere models, ... are those of Model B (see table 5 form Czekaj et al. (2014)).

In the mock catalogues presented here we include the generation of binary systems. For that we have followed the recipes outlined in Arenou (2011) and we have kept the constraints on the final volume mass density in the solar neighbourhood imposed by the luminosity function. Systems are combined depending on the spatial angular resolution that we want to impose to the generated catalogue to mimic the observed one (see Section 3.1.2).

Both Drimmel & Spergel (2001) and Marshall et al. (2006) extinction models are considered here. Marshall et al. (2006) covers the region  $-100 \le l \le 100$  deg and -10 < b < 10 deg, whereas the Drimmel & Spergel (2001) is used in other regions. Note that in the generation of GUMS catalogue only Drimmel and Spergel (2001) model is considered.

The Fortran code used for this simulation has been adapted to generate the Gaia photometry (see Sect. 2.2). This has allowed us to generate a sample limited in Gaia apparent magnitude (G). First we have to fix the spatial resolution of the catalogue to decide if the components of a binary systems will be observed separately or as a combined system. The two mock catalogues presented here are:



- BGMBTG 2.08: with an angular separation of 0.8 arcsec imposed to mimic the Tycho-2 data (Høg et al. (2000)). Notice that in "Tycho Double Star Catalogue" (Fabricius et al. (2002)) they report some double stars with a separation of 0.3 arcsec.
- BGMBTG 2.012: with an angular separation of 0.120 arcsec imposed to mimic the Gaia data. As the Sky-mapper works with a binning of two pixels, the angular separation is assumed to be of about 2 pixels along scan. We expect a much better resolution at the end-of-mission. A more complex strategy taking into account the magnitude difference between both components and the Gaia photometric errors (depending on the components magnitude) can be implemented in future versions.

During the process we have to generate the full set of stars up G=13.8 to ensure to have a final sample of single stars and combined systems complete up to G=13.

### 2.2 Computation of Tycho and Gaia photometry

Gaia photometry is assigned to each star using the polynomial fit proposed in table 3 Jordi et al. (2010). The G is computed for each star using the intrinsic (V-I) following Jordi et al. (2010).

 $G - V = -0.0257 - 0.0924 \cdot (V - I) - 0.1623 \cdot (V - I)^2 + 0.0090 \cdot (V - I)^2$  After that the extinction is added using the differential extinction of Cardelli. For the case of unresolved binary systems G magnitude is computed for each component and combined after the merge.

For the Gaia colour index we used the following expression:

$$G_{BP} - G_{RP} = -0.0660 + 1.2061 \cdot (V - I) - 0.0614 \cdot (V - I)^2 + 0.0041 \cdot (V - I)^3$$

For the case of unresolved binary systems first the (V-I) is computed for each star and after the system merging  $G_{BP} - G_{RP}$  is computed using the expression above.

The Tycho photometric values, as discussed in Czekaj (2013) (PhD Thesis), are computed from the Johnson (B-V) and V generated values through interpolation using in Table 3.4 from ESA (1997).

### 2.3 Statistics

Table 2 provides a first statistics of the BGMBTG 2.08 and BGMBTG 2.012.

Notice that the number of resolved system goes from 15% to 30% when improving the resolution, but as can be seen the total number of stars is just increasing a bit with the better resolution of 120 mas. This behaviour responds to two main things:





FIGURE 1: Sky density map. BGMBTG 2.08. We just plot the BGMBTG 2.08 because the effect of the angular resolution selection is not significant for this map.

- The angular separation generated using Arenou's recipes keeps most of the systems with an angular separation below 0.120 arcsec (TBD).
- Just about 9% of the secondaries are going to have  $G \leq G_{lim}$ .
- For the unresolved binary systems which are in the border with G=13, increasing the resolution may cause the lost of the full system. Once the stars are resolved the total flux is smaller, the magnitude goes above 13 and the star is not detected.

Most of the systems have a larger separation than 0.8 arcsec. The choice of the resolution (0.120 arcsec rather than 0.8) does not impact much the number of stars observed at  $G \le 12$ . When improving the resolution, some systems are lost because one of the two components is close to the limiting magnitude. On the other hand the gain of secondaries is rather small. So the increase of number of stars is going to be just about 0.15%.

Figure 2 shows the mean (Bt-Vt) colour index sky distribution for the BGMBTG 2.08 and the Tycho catalogues. Although the total number of objects differs by less than 5% we can clearly see some discrepancies in the mean colours in some areas of the galactic plane and at galactic latitudes between  $10 \le |b| \le 30$  deg (see alsoCzekaj et al. (2014)).



|  | BGMBTG 2.08 |              | <b>BGMBTG 2.012</b> |
|--|-------------|--------------|---------------------|
|  | $G \le 13$  | $V_T \le 11$ | $G \le 13$          |
| Number of Stars                                    | 7380403     | 899087       | 7392570             |
| % Single Stars                                     | 49 %        | 42 %         | 49 %                |
| % Unresolved Systems                               | 43 %        | 46 %         | 35 %                |
| % Primary components of a resolved binary system   | 7 %         | 11%          | 15 %                |
| % Secondary components of a resolved binary system | 1 %         | 1%           | 1 %                 |
| Total Number of Binary systems                     | 3714602     | 510337       | 3676773             |
| % Unresolved binary systems                        | 85 %        | 81 %         | 70 %                |
| % Resolved Binary systems                          | 15 %        | 19 %         | 30 %                |
| % Primary components of a resolved binary system   | 91 %        | 92 %         | 91 %                |
| % Secondary components of a resolved binary system | 9 %         | 8 %          | 9 %                 |

TABLE 2: Proportions of stars in each disc subcomponent in case of decreasing SFR.



FIGURE 2: Mean  $(B_T - V_T)$  colour index in Equatorial Coordinates,  $V_t \le 11$ . Top: for the BGMBTG 2.08 catalogue. Bottom: for the Tycho 2 catalogue

# **3** The generation of "observed" Tycho, TGAS, and Gaia mock catalogues.

### 3.1 Strategy for the generation of the "observed" parameters

### 3.1.1 Astrometric and photometric errors

We added errors depending on which catalogues/releases the simulated catalogue is going to be compared. For each of the two BGMBTG catalogues we provide additional columns for the observed astrometric and photometric parameters resulting when considering three different cases depending if we want to compare our model data to: (1) real data coming from Tycho-2, (2) from TGAS experiment and (3) from six months Gaia data. If necessary, we can easily compute Gaia observables for a larger fraction of mission.

To simulate Tycho-2 astrometric data we assume the errors in the parameters (position and proper motions) depend on the  $V_T$  apparent magnitude of the star. Errors are assigned following table 2 of Høg et al. (2000). Errors are assigned randomly assuming Gaussian distribution with a standard deviation equal to the uncertainties in astrometry indicated in the mentioned table. The same standard deviation has been assumed for proper motion in both, right ascension and declination. To simulate TGAS astrometric data we proceed in the same way but using values provided by Michalik et al. (2015) (table 1). We notice in this last case that we are able to assign errors to parallax, so observed parallaxes are provided in TGAS simulated catalogue. For the Tycho-2 photometry we used the strategy described in Czekaj et al. (2014). Note that we are assuming no new photometry is provided with the TGAS experiment.

**To simulate 6 month Gaia astrometric and photometric data** we followed the Gaia Science performance web page. The code to add Gaia errors is an update of the code from M. Romero-Gómez and JM. Carrasco<sup>1</sup>. Codes provided in this webpage compute the Gaia errors estimated after commissioning for the end of the mission data (total length of 5 years mission is assumed). To simulate 6 months Gaia mission data we need to add the corresponding factors (see annex 1):

- For the parallax the factor is  $\sqrt{\frac{5}{L}}$ , being L the mission length in years (0.5 in our case when we want to generate 6 month Gaia data).
- For the proper motions we have:

$$\sigma_{\mu}^{(L)} = \frac{5}{L} \cdot g_{ratio} \cdot \sigma_{\pi}^{(L)} = \left(\frac{5}{L}\right)^{3/2} \cdot g_{ratio} \cdot \sigma_{\pi}^{(5)} \tag{1}$$

<sup>&</sup>lt;sup>1</sup>(https://github.com/mromerog/Gaia-errors)



with  $g_{ratio}$  the values indicated in table 6 of the Gaia Science Performance webpage.

It is important to keep in mind that the errors computed using this strategy would probably be underestimated. This is because they are computed assuming that the instruments are going to be perfectly calibrated at time L (e.g. 6 months of mission). In reality the instruments will be not perfectly calibrated until the end of the mission. The effect of this lack of accuracy in the instrument calibration is not included in our simulations and, as a consequence, the errors that we provide for the case of 6 months Gaia data are underestimated. In fact, we have to consider this case only as an exercise and not as a realistic case. As known, the Astrometric Global Iterative Solution (AGIS) is not able to get a 5 parameter solution when considering only the first 6 month of mission data.

### **3.1.2** Binary treatment according to the catalogue angular resolution

For each generated binary system we decide if it will be or not resolved by the instrument assuming a given angular resolution of the catalogue. In this case we used an angular resolution of 0.8" for BGMBTG 2.08 trying to mimic the angular resolution of the Tycho 2 catalogue, and an angular resolution of 0.120" (2 Gaia pixels) for BGMBTG 2.012

### **3.2** Healpix and GAT tools for catalogue comparison

HEALPix is an acronym for Hierarchical Equal Area isoLatitude Pixelation of a sphere. This pixelation produces a subdivision of a spherical surface in which each pixel covers the same surface area as every other pixel.

HEALPix satisfies the following three essential properties:

- The sphere is hierarchically tessellated into curvilinear quadrilaterals. The lowest resolution partition is comprised of 12 base pixels. Resolution of the tessellation increases by division of each pixel into four new ones.
- Areas of all pixels at a given resolution are identical.
- Pixels are distributed on lines of constant latitude, being latitude the angular coordinate from a fixed plane. In our case the healpix have been always calculated using equatorial coordinates. This property is essential for all harmonic analysis applications involving spherical harmonics.

Healpix allows the following (and more):

• Spherical Harmonics Transforms.



- Pixel manipulation.
- Visualization.

For python there are at least the following tools implemented:

- pixelisation manipulation
- spherical harmonic transforms
- plotting capabilities
- reading and writing of Healpix FITS maps.

In the present report we have used two different pixel size. In some of the density maps the healpix index has been set to n = 6 which corresponds to a pixel area of 0.8393 square degrees. For other maps the healpix index has been set to n = 4 which corresponds to a pixel area of 13.4287 square degrees.

GAT (Gaia Analysis Tool, ELA-008), is a complete set of tools which allow us to do automatic statistic analysis of large amount of data. We compute the means and counts for each pixel. With this information computed with GAT we constructed most of the plots and analysis of this document.

## **3.3** First statistics comparing simulated "true" with Tycho, TGAS and Gaia simulated "observed" values

In figure 3 we plotted the parallax distribution of the catalogue BGMBTG 2.08, for the "true" values, values with TGAS errors and values with 6 month Gaia Data. We just plot the BGMBTG 2.08 because the effect of the different angular resolution considered in BGMBTG 2.012 is not significant for these histograms.

Notice how, as it is expected, the introduction of the errors generates some negative parallaxes:

- Assuming TGAS errors, all the stars up to  $G \leq 13$ : we get 84% positive parallaxes
- Assuming TGAS errors, for the stars up to  $V_T <= 11$ : we get 96% positive parallaxes.





FIGURE 3: Parallax distribution of the BGMBTG 2.08 catalogue (units:mas)  $G \le 13$ 

Note that the errors assigned to the parallax when considering six month of Gaia data are very small producing a negligible number of stars with negative parallax. This is due to the fact that, although multiplying the errors by the factor  $\sqrt{\frac{5}{L}}$  (see Sect. 3.1.1) the resulting errors for very bright stars are at the level of few tenths of microarseconds.

In figures 4 and 5 the distribution of  $\mu_{\alpha^*}$  and  $\mu_{\delta}$  are plotted for the BGMBTG 2.08 catalogue. Comparing true values, values with TGAS errors, values with 6 month of Gaia Data errors and values with Tycho 2 errors.

The observed asymmetry in figure 5 is real and reflex the solar motion in first order approximation. It is also present in the real and simulated Tycho data catalogue at  $V_T \leq 11$ 

### 4 First comparison of model and real Tycho-2 data

### 4.1 Star Counts

To compare our simulations with Tycho-2 catalogue we selected the mock catalogue with angular resolution =0.8 arcsec. We cut both, Tycho-2 and the simulations considering only stars up to  $V_T \leq 11$ . As discussed in Høg et al. (2000), Tycho-2 is 99% complete up to this magnitude.





FIGURE 4: Distribution in proper motions in right ascension  $\mu_{\alpha^*}$ . BGMBTG 2.08. (units:mas/yr)

See table 2 for the total number of objects and some statistics regarding binary systems.

There are significant differences in star densities in some regions of the sky. We wonder in which regions of the Sky the difference between BGMBTG 2.08 and Tycho 2 are small enough to be confident on use the BGMBTG 2.08 catalogue to validate, for example TGAS (TBC), or future Gaia releases.

Looking at figure 6, left side, the number of stars per pixel area in the galactic plane goes from 50-200 (60-250 stars per square degree) while when going away from plane we have at most 10 stars per pixel area (12 stars per square degree). That means that the statistical significance away from the galactic plane is poor.

The two main difference in densities are located between l=0 to l=30 and around l=180 (Orion Region). These differences are big enough to think that most of the contribution of these differences comes from the interstellar absorption. In figure 7 we can see the region where Marshall et al. (2006) 3D map extinction is applied (inside rectangle) and the region where the Drimmel & Spergel (2001) 3D extinction map is used (outside rectangle). Whereas Drimmels model is not expected to reproduce the local irregularities (the model without rescaling factors is used





FIGURE 5: Distribution of proper motions in declination $\mu_{\delta}$ . BGMBTG 2.08. (units:mas/yr)



FIGURE 6: Star counts maps in galactic coordinates indicating the logarithm of number of stars per pixel area. The pixel area is 0,8393 square degree. The legend is Logarithm of number of stars per pixel area Left: Tycho 2 catalogue up to magnitude  $V_T = 11$  Right: BGMBTG 2.08 simulated catalogue up to magnitude  $V_T = 11$ 

in BGM) it is expected that Marshall et al. (2006) yes. We have checked that the local irregularities observed in the Tycho-2 star counts map (figure 7) are approximately observed in the total integrated absorption presented in Marshalls map (Marshall et al. (2006)) nonetheless the simulated stars in this regions are not properly absorbed (comparing with Tycho-2). A possible





FIGURE 7: Star counts maps in galactic coordinates indicating the logarithm of stars per pixel area . The pixel area is 0,8393 square degree. The legend is Logarithm of number of stars per pixel area Left: Tycho 2 catalogue up to magnitude  $V_T = 11$  Right: BGMBTG 2.08 simulated catalogue up to magnitude  $V_T = 11$  The black rectangle delimits the region where we used Marshall et al. (2006) extinction. For all the other regions Drimmel & Spergel (2001) extinction is used.

explanation is that the interstellar clouds along the line of sight presented in the model are not well distributed (matter of distance). The problem would probably come from the fact that the Marshall's method is not adequate for short distances (1-2 kpc) and this is exactly where the Tycho stars are in majority. The 3D extinction map for short densities is going to be improved.

In figure 8 we can observe where the biggest differences are found. Notice that the strange curvature behaviour that can be seen in the galactic plane in galactic coordinates is due to the fact that the star counts are computed using healpix in equatorial coordinates. The steps followed were:

- Compute the star counts per pixel area using healpix in equatorial coordinates.
- Plot it using python healpix package
- Using python healpix package plot in different coordinates.

To avoid this visual curvature effect we can repeat the process computing the star counts with healpix for ecliptic and galactic coordinates. For the moment, to save time, we just plot it using python in order to give an idea. This effect is not as relevant when the pixel size is smaller. This effect is present in all the Healpix plots of this document in galactic coordinates.

In figure 8 we plot the relative differences in the sense of model minus Tycho-2 real data. We observe that there are regions near the galactic centre, at about l = -20 deg and other near the Orion regions, at l=200 deg, where the relative differences are larger than 80%. Also near the Sco-Cen star forming area at about (1,b)=(330, 20) some pixel areas have relative error in





FIGURE 8: The relative difference in the density of stars per pixel, between model and Tycho data. The pixel area is 13.4287 square degrees. We computed  $\left(\frac{N_{BGMBTG}-N_{Tycho2}}{N_{Tycho2}}\right)$  for pixel area. The legend indicates  $\frac{\Delta N}{N}$  values. Positive numbers indicates the simulations are overestimating the density. **Top:** Galactic Coordinates **bottom:** Equatorial coordinates.

counts of about 80 %. Again we think these differences are due to both, the peculiar interstellar absorption in this region and the number of stars in this star forming areas. In conclusion, these regions shall be avoided when validating Gaia (or TGAS) data. At higher latitudes, the level of Poisson noise is more significant, such that larger pixel sizes have to be considered to establish the level of reliability of the model in star density.

Figure 9 shows the star count density maps of our simulated catalogues up to Vt=11 but adding, in these cases, information of the regions where the absolute discrepancy in counts is less than  $3\sigma$  of the Poisson noise in each pixel area. These areas could be candidates to be used for TGAS data validation (probably with bigger pixel size we can select larger regions).

It is important to take into account for figure 9 (top) that the star density is low per pixel area, and the Poisson noise is larger. In this case it is better to use larger pixel size and in the comparison between model and data.





FIGURE 9: Star Counts density maps in galactic coordinates. The pixel area is 0.83 square degrees for top figures and 13.42 for bottom figures. All catalogues were cut at magnitude  $V_T = 11$ . **Top left**: Star count density map of Tycho 2. **Top right**:Star count density map (Tycho 2) of the regions of the Sky where the absolute differences between Tycho and our simulations are less than  $3\sigma$  of the Poisson noise per pixel area. The regions with differences larger than  $3\sigma$  are not plotted, so they are white areas in the figure. **Bottom left**: Star count density map of Tycho 2. **Bottom right**:Same as top right but with the pixel area= 13.42 square degrees. **In legend: logarithm of the number of stars per pixel area.** 

### 4.2 **Proper Motions**

Here we present the Healpix maps showing the distribution on the sky of the proper motions  $\mu_{\alpha^*}$  and  $\mu_{\delta}$ . The pixel area for all the following maps is set to 13.42 square degrees. It is important to point out that to extract robust conclusions about the proper motion map we need to study different proper motion projections (work in progress).

### **4.2.1** Sky distribution of $\mu_{\alpha^*}$

In figures 10 (top and midle) we present the mean proper motion in right ascension for the Tycho-2 and the BGMBGT 2.08 catalogues respectively. The directions of highest and lowest values of these mean proper motions are reflecting the motion of the Sun with respect to the Local Standard of Rest. We observe that, in general trends, the sky distribution have the same



behaviour in both real and simulated data. If we consider that the motion of the Sun with respect to the Local Standard of Rest is pointing toward the apex direction, that is to the RA= 18h03m50.2s and dec =  $30^{\circ}00'16.8''$  (galactic coordinates: 58.87 longitude, 17.72 latitude), we expect the most negative mean proper motion values in right ascension at about RA = 12h and the most positive ones toward RA=0h. This is what we observe in figure 10. However, we clearly see that in the BGMBTG 2.08 simulation the mean proper motion, in absolute terms, is larger than those of Tycho-2 data. We interpret these discrepancies in the sense that the adopted solar motion with respect to the LSR assumed in these simulations is not the correct one. In these simulations we have assumed (U,V,W) = (10.3,6.3,5.9) km/s. Although the commonly used values for (U; V; W) are around (10; 5; 7)kms/s (Dehnen & Binney (1998)), several new studies suggest that these values should be modified to (11; 12; 7)kms/s (McMillan & Binney (2010), Schönrich & Binney (2009)). There are long discussions on the value of  $V_0$ , which values covering the range between 7.6 Km/s (Sharma et al. 2014) and 26 km/s Bovy et al. (2012).

According to Høg et al. (2000) the mean standard error in proper motions for Tycho-2 catalogue is about 2.4 mas/yr we decided to split the sky into two groups, those regions where differences between model and data are bigger than 5 mas/yr ( $\sim 2\sigma$ ) and the regions where the difference between model an data are smaller than this  $\sim 2\sigma$ . The results are plotted in figure 11. This discussion is also valid for the figure 13 for  $\mu_{\delta}$ .

In figure 10 (bottom) we plotted the differences between the mean proper motion in right ascension in Tycho-2 and in our simulation. The first impression is that when moving away from the galactic plane the differences are growing. Again, we guess that the primary reason for these discrepancies is the adopted solar motion and not the difference in the kinematic modelling of the populations dominating at high galactic latitudes (thick disk and halo). This will be analysed in a near future.





FIGURE 10: Mean  $\mu_{\alpha^*}$  values plotted in Galactic Coordinates  $V_T \leq 11$ . The dotted grid is in equatorial coordinates. Units are in mas/yr. Up: for Tycho2 catalogue. Midle: for BGMBTG 2.08 catalogue. Bottom: differences between the proper motions of BGMBTG 2.08 and Tycho-2.





FIGURE 11:  $\mu_{\alpha^*}$  Top: differences between the proper motions in right ascension of BGMBTG 2.08 and Tycho-2 up to  $V_T \leq 11$ . Galactic Coordinates. In red are plotted all the regions where Tycho-2 and BGMBTG 2.08  $\mu_{\alpha^*}$  differs less than 5 mas/yr ( $\sim 2\sigma$ ) bottom:Same as top but here we subtracted the regions were the difference between Tycho-2 and BGMBTG in star counts is larger than  $3\sigma$  of the Poisson noise.



### **4.2.2** Sky distribution of $\mu_{\delta}$

In figure 12 (top and midle) we present the distribution of mean proper motion in declination for both Tycho-2 and the simulated catalogue. As discussed in previous section the most significant differences between both distributions can be a consequence of the assumed Solar motion.

In Figure 12 (bottom) we plot the difference in galactic coordinates. The observed discrepancies will be re-examined by running a new simulation with updated values for the solar motion. For that we will consider the values obtained by Schönrich & Binney (2009) and the new values being derived from RAVE data (Robin et al. in prep.).



FIGURE 12: Mean  $\mu_{\delta}$  in Galactic Coordinates. The Grid is in equatorial coordinates up to  $V_T \leq 11$ . Units in mas/yr. **Top**: for Tycho-2 catalogue. **Midle**: for BGMBTG 2.08 catalogue. **bottom**: $\mu_{\delta}$  differences between the proper motions of BGMBTG 2.08 and Tycho-2





FIGURE 13: top:  $\mu_{\delta}$  differences between the proper motions of BGMBTG 2.08 and Tycho-2 up to  $V_T \leq 11$ . Galactic Coordinates. In red are plotted all the regions where Tycho-2 and BGMBTG 2.08  $\mu_{\delta}$  differs less than 5 mas/yr ( $\sim 2\sigma$ )Bottom: Same as top but we substracted the regions were the difference between Tycho-2 and BGMBTG 2.08 in density are larger than  $3\sigma$  of the Poisson noise



### 5 Conclusions and next steps

We have built two new catalogues (BGMBTG 2.08 and 2.012) up to G = 13 to be used in CU9-WP943 to validate Gaia data. The catalogues are available on request <sup>2</sup>. Assuming the model for binary generation is correct, our simulations indicate that the number of unresolved binary systems inside a catalogue up to G = 13 is not significantly different when the Tycho-2 spatial resolution (800 mas) or the Gaia resolution (120 mas) is imposed (see table 2). Note however that the number of stars in multiple systems is significantly high (about 50%).

In section 4 we present a first comparison between Besançon Galaxy Model and Tycho-2 data up to  $V_T = 11$ . Star counts maps show a general good agreement at intermediate and high latitudes. In the Galactic plane, where Marshall's extinction law has been applied for the galactic longitude range  $\pm 100$  some discrepancies are observed. It was already known that this extinction model seems not adequate for short distances (1-2 kpc). Work is in progress to improve the extinction model.

We have observed (see section 4) that differences in mean proper motions between model and Tycho-2 data for stars up to  $V_T = 11$  are larger than 2 times the standard error estimated for Tycho-2 that is about 5mas/yr at intermediate and high latitudes. The smaller differences observed near the plane are due to the fact that stars contained in these pixels have in mean larger distances which corresponds to smaller absolute differences. Nonetheless work is in progress to clarify this point. These differences (see section 4.2) reflect a shift probably due to the adopted solar motion and mean motion of the LSR. Work is in progress to diminish these discrepancies. This would deserve a deep study and improvement of the kinematic model.

It would be interesting to reproduce the analysis done in section 4 as soon as TGAS data will be published. The better accuracy in TGAS proper motions would allow us to better compare model and data. To undertake this work we propose to work with all regions where differences between star counts (model vs. data) do not exceed 3 sigma of the Poisson noise.

Up to now we have not considered the correlations between the astrometric parameters when assigning errors to the parallax, position and proper motion in our Tycho-2, TGAS or six-moths Gaia simulated data. These correlations are easily to be considered.

Tycho-2 correlation matrix has a significant correlations with positions in right ascension and declination. The out of diagonal value for the proper motions correlation (mu-alfa vs mu-delta) is expected not to be large. This is because astrometric data for the first epoch is coming from the on-ground catalogues. More complex correlations for the TGAS catalogue are expected.

Work is in progress to check the differences in the proper motions as a function of the apparent

<sup>&</sup>lt;sup>2</sup>For the catalogue BGMBTG 2.012: http://gaia.ub.edu/files/BGMBTG\_2\_012\_updatedPM.tar.gz and for BGMBTG 2.08: http://gaia.ub.edu/files/BGMBTG\_2\_08\_updatedPM.tar.gz



magnitude of the stars. This would help us to check the effect of gates in the final astrometric parameters. We are also analysing the effects of assuming Drimmel & Spergel (2001) 3D extinction model instead of Marshall et al. (2006) in the region in the range  $(l = \pm 100, b = \pm 10)$ .



### 6 Annexes

### 6.1 Computation of proper motion accuracy for a mission length L

From de Bruijne (2009) we have  $g_{\pi} = \frac{1.47}{sin45} = 2.0789$ . Following the Gaia redbook we have

$$\frac{\sigma_{\mu}^{(5)}}{\sigma_{\pi}^{(5)}} = \left(\frac{g_{\mu}}{g_{\pi}}\right)^{(5)} = g_{ratio} \tag{2}$$

where  $g_{\mu}$ ,  $g_{\pi}$ , are the geometrical factors and  $\sigma_{\mu}^{(5)}$  and  $\sigma_{\pi}^{(5)}$  the standard deviations of proper motions an parallax at the end-of-the-mission data (5 years). The values for the ratio  $\left(\frac{g_{\mu}}{g_{\pi}}\right)^{(5)}$ , hereafter called  $g_{ratio}$  are those published in table 6 of the Gaia Science performance webpage. In the Gaia redbook  $g_{\mu} = \frac{6}{L}$  being L the time in years of acquisition data at the desired moment. To update this equation to the present total mission length let us define  $g_{\mu} = \frac{X_{factor}}{L}$ . To be coherent with the geometrical ratios that can be found at the at present Gaia performance webpage then:

$$X_{factor} = g_{ratio} \cdot g_{\pi} \cdot 5 \tag{3}$$

Since,

$$\frac{g_{\mu}^{(5)}}{g_{\pi}^{(5)}} = \frac{\frac{X_{factor}}{5}}{g_{\pi}} = g_{ratio} \tag{4}$$

To compute any proper motion errors in a fraction of mission we will proceed:

$$\sigma_{\mu}^{(L)} = \frac{g_{\mu}^{(L)}}{g_{\pi}} \cdot \sigma_{\pi}^{(5)} = \frac{\frac{X_{factor}}{L}}{g_{\pi}} \cdot \sigma_{\pi}^{(5)}$$
(5)

where L specifies years of mission. From (3) and (5):

$$\sigma_{\mu}^{(L)} = \frac{\frac{g_{ratio} * g_{\pi} * 5}{L}}{g_{\pi}} * \sigma_{\pi}^{(L)}$$
(6)

$$\sigma_{\mu}^{(L)} = \frac{5}{L} \cdot g_{ratio} \cdot \sigma_{\pi}^{(L)} \tag{7}$$



on the other hand,

$$\sigma_{\pi}^{(L)} = \sqrt{\frac{5}{L}} \cdot \sigma_{\pi}^{(5)} \tag{8}$$

Finally

$$\sigma_{\mu}^{(L)} = \frac{5}{L} \cdot g_{ratio} \cdot \sqrt{\frac{5}{L}} \cdot \sigma_{\pi}^{(5)} \tag{9}$$

Remember that for  $\sigma_{\alpha}^{(L)}$  and  $\sigma_{\delta}^{(L)}$  the only factor that needs to be applied is the  $\sqrt{\frac{5}{L}}$  as in photometry and parallax.

#### 6.2 References

- [ELA-008], Antiche, E.B., R.; Julbe, F., 2014, Description and usage of the GATComplete-Source connector, GAIA-C9-UG-UB-ELA-008, URL http://www.rssd.esa.int/cs/livelink/open/3263450
- Arenou, F., 2011, In: Docobo, J.A., Tamazian, V.S., Balega, Y.Y. (eds.) American Institute of Physics Conference Series, vol. 1346 of American Institute of Physics Conference Series, 107–121, ADS Link
- Bovy, J., Allende Prieto, C., Beers, T.C., et al., 2012, ApJ, 759, 131, ADS Link
- Czekaj, M., 2013, PhD. Thesis. Galaxy evolution: A new version of the Besanon Galaxy Model constrained with Tycho
- Czekaj, M.A., Robin, A.C., Figueras, F., Luri, X., Haywood, M., 2014, A&A, 564, A102, ADS Link
- Dehnen, W., Binney, J.J., 1998, MNRAS, 298, 387, ADS Link
- Drimmel, R., Spergel, D.N., 2001, ApJ, 556, 181, ADS Link
- Fabricius, C., Høg, E., Makarov, V.V., et al., 2002, A&A, 384, 180, ADS Link
- Høg, E., Fabricius, C., Makarov, V.V., et al., 2000, A&A, 355, L27, ADS Link
- Jordi, C., Gebran, M., Carrasco, J.M., et al., 2010, A&A, 523, A48, ADS Link
- Marshall, D.J., Robin, A.C., Reylé, C., Schultheis, M., Picaud, S., 2006, A&A, 453, 635, ADS Link



McMillan, P.J., Binney, J.J., 2010, MNRAS, 402, 934, ADS Link

Michalik, D., Lindegren, L., Hobbs, D., 2015, A&A, 574, A115, ADS Link

Robin, A.C., Reylé, C., Derrière, S., Picaud, S., 2003, A&A, 409, 523, ADS Link

Schönrich, R., Binney, J., 2009, MNRAS, 399, 1145, ADS Link

### 6.3 Acronyms

The following is a complete list of acronyms used in this document. The following table has been generated from the on-line Gaia acronym list:

| Acronym | Description                                       |
|---------|---|
| AGIS    | Astrometric Global Iterative Solution             |
| BGM     | Besançon Galaxy Model                             |
| ESA     | European Space Agency                             |
| FITS    | Flexible Image Transport System                   |
| GAT     | Gaia Analysis Tool                                |
| GOG     | Gaia Object Generator                             |
| GUMS    | Gaia Universe Model Snapshot                      |
| HEALPix | Hierarchical Equal-Area iso-Latitude Pixelisation |
| IMF     | Initial Mass Function                             |
| PhD     | Doctorate in Philosophy                           |
| RA      | Right Ascension                                   |
| RAVE    | RAdial Velocity Experiment                        |
| SFH     | Star Formation History                            |
| SFR     | Star Formation Rate                               |
| TBC     | To Be Confirmed                                   |
| TBD     | To Be Defined (Determined)                        |
| TGAS    | Tycho-Gaia Astrometric Solution                   |

### 6.4 BGMBTG catalogue format

The BGMBGTG catalogue format is available on request to the first author at rmor@am.ub.es.