



EDITORIAL

The Gaia era has started

Katherine Vieira*

Within hours of the first data release of the Gaia space astrometry mission, a paper in the arXiv repository appeared with results based on it. "First Gaia local group dynamics: Magellanic Clouds proper motion and rotation" by van der Marel and Sahlmann (<http://arxiv.org/abs/1609.04395>) simply reveals how eager astronomers are to explore and exploit the exquisite parallaxes and proper motions promised by this ESA space mission. The Gaia era has started.

*Corresponding author: Katherine Vieira
E-mail: kvieira@cida.gob.ve

Additional information is available at
the end of the article

Determining our place in the universe is one of the most profound driving forces in the human quest for knowledge. Its implications range from philosophy and religion, to the measuring of time and its consequences for weather prediction, agriculture, economical activities and so on. Since ancient times, we have used stars as location beacons for our position on Earth and in space. Greek astronomer Hipparchus of Nicaea was able to find out that Earth's axis was precessing by comparing his own star map with one made by Timocharis of Alexandria 150 years earlier. He found that star coordinates, measured as an angle from the vernal point, have shifted all by the same amount, about one degree per century. He correctly attributed this to a change in the Earth axis orientation and he did so more than a century before the Common Era. More than two millennia later, Gaia is still measuring angles, this time with a precision of eight orders of magnitude better, equivalent to measuring a one-euro coin on the Moon as seen from the Earth.

European astronomers have been behind fundamental astrometric catalogues for many centuries, except during the Middle Ages when Middle East scientists kept science running. The twentieth century witnessed a shift towards US as a new place for research and discoveries, and astrophysics became the newer and modern version of astronomy. Nonetheless, astrometry has kept his stronghold in Europe and the European Space Agency (ESA) has been a key player to continue this role.

Astrometry, as the brand of astronomy in charge of measuring the positions and motions in the sky of stars and other space objects, is mainly concerned with the determination and definition of the most precise and accurate reference frame in space with respect to which astronomical observations can be located. It all boils down to measuring angles, as precisely as possible. From Hipparchus times and until the sixteenth century, astrolabes, quadrants and similar instruments were the tools used for such purpose. Then came the meridian circles, telescopes that pointed exclusively to the local meridian and measured time intervals between stars as they passed in front of it, another way to measure angles to establish a reference frame in the sky. Many astronomical observations, especially those from large photographic plates had to be locally tied to these fundamental reference frames, maintained by selected observatories mostly in Europe, using only a small number of so called reference stars contained in them, that had coordinates in such catalogues. This small-field relative astrometry dominated much of the nineteenth and twentieth century astrometry. Only in 1989, and after more than 20 years of planning and work, ESA launched the astrometric satellite Hipparcos (HIgh Precision Parallax COLlecting Satellite), which scanned the whole sky and measured angles among stars, as seen simultaneously through two lines of vision. After four years of operation, and four more of processing and reducing data, in 1997 the Hipparcos catalogue was published, with more than 118,200 stars and a two orders of magnitude jump in precision for positions and proper motions. The Hipparcos revolution started.

Space astrometry has been a long dream that started officially in 1967 when Pierre Lacroute proposed a space telescope for astrometric measurements during a talk in Prague. But as explained by Eric Høg in his 2001 *Miraculous approval of Hipparcos*, the key idea of using slits and photo cells to measure the position and brightness of stars as they pass in front of a detector, was posed first in 1926 by B. Strömngren. Høg himself in 1960 extended the idea by including counting techniques that he had already implemented in the meridian circle at the Hamburg Observatory.

Fifteen years later, the Hipparcos mission was designed but it took five more years for ESA to finally approve it. Hipparcos was made possible because a handle of European astronomers truly believed that optical astrometry deserved such mission. At about the same time, by means of long baseline radio interferometry of far-away quasars, the International Celestial Reference Frame (ICRF) had been built with a precision of a few microarcseconds, almost three orders of magnitude better than the already available Hipparcos catalogue, but their optical counterparts were too faint to be useful for astrometric purposes. The overwhelming majority of deep optical astronomical observations taken in the twentieth century, especially those with CCD technology, lacked such a precise reference frame. Hipparcos was very good but too shallow in terms of distance to stars in the galaxy. The pressing need for a better and deeper Hipparcos was already in the air. It would take 20 more years to make this step and its name would be GAIA.

On 14 September 2016, 09:30 GMT, at the European Space Astronomy Centre (ESAC) in Madrid, Spain, a press conference was held to announce the first data release of the Gaia astrometric catalogue. One hour later access to data was granted and that very same day a non-refereed paper was published online based on it, a record that probably should be annotated. Two weeks after, the VII Dynamical Astronomy in Latin America, held at Universidad de los Andes in Bogotá, Colombia, was the first international astrometry meeting to discuss about the Gaia Data Release 1 (DR1), along with specialists coming from Argentina to Mexico and special guests from US and Europe, including members of Gaia's own mission teams.

The Gaia DR1 is just the first step of a series of planned annual releases, the final scheduled for 2022. In this release, positions and magnitudes (an astronomical term for apparent brightness) were measured for more than one billion stars, and impressive feat that yielded an equally breathtaking map of our galaxy. But astronomers are more interested in a secondary smaller data-set product, the Tycho2-Gaia Astrometric Solution or TGAS, that has parallaxes and proper motions for some 2 million stars. As initial as it can be, TGAS is already 2 times better and has 20 times more data than Hipparcos. Stars have proper motions precisions within 60–100 microarcsecond per year, and the reference frame zero point for these proper motions has an error of about 30 microarcsecond per year, defining the accuracy of such measurements. Parallaxes uncertainties are all below 1 milliarcsecond. TGAS contains all stars in Tycho-2¹ observed by GAIA, except those that are too blue, too red, too fast, variable or belong to binaries. Another data product of the DR1 is the so-called quasars solution containing some 135,000 of these extragalactic objects, which by definition should have zero proper motion given their cosmological distances. The subset of them that are defining sources in the ICRF2 (the current accepted version of the ICRF) display a very slight bias in proper motion still to be investigated and explained. Tying the radio-interferometry-based ICRF to an optical reference frame is one of the key goals of the GAIA mission.

Gaia's payload comprises two identical optical telescopes, a radial velocity spectrometer, and blue and red photometers. The two telescopes point simultaneously at two different points in the sky separated by a so-called fundamental angle, very accurately built to be 106.5°. A CCD mosaic array in the focal plane spanning 0.5 m × 1 m with nearly 1 billion pixels arranged in 106 chips is the largest digital camera ever used in space. Yet, as precisely built as it was possible, it has been found that the fundamental angle has an unexpected variation that amounts to 1 milliarcsecond in size. The cause is still being investigated but in the mean time it has been corrected as necessary to avoid a bias in the parallaxes measurements that would be affected by it. Scattered stray light into the focal plane has also increased noise contribution into the measurements, but it mostly affects the fainter objects observed.

Gaia circles the Sun in a Lissajous-type orbit at the L2 Lagrangian point, 1.5 million km from Earth in the opposite direction with respect to the Sun, always keeping an angle of 45° with respect to it. At this location and orientation, and spinning every six hours around its axis, Gaia is scanning the sky since 2013 and will continuously do so until at least 2022. A few years extension, from two to five years, is already being considered. Ground tracking of the Gaia satellite is critical to its astrometric performance, its orbit calculation is an input parameter for the astrometric solution and velocity errors would introduce aberration effects. Such tracking proved to be more difficult than assumed as the satellite ended up being 3 magnitudes fainter than expected. Despite some few minor setbacks and everything considered, Gaia is a great success and the best is still to come.

Ground-based astrometry still has many science goals to pursue on its own. All current and future planned large-scale deep faster surveys of the sky, e.g. VISTA, LSST, PanSTARR, etc., can extend Gaia's faint limit and obtain proper motion errors from 0.1 to 1 mas/year and parallax errors from 0.5 to 3 mas, if their astrometry is carefully performed using Gaia as a reference frame for such task. Many of the faint red low mass objects that can potentially add up to some significant fraction of the mass of the Milky Way are out of reach for Gaia but well within these surveys limiting magnitudes. Challenges in this work are related to the electronics and read-out related systematics affecting the measured position of galaxies and stars differently. But even the astrometric re-reduction of already available catalogues, astrometric or not, proves valuable to science. Anything changing positions at timescales larger than 10 years would not be properly measured by Gaia but when combined with older and good enough data, this can yield new valuable information on such objects.

Gaia's name original meaning (Global Astrometric Interferometer for Astrophysics) is a reminder of a failed attempt to do optical interferometry from space for astrometric purposes. It seemed the natural step to do but soon enough ESA realized that it was better to follow up Hipparcos with an improved version, only the name stayed. Proposed space interferometric missions like SIM (Space Interferometry Mission) and OSIRIS/LIDA (Light Interferometry for Space Astrometry), from one reason or another have failed to go from paper to space.

Space astrometry is not free of controversy. When Hipparcos measured some tens of stars in the well-known visible to the naked eye Pleiades open cluster, a surprising result emerged, parallaxes suggested a significantly smaller distance of 118 parsecs as compared to the so far accepted ground-based 135 parsecs. One parsec is the distance to which the mean distance between the Earth and the Sun (called an astronomical unit), subtends an angle of one arcsecond. Distances have been always very hard to measure in astronomy and absolute calibration of all astrophysical theories, from stellar structure and evolution to 3D large-scale distribution of galaxies in the universe, rests on the measurements of only a few hundreds of well-measured parallaxes of nearby stars (in the so-called cosmic distance ladder, parallaxes are the first defining fundamental step). That is why Gaia's promised billion parallaxes are so, almost desperately, sought after. Gaia DR1 has put this issue to rest, by confirming the old ground-based numbers. The Pleiades Hipparcos *affair* has now been explained by spin-synchronous errors of the satellite.

What comes after Gaia? A second Gaia, but in the infrared. Pretty much the same design and principles, except that the spectrometer would be substituted for more (possibly three bands) photometry. Technology is not ready yet though, as tunable HgCdTe sensors in the infrared would be required for such mission. Industry should take care of this in the coming years. But more importantly, this must be decided within the next 5–10 years, so it can fly in 20–30 years, before the astrometric experience from Gaia is lost. As with Hipparcos, the results are barely starting to be obtained but a new improved version is already being outlined in paper.

As Hipparcos did at the very end of last century, Gaia is expected to do a few times fold in the current one, a revolution in our understanding of the stars, planets, our own galaxy, nearby galaxies and the whole universe. And we are all invited to participate, all GAIA data releases are free for everybody to use, as soon as they are ready for science, no proprietary rights or protected data times are in place. We are still far from the most outstanding and paradigm-changing phases of the Gaia mission, that should happen after the final release scheduled for 2022. In the mean time, we can enjoy and marvel at the vision of the proper motion vectors of barely 29 stars in the Large Magellanic Cloud, which beautifully display the internal clockwise rotation of the disc of this nearby small galaxy, even though it takes more than 100 million years for these stars to complete one revolution. Results are consistent with ground-based line-of-sight velocity measurements, so we are off to a good start.

Author details

Katherine Vieira
E-mail: kvieira@cida.gob.ve

Citation information

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Note

1. Tycho-2 catalogue, published in 2000, was based on measurements from the star mapper on board Hipparcos satellite and previous ground-based astrometric catalogues that relied on photographic observations made since late nineteenth century. It is less accurate but much larger than Hipparcos and contains positions and proper motions for 2.5 million stars.



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