A STUDY GUIDE FOR THE ANALYSIS OF *GAIA* ASTROMETIC DATA

W. F. van Altena[1]

RESUMEN

El propósito de este artículo es apoyar de manera entusiasta el uso de datos de *Gaia*, y sugerir una estrategia para mejorar nuestro conocimiento y habilidades, de modo que estos datos se puedan utilizar de la mejor manera posible. Los objetivos principales de la misión *Gaia* son: investigar el origen y evolución de la Via Láctea a través de un mapeo de la Galaxia hasta la magnitud 20 y la determinación de posiciones, paralajes y movimientos propios para 10^9 estrellas. Además, *Gaia* obtendrá espectroscopía, incluyendo metalicidad, distancia, extinción y velocidades radiales para 150×10^6 estrellas mas brillantes que la magnitud 15.

ABSTRACT

The purpose of this paper is to enthusiastically support the use of *Gaia*'s data and to suggest an approach for improving our backgrounds so that its data is used in the best possible manner. The principal goals of the *Gaia* mission are to investigate the origin and subsequent evolution of the Milky Way by mapping the Galaxy to the 20th magnitude and the determination of positions, parallaxes and proper motions of 10^9 stars. In addition, *Gaia* is to determine spectroscopic data including the metallicity, distance, extinction and radial velocities for 150×10^6 stars brighter than 15th magnitude.

Key Words: astrometry — parallaxes — proper motions

1. INTRODUCTION

Data Release #1 (DR1) as described in detail by Lindegren et al. (2016) and by Fabricius et al. (2016) and in these *proceedings*, will contain preliminary positions for most of the planned 10^9 stars down to approximately 20th magnitude. In addition, a solution for parallaxes and proper motions will be made for the approximately 2 million DR1 stars brighter than 12th magnitude that are in common with the Tycho Catalog. This is called the Tycho-Gaia Astrometric Solution, or TGAS. TGAS will be independent of the major ground-based catalogs except for those that incorporated Tycho or its constituents as a component. TGAS, and DR1 for stars fainter than the TGAS limit, can be used to determine corrections to the reference frames and systems of the various ground-based catalogs, for example: 2MASS, UCAC4, URAT, SPM & NPM, USNO-B, XPM, PPMXL, etc.

Gaia DR1 and future releases are unique opportunities to dramatically advance our astronomical research. Ground breaking data is now available on our desktop computers and opportunities are at hand to compete at the international level without special access to large telescopes. How should we prepare ourselves to take advantage of *Gaia*'s fantastic data? In October 2007 IAU Symposium 248, *A Giant Step: From Milli- to Micro-arcsecond Astrometry* (IAU S248) was held in Shanghai, China. Approximately 200 specialists in astrometry attended and presented an array of outstanding talks and a commitment was made to develop an introductory text on Astrometry appropriate for the era of *Gaia*-accuracy data. The resulting text, *Astrometry for Astrophysics: Methods, Models and Applications* (van Altena 2013), is the result of advice from many individuals in the worldwide astrometric community, most of whom were present at that meeting. In what follows I will be referring to relevant chapters of this book.

2. DEVELOPING THE TOOLS TO CREATIVELY ANALYZE *GAIA* DATA

Part V of *Astrometry for Astrophysics* highlights several applications of the techniques and tools developed in earlier parts of the text that are especially relevant to solving various astrophysical areas of research through the use of *Gaia* data. In this section I will mention a few of the areas that I believe will benefit most from *Gaia*'s revolutionary data.

1. Galactic structure, kinematics and dynamics are probably the areas that will receive the greatest impact from *Gaia* as described by Altmann in these *proceedings*. However, proper treatment of those topics requires being able to analyze enormous amounts of data to extract the relevant parameters. Future

[1]Astronomy Department, Yale University, New Haven, CT 06520 (william.vanaltena@yale.edu).

data releases of *Gaia* data will have improved accuracy and be more complete, but TGAS proper motions are a bit more precise than those in ground-based catalogs and they should have different systematic errors. For that reason a redetermination of the local Galactic structure and kinematics of Goulds Belt, Populations I, II, and III would be beneficial right now. With the future releases it will be possible to determine the rotation rate of the Galactic Bulge and kinematics of the Galactic Bar. In addition, it will be easy to determine the rotation of the galactic Halo, the kinematics of its substructures and their associated tidal structures. Finally we should be able to trace the inner and outer spiral structure of the Galaxy as well as its kinematics. Therefore, we need to update our skill-sets in both galactic structure theory as detailed by Méndez in chapter 22 and modern statistical methods for astrometry as developed by Brown in chapter 16.

2. There are many unsolved questions about the origin and future evolution of the Magellanic Clouds. Numerous investigations have been made of the kinematics and dynamics of the Clouds including those by Vieira and Casetti whose contributions and relevant references to the literature are a part of these proceedings. In particular, there is still considerable uncertainty about the orbital velocities of the Clouds and especially their relative velocities, which are all of critical importance for deciding whether or not they are bound to the Galaxy, as well as to each other. In addition, there are ongoing investigations into the membership of several classes of stars including very young stars that may have formed in the outer reaches of the Clouds, e.g. Casetti-Dinescu et al. (2014), Moni Bidin et al. (2017), and Zhang et al. (2017).

3. *Gaia* will provide a wealth of data on Open and Globular clusters, Tidal Streams in the Halo and Star Streams in the Disk. As outlined by Platais in chapter 25, we can use *Gaia* to determine their distances, ages, internal kinematics and for the first time reliable kinematic distances and orbits.

4. DR1 positions will add data points for new orbit calculations to many of the already known binaries and future releases will add many new binaries down to *Gaia*'s resolution limit of about $0''.1$. Speckle Interferometry, as discussed by Horch in these *proceedings* should be used to continue the observations of the important close binaries as well as to screen critical *Gaia* objects for contaminating nearby companions. Methods to search for those unknown binaries are described in chapters 10 and 11 respectively by Ghez and Glindemann, while using those astrometric measures to derive orbits is found in chapters 23 and 24 by Horch and Pourbaix. Once the *Gaia* parallaxes have been properly corrected for the perturbing effects of unknown binary companions, stellar masses accurate at the $1-2\%$ level will lead to a revolution in our understanding of the stellar mass-luminosity relation.

5. *Gaia* will discover many new Minor Planets, Kuiper-Belt objects and Comets. Their cataloging and orbit computation will be a part of future data releases and will lead to a better understanding of the dynamics of our Solar System and the improvement of reference frames as described by Mignard et al. (2016). Asteroid masses can be determined from near encounters, while their shapes and sizes are obtained from stellar occultations. Post-*Gaia* ground-based follow up observations will be vital for these Solar System objects as described in chapter 26 by Mignard.

6. As mentioned before, existing star catalogs will have completely different systematic errors from *Gaia* so that we can use *Gaia* data to derive their systematic corrections. Details on this topic are given by Zacharias and Bustos in these *proceedings* and by López in chapter 20.

7. Finally, in this brief summary, ground-based optical observers with interests in photometry can participate in *Gaia* follow-on observations by looking at the *Gaia Photometric Science Alerts* web page (*http://gsaweb.ast.cam.ac.uk/alerts*). This page lists objects suspected of photometric variation and their observational histories. It is updated regularly and is a gold mine for those interested in variable star research.

3. *GAIA* CHARACTERISTICS

The astrometric characteristics of DR1 are detailed by Fabricius in these *proceedings*, but in summary, the median magnitude for the TGAS stars is 11.0, while that for the *Hipparcos* stars is 8.3. The median uncertainties are 0.3 milliarcseconds for the positions and parallaxes of those stars, while for the proper motions it is 1.3 mas yr^{-1} and 0.07 mas yr^{-1} respectively. It is important to note that those values are precisions and systematic errors several times larger may exist, especially in local areas. There are a variety of sources for astrometric errors including those from the input parameters, such as relativistic and aberration corrections, as well as spacecraft and solar system ephemerides. Instrumental calibration problems include point spread function variation, sky background and noise variations, uncorrected Basic-Angle variations, uncorrected or changing optical field-angle distortion and spin-synchronous errors.

Gaia is a satellite with a rotation period of 6 hours, or $60''$/second of time with two lines of sight separated by a Basic Angle. Both the scan rate and the basic angle must be calibrated and remain constant or else their variations must be accurately known. Background on *Gaia* can be found in chapter 2 by Lindegren, coordinate systems in chapter 7 by Capitaine and Stavinschi and measurement system reductions in chapter 19 by Tang and van Altena.

4. *GAIA* SCANNING AND CHARGE-DELAYED INTEGRATION

As objects drift across the charge-delayed integration (CDI) CCDs in the *Gaia* focal plane, charge accumulates and is transferred in synchronism with the rotation of the satellite. The first two columns are called the Sky Mapper, which creates a map of the region and then depending on the brightness of the object, the integration of each detected object over the balance of the CCD array is terminated in one of 12 steps to extend the dynamic range and avoid saturation for the brighter objects. This procedure may lead to position errors that are a function of the magnitude. Subsequent columns measure the color and spectral characteristics of each object. It is estimated that magnitude and color dependent systematic errors exist on the order of ± 0.2 mas in the DR1 data. Some of the magnitude and color-dependent errors can be calibrated if you are analyzing astrometric data in a star cluster since member stars are at the same distance and have the same proper motion, aside from very small internal motions. For more details see the contribution by Fabricius in these proceedings as well as chapter 2 by Lindegren, chapter 14 on CCDs by Howell and chapter 15 on CDI mode by Rabinowitz.

The Sky Mapper has a resolution along-scan and across-scan of $0\farcs23 \times 0\farcs70$, which means that positional bias can arise from the presence of close double stars within the PSF of the Sky Mapper. However, over the course of *Gaia*'s lifetime many scans are made at random angles and the final positions derived from the main body of the CCD array should yield a resolution of about $0\farcs06$.

5. SPIN SYNCHRONOUS *GAIA* ERRORS

Spin-synchronous errors in the *Gaia* astrometry result from a limited and incompletely calibrated field-of-view which has dimensions of $0.75° \times 0.75°$. For example, time-variable optical field-angle distortion within the FOV, might remain and cause systematic errors so that large-number averaging would not work. For DR1 data within a FOV of several degrees radius the random error of an individual object is limited to about ± 0.3 mas, while for areas less than a 2 degrees radius the random error is about ± 1 mas. This of course means that 3-sigma errors can be expected and the extreme deviations from truth are expected to be 1 and 3 mas respectively. This is illustrated nicely by the figure (see also slide 25 in Fabricius contribution in these *proceedings*) from the Gaia Collaboration's (2016) excellent introduction to *Gaia* parallaxes for the DR1 data. In this figure the old *Hipparcos* parallax for the Pleiades cluster is shown along with other determinations. Eventually it was found that the outlying *Hipparcos* value was affected by spin-synchronous errors. Of course, the *Gaia* value that now agrees with Isochrone fitting, binary orbits and spectroscopic twins may also be affected to some degree by the same problem.

6. CONCLUSIONS

Gaia DR1 and future releases are unique opportunities to dramatically advance our astronomical research. Ground breaking data is now available on our desktop computers and we have opportunities to compete at the international level without special access to large telescopes. We must prepare ourselves now to take advantage of the *Gaia* data being released.

7. ACKNOWLEDGEMENTS

I would like to thank Alejandro Garcia for his outstanding work in making ADeLA2016 a success and the organizers who invited me to present this talk. I am indebted to Dana Casetti for assistance in preparing this paper for publication. We must all express our gratitude to the European Space Agency, the contractors that developed *Gaia* and our European *Gaia* colleagues, who worked so hard to provide us with an outstanding facility for astrometric research.

REFERENCES

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, A&A, 595, A2

Casetti-Dinescu, D. I., Moni Bidin, C., Girard, T. M., et al. 2014, ApJ, 784, L37

Fabricius, C., Bastian, U., Portell, J., et al. 2016, A&A, 595, A3

Lindegren, L., Lammers, U., Bastian, U., et al. 2016, A&A, 595, A4

Mignard, F., Klioner, S., Lindegren, L., et al. 2016, A&A, 595, A5

Moni Bidin, C., Casetti-Dinescu, D. I., Girard, T. M., et al. 2017, MNRAS, 466, 3077 van Altena, W. F. 2013, "Astronomy for Astrophysics" by William F. van Altena, Cambridge, UK: Cambridge University Press 2013

Zhang, L., Moni Bidin, C., Casetti-Dinescu, D. I., et al. 2017, ApJ, 835, 285