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The history of Belgrade research of star positions around quasars

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Abstract. Due to the interest to establish the connection between positions of stars determined by optical way and the positions of extragalactic radio sources, determined by interferometric way, in Belgrade was made a stellar catalogue on this subject. Namely fundamental stars near the extragalactic radio sources (quasars) were observed systematically few years and the corresponding stellar catalogue was published.
Here we will describe and review the work on this catalogue which was the contribution of Belgrade Astronomical Observatory to the formation of the new international reference system based on quasar positions. This is very convenient since quasars practically have not proper motions.

Key words. Quasars – reference system – reference frame

1. Introduction

Among the tasks which appeared in the frameworks of fundamental and observational astrometry, during the last decades of the XX century, simultaneously with formation of qualitatively new coordinate systems, an important place belongs to the study of orientation of the traditional, optical, fundamental systems with respect to the new coordinate systems linked to the compact extragalactic radio sources.

It was of special importance to provide such link in order to use the advantages offered by both in a way as suitable as possible. In other words it was necessary to obtain a kinematical reference frame linked to the extragalactic objects and in which both optical and radio interferometric observations would be used. The ultimate goal was the determination of the positions and study of the motions concerning celestial objects both within the Solar System and beyond it, within the Galaxy and in extragalactic dimensions.

2. Formation of an inertial frame

When speaking about the positions and motion of objects within the Solar System and in the universe, special systems of reference should be borne in mind where these two are presented as objectively as possible. The formation of such systems in astronomy was followed by great difficulties, but with the course of time it was realized step by step, following the general development of science and technology.

In classical mechanics as fundamental systems in coordinate determination the inertial ones were accepted, characterized by their uni-

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form rectilinear motion. In order to form such a system in astronomy classical mechanics adopted the notion of "absolute" space which was in Newton's times identified with, as then thought, fixed stars. After the discovery of proper motions of stars in the practical realization of an inertial system the necessity of accurate determination of positions and motions of reference objects appeared. The definition of the main plane was also a problem so that astronomers had to determine precisely the motions and masses of the Solar-System bodies for the purpose of defining the main planes and principal axes (dynamical concept).

A much more simple approach is to link a frame to immovable objects and form a system where the use of no dynamical equations is required because the assumption is that the principal axes are given in space (kinematical concept). Due to this in the early XX century astronomers began to choose extragalactic nebulae which could serve as reference objects in the determination of principal axes and formation of an inertial system. However, in the course of realization of the first observing programmes serious difficulties appeared when the positions of these nebulae were determined due to their significant angular size and, also, low brightness ($m > 14$).

In 1963 the extragalactic origin of quasars, observable both in optical and radio bands, was discovered. The application of the long-base radio interferometry in the position determination of these sources gave rise to the beginning of the new era in the formation of inertial reference systems. Nowadays in order to solve problems of astronomy and geodynamics successfully the inertial system with axes linked to the directions towards extragalactic radio sources and origin at the gravity centre of the Solar System is used. Considering this task rigorously one may say that this system is quasi-inertial because its origin moves with a minor acceleration and the directions, nevertheless, change in the course of time.

From the practical point of view different tasks require different degrees of calculating the changes of the reference system, more precisely its motion. For the purposes of some tasks it is enough that the system has no rotation because a rectilinear motion of the origin is of no importance. On the other hand, an inertial system also does not satisfy the needs of stellar astronomy completely since the motion of the origin, even when it is uniform and rectilinear, deforms the picture of stellar kinematics in the Galaxy. In the ideal case we should have an "immovable" system understanding as such a system with completely known motion, something still hardly realizable.

3. The inertial system and extragalactic radio sources

As already said, one of the ways to realize an inertial system of reference of high accuracy is to link it to extragalactic radio sources (basically these are quasars). This has been realized by combining optical observations with the methods of long-base radio interferometry. The formation of such a system was followed by the assumption that the directions towards extragalactic sources do not show any changes within several decades. Modern views and the development of technology have made it possible to form this system of reference with an accuracy within a few milliarcseconds and with the same stability within a sufficiently long time interval with regard that quasars and galaxies, due to their distances, are practically fixed on the celestial sphere.

The main difficulties following the realization of this project have arisen due to the fact that the structure of radio sources and the atmosphere influence are not sufficiently well known. An arbitrary radio source cannot be suitable to the formation of the inertial system of reference because radio sources are mostly not compact sources, their structure is very complicated, it depends on the wavelength and changes over time. Even if the structure of some radio sources were neglected, the error of the position in a given system could attain a value of a few milliarcseconds. In order to avoid this at the beginning of the action of forming the system two conditions were followed: a) after the structure of a radio source had been well studied, only those were chosen where the positions of structural features do not attain one milliarcsecond; b) on the basis of the operational structure of a radio source adequate corrections were introduced.

Besides, when the inertial system of reference of extragalactic radio sources was formed, an assumption traditional in astrometry should have been applied: the mean motion of all reference objects, adopted for the given system, is equal to zero. This assumption satisfies an accuracy an order of magnitude greater than that achieved in classical astrometry.

4. Relationship between optical and radio interferometric coordinates

During the seventies of the last century the observation orientation was suddenly changed: instead of extragalactic nebulae, the extragalactic radio sources having optical counterparts became targets of observations. The comparison of the coordinates for objects common to both systems started: on the one hand, coordinates obtained by using methods of optical astrometry and on the other one, those obtained by radio interferometry. No matter how simple this seemed, such an approach was followed by a number of difficulties, among others the brightness difference of objects belonging to these two systems.

For the purpose of solving the problem of high difference in apparent magnitudes of stars and extragalactic objects intermediate systems of reference stars were introduced. In other words, an extension of the system of reference, carried out in several stages and aimed at including faint extragalactic sources, was initiated. Such systems were selected according to the instruments used in the given stage:

- system of faint stars brighter than or equal to nine in apparent magnitude within 2 degrees from a radio source obtained from meridian observations with classical astronomical instruments;
- system of faint stars between 12 and 14 in apparent magnitude obtained from photographic astrometry;
- in the case of extremely faint radio sources one should have used stars between 16 and 18 in apparent magnitude as intermediate objects where these two systems include stars within half a degree from a radio source.

The sources emitting at both optical and radio wavelengths are optically very faint. Though they were not foreseen to have apparent magnitudes over 18, in the list proposed by IAU Commission 24 the limiting apparent magnitude was shifted towards m = 22. It is clear that the link of the FK5 system (adopted in the eighties of XX century as the official system of reference in the position determination for celestial bodies) to so faint objects can be indirect only and at that time it was represented by means of the following chain (Gulyaev 1987):

FRS - RS1 - RS2 - RS3 - RRS.

The links in this chain connecting the optical system with the radio interferometric one are the following ones:

FRS - a fundamental system like, for instance, FK5 obtained by applying the methods of optical observations and formed on the basis of absolute astrometric measurements.

RS1 - reference coordinate systems serving for the purpose of solving many tasks of positional astronomy and, partly, tasks of astrophotographic observations. These systems were realized in the form of derived catalogues, for instance, AGK3R and SRS obtained by applying the method of differential meridian observations.

RS2 - second-order reference systems serving for the purpose of determining many coordinates for faint objects, studying the kinematics of stellar systems and others. These systems are formed by applying photographic methods where as reference objects are taken stars whose coordinates are in the systems RS1. An example for such systems may be AGK3.

RS3 - third-order reference systems. They are used in the coordinate determination for very faint objects (m > 12), for instance quasars. In the formation of RS3, depending on the instrument type, one uses reference systems RS1 and RS2.

RRS - radio interferometric coordinate system obtained from observations of extragalactic objects (quasars and active galactic nuclei) at radio wavelengths.

In addition to the cited ones, other coordinate systems, not included in this chain, were also considered. They are special-objective systems. As an example one may mention the systems serving for the purpose of determining the parameters of the terrestrial rotation, as well as the systems applied in the treatment of orbits of artificial satellites of the Earth.

5. Observations at the Belgrade Observatory

Thus in the last decades of the XX century the activity of astronomers concerning linking the coordinates of celestial bodies in the optical system of reference to the ones of compact extragalactic radio sources obtained by applying the methods of radio interferometry (VLBI) was intensified. It was one of very important, but realizable, tasks in astronomical science aimed at forming a qualitatively more accurate and significantly more stable system of reference, especially bearing in mind the progress of technology and the improved precision of measuring devices which made it possible to detect the slightest movements and position changes in the case of celestial objects.

Astronomical Observatory in Belgrade also joined this international activity by determining the positions of the reference stars in the vicinity of radio sources. From Kiev a list containing 315 stars (belonging to RS2 class) distributed within 87 fields with radio sources was obtained. The stars were distributed over the whole sky within a declination zone from −44° to +90° (Lazorenko 1982). From 1982, when the first observations started, by 1987 with the Large Meridian Circle of the Belgrade Observatory the positions of these stars were determined by using the differential method within a declination zone from −30° to +90°. In addition to the programme stars listed there, as reference ones, stars belonging to the FK5 system of reference were also observed.

On the basis of these observations a position catalogue containing 290 stars distributed within 78 fields with radio sources and 198 FK5 stars, with a mean observational epoch of 1984.5, resulted (Sadžakov et al. 1991). The rms error per single determination was $\pm 0.^{s}024 \cos\delta$ in right ascension and, $\pm 0.''30$ in declination, quite as could be expected in the case of a classical instrument like the Large Meridian Circle of the Belgrade Observatory. With regard that every star was observed on the average more than five times, we find as position errors in this observational catalogue $\pm 0.^{s}010 \cos\delta$ in right ascension, $\pm 0.''13$ in declination. The comparisons with AGK3 and Kiev Declination Catalogue, both containing all stars observed in Belgrade, showed that the obtained results can be regarded as satisfactory.

At Astronomical Observatory in Belgrade after this the position determination for the reference stars in the vicinity of radio sources was still practiced. In the period between 1991 and 1993 the star positions were determined within a declination zone from −30° to +30°. A catalogue containing the positions of 351 programme stars and the ones of 267 FK5 stars, with an epoch of 1992.5, resulted (Sadžakov et al. 1997). The rms error per single determination was $\pm 0.^{s}028 \cos\delta$ in right ascension, $\pm 0.''39$ in declination. Due to the large position error and, above all, because at that time the HIPPARCOS satellite was already active, this catalogue has a historical importance only.

6. Epilogue

In Resolution B5 accepted at the XXII IAU General Assembly (Information Bulletin 1995) the final list was formed which contained about 600 extragalactic objects foreseen to be considered as candidates to be included in the new reference frame, i. e. system of reference. The Working Group for reference frames finalized the positions of these extragalactic objects during 1995 and reduced them into a single reference frame coinciding with the FK5 catalogue within the limits of its errors. Besides, in 1996 the HIPPARCOS (HIgh Precision PARallax COllecting Satellit) Catalogue was finished. It has a link to the mentioned objects with a deviation in the position of $\pm 0.''0006$ for the epoch 1991.25 and an error of $\pm 0.''00025$ per year in the rotation. This catalogue, among others, contains positions and proper motions for more than hundred thousand stars with apparent magnitudes not exceeding m = 12.5 (Turon 1996). Starting from this at the XXIII IAU Genera Assembly in Resolution B2 (Information Bulletin 1998) it was decided that from January 1, 1998 ICRS (International Celestial Reference System) had to be accepted as the IAU celestial system of reference according to the definition of the International Earth-Rotation Service (IERS). The corresponding reference frame will be ICRF (International Celestial Reference Frame) formed by the Working Group for Reference Frames. Here the HIPPARCOS Catalogue appears as the ICRS primary realization at optical wavelengths.

In this way a link was found between optical and radio interferometric observations and another one between the dynamical and kinematical systems of reference was established. ICRS appears, in some way, as an extension of the FK5 system towards the radiation sources unavailable to the classical astronomical observations. Due to the enormous distance and (angular) fixedness of quasars the new system of reference provides, within a sufficiently long time interval, an increased position accuracy for the case of extragalactic objects and, in this way also, of the objects covered by FK5 (stars and Solar-System bodies).

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