Classical Astrometry after HIPPARCOS

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Abstract

HIPPARCOS mission was launched in 1989. It had not a long lifetime, dying in August 1993, but its life was exceptionally fruitful. It is enough to analyze its main results – the HIPPARCOS catalogue and then the TYCHO catalogue – to see how the expectations of the scientists were surpassed: more stars than expected were observed and measured; an accuracy better than predicted and, last but not least, a window to a new kind of astrometry.

1 What does the astrometry mean?

To open the new window, we have to look inside the classical astrometry. But what is it? The astrometry is that part of the astronomy which provides the position and, by extension, the dimensions and the shapes of the celestial bodies. As the stars change their positions in time, the astrometry has to describe their motion. Astrometry allows us to determine the geometrical and dynamical properties of the bodies from our Universe.

To measure the motion of the closest objects we need to materialize a fixed reference system on the sky. This is absolutely necessary to determine any apparent motion free from spurious effects such as global rotation and, in dynamics, the Coriolis acceleration.

Quasars and distant galaxies are ideal fiducial points for such a celestial reference frame. The reference frame is materialized by a reference system, which is therefore a theoretical concept.

How to realize a reference frame? Simply: by continuous and more and more precise astrometric observations, by positions of fiducial points in the sky, which may be stars, galaxies, or quasars. Of course, it is impossible to have a good reference frame without a reliable and accessible celestial reference system.

2 HIPPARCOS

The star positions were determined for years by ground-based observations, within the framework of a large international campaign, known as "Carte du ciel".

But the results were far from satisfactory. So, the astronomers conceived a special mission for the sky mapping. The result was the space mission **HIPPARCOS** (**Hi**gh **P**recision **Par**allax **Co**llecting **S**atellite), the first space experiment fully dedicated to astrometry.

The results are the catalogues of star positions with greater and greater accuracy, more precise than the previous ones, obtained by ground-based astrometry.

The International Astronomical Union decided to replace the FK5 reference system by a celestial reference system based on the positions of extragalactic radio sources. This is the International Celestial Reference System, **ICRS**. Its epoch is 1998, January 1, and it is consistent with **FK5−S** at J 2000.0. It is materialized by equatorial coordinates of extragalactic radio sources observed by VLBI. It is based on a kinematical definition (assuming that the visible Universe does not rotate, that is, the most distant sources do not exhibit global motion).

The **HIPPARCOS** system coincides with the principal axes of the ICRS at the level of +0.6 mas and with individual proper motions consistent with an inertial system at the level of +0.25 mas/yr.

HIPPARCOS Catalogue is the optical counterpart of the International Celestial Reference Frame, ICRF, and provided the primary realization of the ICRS in optical wavelengths. The adopted catalogue epoch is J 1991.25, close to the mean central epoch of the observations for each star. It is aligned within +0.6 mas at this epoch and to within +0.25"/y in rotation.

HIPPARCOS catalogue contains 118 218 stars; this means a density of 3 stars per square degree. It contains the astrometric parameters, their standard errors, the correlation coefficients. It includes a variety of accurate and homogeneous photometric information, as the Johnson V magnitude, B-V and V-I colour indices and accurate multi-epoch broad-band photometric data. The astrometric precision in position, proper motion and parallax are of order 1 mas or mas/yr, or better for the brighter stars.

The mean magnitude of the HIPPARCOS catalogue is $Hp = 8.7$ and half of the catalogue lies in the interval $8 < Hp < 9.5$.

The astrometric results after 37 months of effective observations and several years of data processing exceed significantly the goal of the mission.

One must keep in mind that, having measured the parallaxes to within 1 mas instead of 2 mas, this makes the accessible universe eight times larger than expected from the nominal mission.

Among the stars of the HIPPARCOS catalogue, one can find double and multiple systems. More than a third of them were considered before as being single stars.

The HIPPARCOS catalogue was the source for another one: the TYCHO catalogue, which contains one million stars. This one was obtained from photon counts obtained by scanning with the HIPPARCOS star mapper, carried out with the HIPPARCOS observations in the adjacent main field of view of the telescope.

A few years later **HIPPARCOS** and **TYCHO** catalogues were published to satisfy the adequate accuracy required by navigators and astronomers, systematically over the whole sky. The achievements of HIPPARCOS touch many areas of astronomy: identification of radio sources, stellar physics, dynamics of our galaxy.

The mean value of internal standard errors of TYCHO catalogue is 25 mas for the position components and 0.10 mag for BT-VT color index.

Such a large set of data was exploited in several steps. The most recent result is TYCHO 2 catalogue, which contains about 3 million stars. 99.9% of the stars are brighter than V = 10.0 mag. Each one is accompanied by all astrometric parameters: position (right ascension α and declination δ), the angular parallax and the proper motion components, in angular units per time unit.

As good it is, the proper motions of the HIPPARCOS catalogue have to be linked to an extragalactic reference system. Absolute proper motions were derived from measurements of photographic plates taken with the best telescopes.

3 What about the future of space astrometry?

As HIPPARCOS was not enough, the astronomers like to reach better and better accuracy for position, proper motion, parallax and other astrometric parameters as soon as possible. So, other missions are ready to be launched to accomplish this goal.

FAME (**F**ull-Sky **A**strometric **M**apping **E**xplorer) will be launched in 2004 as a result of a collaborative effort of U.S. Naval Observatory and several other institutions. It is an astrometric satellite designed to determine with unprecedented accuracy the positions, distances, and motions of 40 million stars within our galactic neighborhood. It will measure stellar positions to less than 50 μas at 9th visual magnitude and 500 μas at 15th visual magnitude (to put an angle of 50 μas in perspective, the width of a typical strand of human hair would substent 50 μas if you were viewing it from a distance of 170 to 250 km).

Another mission is projected to be launched between 2007 and 2010. It is **LIGHT**, conceived for stellar and galactic astronomy. It would observe about one hundred million stars up to V = 18 mag with an accuracy better than 0.1 mas in parallaxes and better than 0.1 mas/yr in proper motions, and will establish the precise photometric characteristics of the observed stars. It will observe almost all of the giant and supergiant stars belonging to the disk and halo components of our Galaxy to within 10 kpc from the Sun. Perhaps LIGHT will be the precursor of a more sophisticated future astrometric interferometer satellite, like GAIA, projected to be launched no later than 2012.

The ESA candidate cornerstone mission **GAIA** will analyze the composition, formation and evolution of our Galaxy by mapping with unprecedented precision the stars. It is estimated to provide the positions, proper motions and parallaxes of at least 4−50 million objects, down to the magnitude V = 15 mag, with an accuracy better than 10 mas, along with multi-color multi-epoch photometry of each object.

It could offer the possibility to detect the presence of Earth-like planets around stars within 20 pc.

The **S**pace **I**nterferometry **M**ission, **SIM**, will be launched in 2004. It will determine the positions of pointlike sources to an accuracy of 4 μas globally. We expect a deeper understanding of stellar evolution, a new definition of the

Milky Way. SIM will perform 4 mas measurements on objects as dim as 20th magnitude using optical interferometric techniques with a 10 m baseline. The problem is to find suitable astrometric grid objects to support microarcsecond astrometry.

Another project is **DIVA** (**D**eutsches **I**nterferometer für **V**ielkanalphotometrie und **A**strometrie). This is a small satellite designed to perform astrometric and photometric observations of at least one million stars. It will perform an all-sky survey to V = 10.5 mag at least. The limiting magnitude will be 15.0 mag. After two years, DIVA will provide parallaxes accurate to 0.3 mas, proper motions accurate to 0.5 mas/yr, broad-band photometry with a typical precision of 0.003 mag, it means all better than what HIPPARCOS provided.

Pulkovo Observatory has another astrometric project, **STRUVE**, expected to be launched before 2010 for at least three years. It will include about 20 million stars down to V = 19.5 mag. The proper motions of HIPPARCOS stars are to be determined with a mean accuracy of at least 0.6 mas.

4 What does it happen with the classical astrometry?

There are three kinds of opinion:

The optimists don't care of the spectacular results of space astrometry. They like to continue to observe every clear night the stars for determining their position, in spite of the well-known limits of the ground-based astrometry.

The pessimists want to stop all the observations on the ground, considering them too not more useful as result of the space astrometry.

But there are the realistic ones, too: they understand that the competition with the space missions is very hard. They understand that whatever sophisticated the instruments would be, they are limited by the atmospheric turbulence, the atmospheric refraction, the instrumental errors. At the same time the fact that they are moving with the Earth is both an advantage (we need to have a good terrestrial reference frame) and a shortcoming (the Earth rotation is far from regular). But it is not a reason to stop all observations, even if certain instruments became obsolete or good for teaching of astronomy or even as museum objects. In this case one should not hesitate to stop their operations. The last two decades, about 80% of the existing types of instruments have been replaced by new ones or modernized to the extent that they became new instruments, and this has led to a major increase in accuracy. These ones could continue to be competitive to the space missions, but consequently to this renewal, the instruments are now much more powerful and sophisticated, hence much more expensive to build and to run. This limits their number and increases the need for a careful programming of observations.

Not only the instrumentation has changed, but also the reduction techniques have considerably evolved.

There are some programs that are not of interest for space missions. Much more, even if new space missions are expected to be launched the next years, they are very expensive and not regular, so they couldn't fulfil all the tasks of the astrometry, e.g. for the proper motion. This is one of the reasons for which HIPPARCOS catalog is degrading in time. At the same time we couldn't send a mission for every asteroid, especially for those which could become dangerous for the Earth. What to do?

So, compared to the performances of the space astrometry, it is the ground-based one doubtful? Is this one still useful? If yes, in what manner and to what extent? These are the problems the researchers working in classical observatories have to face.

To identify the programs and make assessment of the whole situation including available instrumentation, a new WG on *"The Future Development of Ground-Based Astrometry"* (chair: M. Stavinschi, co-chair: J. Kovalevsky) has been set up during the last General Assembly of the International Astronomical Union.

The main objective of this WG is to identify scientifically important programs that can be realized using ground-based astrometric or related observations, and to study what kind of modifications, upgrades or additions to the existing instruments should be performed in order to provide useful astronomical information with necessary accuracy, keeping in mind what the future astrometric satellites will contribute.

A final objective that we see for this working group is to identify programs that could be made on instruments that are either insufficiently used or working on projects that have no longer significant value for the present day astrometry. A major reason for this is that these instruments can be used as they are or with not too expensive modifications to train students in astronomy how to use telescopes and at the same time to contribute in a significant way to astronomy.

Indeed, there are some objects which could be still observed from the ground:

Major planets belong to this category. The planetary motion constitutes the basis for the definition of a dynamical celestial reference system that has been in use until now as the fundamental system (FK5 system) and should continue to be maintained for comparison with the extragalactic reference system – a major theoretical objective. Only very precise observations are useful for this goal, which is also true for the preparation of space missions and their operational fulfillment.

Some very well observed asteroids contribute, along with major planets, to the definition of the dynamical reference system.

The solar diameter will be measured every clear day only from the ground (by the Danjon astrolabes), even in parallel with the proposed space mission PICARD.

As we know, in space most of these causes of errors face by the ground based astrometry are avoided. But there are other difficulties to overcome: technical problems in building the instruments, their cost and the difficulty of operations. So, despite HIPPARCOS and HST, only a part of the objectives of astrometry will ever be achieved from space, and the ground-based astrometry is far from becoming obsolete. Contrariwise, the competition with space astrometry thrusts the first one in various directions, gaining in accuracy and usefulness. Our role is to identify the true direction of the classical ground-based astrometry and its capacity to compete the space missions. If these objectives are attained, the astronomy will gain in precision and all its fields of interest will be satisfied.