# MODERN ASTROMETRY IN DIFFERENT RANGES OF ELECTROMAGNETIC WAVES

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A contribution of various astrometry school beginning from the German school after F. Bessel is described. Besides, the modern astrometry problems and prospects connected with the further increasing of the accuracy and with developing of a single reference system for astrometry subdivisions in seven spectral ranges from gamma-ray to radio are discussed.

## WHAT IS ASTROMETRY?

Various astrometry schools give different answers to this question. According to the oldest German astrometry school after F. Bessel, the main goal of astrometry is the development of a reference frame on the base of fundamental catalogues. Positions and proper motions in these catalogues must have an independent system, and this one must be disseminated with help of differential observations.

The same point of view has been supported by practically all successors of the German school. There were the Russian Pulkovo astrometry school after V. Struve, the USA astrometric school after S. Newcomb, Luis and Beniamin Boss, W. Eichelberger, H. Morgan, and F. P. Scott. Two astrometry schools took place after 1918 in the Soviet Union. The first one was the Saint-Petersburg astrometry school that inherited the Pulkovo observational methods and traditions. B. Gerasimovich, N. Dneprovsky, N. Zimmerman, A. Nemiro, A. Deutsch, M. Zverev, and D. Polozhentsev were its leaders. The second one was the Moscow (Sternberg Astronomical Institute, Moscow University – SAI) theoretic astrometry school. S. Blazhko, K. Kulikov, V. Podobed, and V. Gulyaev were its leaders.

As a result, a number of fundamental catalogues for different epochs were released. In Germany “Tabulae Regiomontanae” was the first fundamental catalogue, compiled by F. Bessel, and the series of fundamental catalogues from FK to FK5 were developed by A. Auvers, A. Kopff, W. Fricke, and W. Gliese. In the USA there were the Normal system catalogues N 1 and N 2 compiled by F. Newcomb, the fundamental catalogue with more than one thousand stars observed and compiled by W. Eichelberger, the catalogue containing more than five thousand standard stars in the Normal system N 30, which was compiled by H. Morgan, and the General Catalogue (GC) compiled by B. Boss.

The Russian and Soviet astrometry schools have presented only famous meridian absolute and differential observational catalogues that were used for the fundamental catalogues, which were compiled in Germany and USA. Besides, the original project of the Fundamental Catalogue of faint stars (FKSZ) was also proposed by these schools. Unfortunately, only a summarized differential catalogue was released instead of a fundamental one [5].

The modern European astrometry school has been formed in the last three-four decades of the 20th century. One of the leaders of this school, Prof. J. Kovalevsky, gives the following three definitions of astrometry [1]: “... Astrometry is the part of astronomy that provides the positions, and by extension, the dimensions and the shapes of celestial bodies. These quantities generally are changing with the time so that the primary goal of astrometry is to describe their motions.”

“... Another definition says that astrometry is the application of certain techniques, which one may call “astrometric techniques”, to determine the geometric, kinematic, and dynamic properties of the celestial bodies in our Universe.”

Kovalevsky has also proposed, besides the five parameters (right ascension, declination, proper motions in right ascension and declination, and parallaxes), which were traditionally determined by astrometric methods, to include also the radial velocity as the sixth one, that are observed with spectral astrophysical methods, because it is also the third component of the space velocity.

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Thus, it is easy to conclude that the main aim of astrometry is to find out two vectors: the vector of position and the vector of space velocity. Just the same conclusion has been made by K. Kuimov [2, 3], who is the new leader of the Moscow (SAI) astrometry school.

## WHAT IS THE MODERN ASTROMETRY?

According to J. Kovalevsky [1], the modern astrometry is the astrometry that appeared after the technical revolution in astronomy that took place in the last 3–4 decades of the 20th century. It means that new, more effective astrometrical instruments and methods appeared instead of old visual ones. Technical revolution in astrometry began in the 1960s when the timing technology had been improved and the accuracy of time measurement increased by 5–6 orders in comparison to the classic astrometrical approach. About ten years later (in the 1970s), the ground-based radio astrometry (VLBI) appeared and the milliarcsecond (*mas*) level of the accuracy both of celestial stellar object positions and terrestrial station coordinates was achieved. As a result, the new International Celestial Reference System (ICRS) was declared. It was presented by the Radio Interferometrical Catalogue ICRF that replaced the fundamental coordinate system based on the Fundamental Catalogue FK5, which presented the International Celestial Reference System before January 1, 1998.

Lastly, in the 1990s the HIPPARCOS and TYCHO projects were accomplished, and this also allows one to extend the ICRS coordinate system to the visual range with the same *mas* accuracy. Besides, in the same last 3–4 decades a new CCD astrometry was introduced and replaced both the visual meridian astrometry and the small field photographic one as well.

As a result of new space technologies, many new precise methods of timing and ground-based determination of positions were developed as an alternative to old astronomical ones which were based on visual observations. Those include the radio navigation systems GPS and GLONASS, laser ranging, and the above mentioned VLBI method, which may also be used for such determinations.

The methods of the modern astrometry were considered by Kovalevsky for the optic and radio ranges only. But other methods are rapidly developing now in all other ranges of electromagnetic waves.

## ASTROMETRY SUBDIVISIONS ARE DEPENDING ON SPECTRAL RANGE AND PHOTON'S ENERGY

It is known from ground-based or space astronomical practical experience that astrometry and astronomy as a whole can be divided, depending on the range of electromagnetic spectrum where the objects are detected, into the following seven astronomical or astrometrical subsections. They are as follows:

1. Gamma-ray astrometry
2. Roentgen (X-ray) astrometry
3. Ultraviolet astrometry
4. Visual astrometry
5. Infrared astrometry
6. Submillimeter astrometry
7. Radio astrometry

Every of these branches has its specific features and some of them has the subdivisions, determined by different photon's energy. Thus, the specific astronomical or astrometrical tasks include different requirements to the instrumentation (telescopes, sensors, and auxiliary devices), to methods of observations and the following processing, and finally to special methods of excluding of Earth's atmospheric influences from ground-based observations.

In accordance to these circumstances, the accuracy of astrometrical observations in different electromagnetic ranges is essentially different. The ground-based radio (VLBI) and space optical (HIPPARCOS) observations have, as it was mentioned above, the highest accuracy at a level of *mas* and the gamma-ray flare sources localization has the lowest accuracy at a level of some arcminutes.

Now the International Celestial Reference System (ICRS) is common for two from the seven above mentioned ranges: the radio and visual ones. But in accordance with the XXII and XXIII IAU GA resolutions, the ICRS coordinate system has to be extended to other five electromagnetic wavelength ranges. It is now the most actual astrometrical problem. It is necessary to look for some ways to solve it.

## MAIN ASTROMETRICAL PROBLEMS AND PROSPECTS IN VARIOUS SPECTRAL RANGES

### *Prospects in radio and optical energy ranges*

The atmosphere has two transparent windows for both these spectral ranges. Therefore, the radio and optical observations can be carried out using either ground- or space-based techniques. But the ground-based accuracy of about one milliarcsecond has been achieved only with the radio interferometry technique. M. Shao's experiments at Mount Palomar with the ground-based optical long based interferometers were aimed to achieve the same accuracy of about 1 *mas* for one thousand stars. Probably, it could not be achieved, and the catalogue NPOI is not yet published.

The main astrometrical task for these two spectral ranges is to increase the achieved accuracy of 1 *mas* by two or three orders. By this reason, the project "Radioastron" in the radio domain and several projects (DIVA, GAIA, SIM) in the optical range have been proposed; they are now in progress. A more detailed view on prospects of radio and optical astrometry is presented in the second edition of "Modern astrometry" [1].

### *Problems and prospects in the infrared range*

The terrestrial atmosphere is more non-transparent in the IR range than in the optical one. Beginning from 0.7 mkm it is transparent only within some bands because the absorption by water vapour and carbon dioxide. Due to this and some other circumstances, the ground-based IR observations are more complicated in comparison with the visual ones.

The space observations are free from these difficulties. An advantage of the space IR observations in comparison with the ground-based ones were demonstrated by the satellite IRAS survey. This advances of space IR observations were connected tightly with the progress of the IR sensors technology.

Successful ground-based near-infrared observations (the DENIS and 2MASS Surveys) became possible due to a further development of CCD and IR array detectors, as well as the total automation of telescope control, and the computer data processing. But the next advance in infrared astrometry, the same as in optical one, will be connected probably with an implementation of three space based interferometers accordingly to the above mentioned projects DIVA, GAIA, and SIM, which promise the manifold increasing of the accuracy of the amount observed stars and other objects. If these projects will be successful they would contribute to extend the infrared coordinate system to ICRS.

The IR Reference Catalogue which contains precise positions and proper motions is needed both to present a coordinate system and to organize differential observations in this spectral range. Now such a catalogue may be released by identification of IR stars from the catalogues IRAS PSC, DENIS, and 2MASS with their optical counterparts from the precise astrometrical space catalogues HIPPARCOS and TYCHO or ACT and TYCHO2.

### *Problems and prospects in gamma, roentgen, and ultraviolet energy ranges*

These three spectral diapasons have one common problem. The terrestrial atmosphere is not transparent practically in all these ranges. Because it is evidently that the precise astrometry in these three domains is prospective as space astrometry only. Nevertheless, some not precise ground-based observations of gamma, roentgen or not far ultraviolet sources may be carried out.

Gamma-ray bursts (GRB) are bright, transient events in gamma-ray sky, unpredictable in time and location, with typical duration from some few to 100 seconds. Most of the energy of bursts is released in the 0.1–1 MeV range. It is enough to lead to detectable disturbances of the Earth's upper atmosphere. The first GRB was recorded with the Vela satellites on July 2, 1967. But since, during the following 30 years, the problem to define the precise position of GRB has not been solved.

One can see now the following picture. The gamma radiation cannot penetrate the terrestrial atmosphere, but gamma photons, high energy quants, are interacted with atoms and molecules of the atmosphere. As a result, a stream of second cosmic ray is borne and the Cherenkov light is being emitted in the optic and $UV$ spectral ranges. This phenomenon is used to determine the direction to a gamma source with the aid of special gamma telescopes which may be both orbital or ground-based. One such ground-based telescope was constructed at the Crimean Astrophysical Observatory [4]. It allows to determine the position with an accuracy of about $0.1^\circ$. This telescope can also observe roentgen sources.

But the high-precision space astrometry of gamma-ray bursts is possible used the cosmic triangulation method. The accuracy of this one is about one arcsecond. It is enough to identify the gamma-ray sources with their counterparts in other spectral ranges where it is possible to get precise coordinates.

One more phenomenon, connected with GRB, is its afterglow, which appears some times after GRB and can be detected practically in all spectral ranges from roentgen to radio. Usually, the optical transient following a GRB has an $R$-band magnitude of about 18–22 mag when it is detected some hours after the burst, provided that no strong extinction occurs in the GRB host galaxy or in our own. This can make the optical transient detectable with the 1-m class telescopes. By optical observations of GRB afterglows the question whether all GRBs are of extragalactic nature can be solved.

***Problems and prospects in submillimeters and millimeters arrays***

Submillimeter (from mid-infrared to millimeters waves) astronomy opens new deep space horizons. New submillimeter space telescopes and instruments that appeared during last ten years are the ISO, SOFIA, FIRST.

The radio window of the terrestrial atmosphere has an extension in the direction of the millimeter and submillimeter diapasons because ground-based observations in these two ones may also be carried out. ALMA is the next generation submillimeter ground-based telescope which is being created now. Its position accuracy will be about $0.03''$.

## INEVITABILITY OF THE ALL-WAVE ASTROMETRY

In the visible range the Galaxy Centre is hidden behind 30 magnitudes of the Galaxy foreground extinction. Optical and ultraviolet observations of the Milky Way Centre are impossible or very difficult as well as vicinities of centers of many other galaxies, which are obscured by dense gas and dusty clouds. Because our knowledge of such regions are derived from observations at both shorter (X- and $\gamma$-rays) and longer wavelengths (infrared, submillimeter, and radio) that can penetrate through the above mentioned obscuration. Thus, one may confirm now that a real model of our Galaxy as well as the same of the near part of Universe cannot be developed only on the base of visual optical observations.

## CONCLUSIONS

1. Astrometry as well as astrophysic has to be the all-wave one.
2. Astrometry is going now to a new more high, microarcsecond ($\mu as$) level of accuracy, which may be achieved only by space astrometry observations. Ground-based astrometrical observatories may be, as the rule, an experimental base for preparing space astrometry missions.
3. A single coordinate system must cover all the ranges of electromagnetic waves. Now the ICRS is common for the radio and optical ranges, and in particular it may be extended to the IR range by compiling an IR Reference Catalogue based on the HIPPARCOS stars which have counterparts in IRAS PSC, DENIS, and 2MASS.

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