ASTRONOMY AND SPACE SCIENCE
eds. M.K. Tsvetkov, L.G. Filipov, M.S. Dimitrijević, L.Č. Popović,
Heron Press Ltd, Sofia 2007

Contribution of Belgrade Astronomical Observatory in Establishment of Modern Reference Frames

M. Dačić

Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia

Abstract.

The Astronomical Observatory in Belgrade possessed the three classical instruments for fundamental astrometry with which the positions of stars and other celestial bodies were determined. From 1960, when the instruments were mounted to be followed by the first examinations and test observations afterwards, till 1995, when the observations ceased, eight observational star catalogues were finished, regular measurements for the Sun and internal planets followed the star observations and based on these observational catalogues two general catalogues of star positions were compiled. In this the most numerous and most valuable results were obtained with the Belgrade Meridian Circle.

1 Introduction

The instruments for position determination of celestial bodies (field of fundamental astrometry) the Astronomical Observatory in Belgrade acquired after the First World War as war reparations from Germany. These are: Large Transit Instrument for absolute right-ascension determination, Large Vertical Circle for absolute declination determination and Large Meridian Circle for determination of right ascensions and declinations by using the differential method. They were designed and produced by the German company Askania - Bamberg. At the given moment, with aperture of 19 cm and focal length of 258 cm, these were representative instruments of fundamental astrometry. Unfortunately, due to lack of finances needed to pavilion building and mounting these instruments together with the corresponding equipment remained locked for more than thirty years.

Due to an initiative of Pulkovo astronomers, especially, Prof. M. S. Zverev, involving the International Astronomical Union and also leading astronomers of Belgrade Observatory, credits were obtained by the State in 1957 and 1958 for the purpose of building the pavilions and piers at which the instruments should be mounted [1] (*Les Premiers Travaux de l'Astrometrie Fondamentale a l'Observatoire Astronomique de Belgrade*). The pavilions and piers were finished during 1959 and as early as in 1960 the instruments occupied provisorily

their places. After this an examination of organs and tools started, as well as the rectification of the instruments, themselves. In the middle of the sixties test observations and determinations of right ascensions and declinations took place in order to verify the quality of the preparation works which had been finished till that time and to get an insight into the accuracy and usability of the newly mounted instruments.

From 1968 regular star observations with the Large Meridian Circle started and the total result with this instrument covering quarter century is the seven published observational catalogues. In addition, day-light observations of selected stars combined with those of the Sun, Mercury, Venus (and Mars) aimed at correcting the reference-frame orientation (Catalogues FK4 and FK5) were performed regularly. The results of the day-light measurements were published in the publications of the Astronomical Observatory. With the Large Vertical Circle three observational programmes were performed from 1976, but only in the case of the first one the results were obtained and published. With the Large Transit Instrument after adding the so-called "vacuum mires" important results were expected, but the observations were late and the programme lost in its actuality so that the right-ascension catalogue resulted from the observations with this instrument did not see the day light. All in all, the possessing of the three instruments for fundamental astrometry and the published observations, above all with the Meridian Circle, enabled the Belgrade Observatory to give its modest contribution to the formation of modern reference frames.

2 Observations of Stars and Day-Light Measurements

The first observational catalogue, resulted from observations with the Large Meridian Circle of the Belgrade Observatory, was the one of Latitude Stars [2]. Namely, following a proposal made at the XIII Astrometric Conference of the USSR, which was accepted at the X IAU General Assembly in 1958, the stars from the programmes of various visual and photographic zenith telescopes (their total 26) should have been included into a unified system. After preparations, the observations were performed between 1968 and 1971. The declinations of the so-called latitude stars were determined. The mean epoch of the catalogue was 1969.46, whereas the published catalogue contained 3957 programme stars. The rms error of a single observation (weight-unit error) was $\varepsilon_\delta = \pm\, 0.34''$. Since the positions were determined by applying the differential method within five-degrees zones, for the purpose of determining the instrument parameters 450 reference stars from the FK4 Catalogue were observed. A part of the FK4 stars had been already included in the programmes of the zenith telescopes mentioned above. The positions of some stars from this Belgrade observational catalogue were used in the compilation of FK5 Ext [3]

At the XIV IAU General Assembly in Brighton in 1970 a list of stars observed

with photographic zenith telescopes of the northern Earth's hemisphere was formed and this programme was proposed to be carried out at all observatories possessing meridian circles. The programme was aimed at putting in accordance the star catalogues of positions obtained with 14 photographic zenith telescopes and their reducing to a unique system, in particular to that of FK4 which was valid at that time. In this international project the Belgrade Observatory also took part. The list was made by H. Yasuda from the Tokyo Observatory. After the Large Meridian Circle had been prepared to determine right ascensions, the stars from this list were observed between 1973 and 1980. Each programme star was observed six times where both right ascensions and declinations were determined by applying the differential method. The Belgrade Catalogue of NPZT-Programme Stars [4] contains positions of 1685 programme stars. The mean observational epoch is 1976.90. The error of a single observation is ε_α cos $\delta = \pm\, 0.030^s$ in right ascension, i. e. $\varepsilon_\delta = \pm\, 0.26''$ in declination. The positions for 357 fundamental FK4 stars observed for the purpose of determining the instrument parameters are given separately. The positions of these fundamental stars were used together with the data from many other observational catalogues in correcting the star positions during the formation of the FK5 system [5]

From 1981 to 1987 with the Large Meridian Circle right ascensions and declinations of the double stars contained in a list proposed by M. S. Zverev and accepted at the X IAU General Assembly in 1958 were determined. These are nearby double stars where the astronomical positions were of interest and which could not be separated at that time photographically or photoelectrically. On the contrary, visually in the view field of the instrument their components could be distinguished without any problem. Because of this Prof. Zverev proposed this programme to be realized with our instrument before its modernization took place. The Belgrade Catalogue of Double Stars [6]contains right ascensions and declinations for 1576 programme stars. In the observations only one component was treated. This was either the brighter star in the pair or, if the apparent magnitudes of both were equal, the component preceding in right ascension which culminated first. The mean epoch of the catalogue is 1984.3. The rms error of a single observation in right ascension and declination is ε_α cos $\delta = \pm\, 0.026^s$ and $\varepsilon_\delta = \pm\, 0.34''$, respectively. Since the positions were determined by applying the differential method, the ones of 490 fundamental stars from FK4, i. e. FK5 being the reference frame of the FK5 system adopted in the middle of the eighties, were also given.

In the same period when double stars were observed, with the Large Meridian Circle a programme of reference stars in the vicinity of radio sources was realized. Namely, the technology development made possible detecting and observing very distant objects, practically immovable for several decades. Due to this it was possible to form a reference system which would be based on the positions of extragalactic radio sources and, consequently, by far more stable and precise than the system taking as reference points the positions of stars and, besides,

one must also take into account the dynamics of the Solar System. Therefore, it was necessary to establish a link between the optical and radio interferometric positions. For this reason at the Astronomical Observatory of the Ukrainian Academy of Sciences a list containing AGK3 Catalogue stars situated in the vicinity of 87 extragalactic radio sources with optical counterparts as bright as an apparent magnitude of about 16 was made. With regard that with classical astrometric instruments one can determine the positions of objects brighter than the apparent magnitude of ten, the idea was to establish photographically in an indirect way a link between star positions and those of extragalactic objects for which positions can be determined by applying radio interferometric methods. The reference stars in the vicinity of extragalactic radio sources were observed between 1982 and 1987. The published catalogue of these stars [7] contains positions for 290 programme stars and 198 fundamental ones from the lists of FK4, i. e. FK5. The mean epoch of the Catalogue is 1984.5. The rms error of a single observation is $\varepsilon_\alpha \cos\delta = \pm\, 0.024^s$ in right ascension, i. e. $\varepsilon_\delta = \pm\, 0.30''$ in declination.

In the period 1985-1990 the Catalogue of stars from the Ondrejov PZT Programme [8] was formed. It contains 223 stars which were not included in Yasuda's list because they are too faint. Due to the relatively low observational accuracy ($\varepsilon_\alpha \cos\delta = \pm\, 0.020^s$ and $\varepsilon_\delta = \pm\, 0.30''$) at the moment of its publication this catalogue had no practical importance.

The next two catalogues for which observations took place between 1991 and 1993 - Catalogue of Positions for 146 HLS Stars and 78 Radio Stars [9] and Catalogue of Positions for 351 Stars in the Vicinity of Radio Sources [10] - due to the low accuracy ($\varepsilon_\alpha \cos\delta = \pm\, 0.025^s$ and $\varepsilon_\delta = \pm\, 0.32''$, i. e. $\varepsilon_\alpha \cos\delta = \pm\, 0.028^s$ and $\varepsilon_\delta = \pm\, 0.39''$) of the Large Meridian Circle, as a classical instrument, at the time of realisation of these programmes have a historical importance only.

To the list of observational catalogues obtained at the Belgrade Large Meridian Circle one should add a catalogue of right ascensions and declinations for FK4 stars [11], which were observed from 1981 to 1987. Namely, during the work on the programmes of double stars and reference ones in the vicinity of radio sources selected FK4 stars were also observed for the purpose of obtaining the parameters of the instrument for the differential method of determining the positions of the programme stars. The observations for the first programme (DS) comprised 485 fundamental stars and those for the second one (stars in the vicinity of radio sources) 247 ones. The observational data concerning the fundamental stars in one observational series were used for the purpose of calculating the parameters (equatorial point, u + m, n) and their variations and also for the purpose of calculating the parameters and their changes, as well as for the purpose of computing the position corrections for the given stars. This catalogue contains 578 positions of fundamental stars where 35 of them were also observed in lower culmination. The mean epoch of the catalogue is 1983.90

in right ascension, i. e. 1983,84 in declination. The mean rms errors are per one determination $\varepsilon_\alpha \cos\delta = \pm\, 0.022^s$, $\varepsilon_\delta = \pm\, 0.32''$ in right ascension and declination, respectively, and it concerns the entire catalogue.

The Belgrade Vertical Circle was ready for astronomical observations only after a detailed reconstruction which was finished in 1974. At the Twentieth Soviet Astrometric Conference held in 1975 following an initiative of M. S. Zverev it was proposed to the Belgrade colleagues, participants of the Conference, to obtain a catalogue of declinations in the framework of the Programme of Bright Stars (BS). This programme is formed at Pulkovo and accepted at the 14^{th} Soviet Astrometric Conference whereas its stars were recommended to be observed at the X IAU General Assembly. From Pulkovo a list of bright stars in the declination zone between $+65^\circ$ and $+90^\circ$, out of which about three quarters had apparent magnitudes between 5.0^m and 6.9^m, was received. This programme was aimed not only at obtaining better positions of bright stars, but also to determine as reliable as possible from absolute observations of stars in both culminations the position of the north celestial pole. It was foreseen to obtain the declination of every star by applying the absolute method from at least four observations in the upper culmination and also four observations in the lower one. The observations were carried out from the middle 1976 till the end of 1980. As a result of this campaign we have a catalogue of declinations for 307 bright stars [12] with a mean epoch of 1978.62 and a rms error in declination $\varepsilon_\delta = \pm\, 0.13''$. It should be also mentioned that out of 307 stars from this list 110 of them belong to the FK4 Catalogue, 237 stars can be also found in the FK5 Catalogue and there are 198 bright stars not found in either of the two fundamental catalogues.

In addition to the night observations of stars with the Large Meridian Circle of the Belgrade Observatory in the period 1975 – 1994, when the conditions allowed it, together with the fundamental stars the Sun, Mercury and Venus (from 1981 also Mars) were regularly observed in the day light. This was carried out in order to obtain data making possible to improve the orientation of the reference frame (FK4, i. e. FK5). In principle, the instrument parameters were determined from observations of the fundamental stars and the coordinates of the Sun, Mercury and Venus were derived by using these parameters. These data were used for the purpose of obtaining the (O-C) differences in right ascension and declination. As a next step based on these differences and applying the least-square method one calculated, from one side, the corrections to the orbital elements for the Earth, Mercury and Venus and, from the other one, the corrections to the positions of the vernal-equinox point and equator with regard that the vernal-equinox point and the equatorial plane were defined by the star coordinates from FK4, i. e. FK5.

During the twenty-year period the treatments included about 600 observations of the Sun, about 200 observations of Mercury and about 500 observations of Venus. The results (O-C) were published regularly in *Bulletin de l'Observatoire astronomique de Belgrade*, i. e. *Bulletin astronomique de Belgrade*, whereas a

review of the published results was given in the last report concerning 1994 [13]. Since the coordinates of the Sun were determined by obtaining the right ascension from observations of the front and back solar-disc limbs, i. e. declination from observations of the upper and lower limbs of the solar disc, it was possible to calculate the solar diameters in both directions. These data were used in calculating periodic changes of the solar diameter [14, 15].

3 General Catalogues

As mentioned already, at the 13th Astrometric Conference the Soviet astronomers proposed to compile a General Catalogue of Latitude Stars which would comprise the stars of the programmes of all latitude stations distributed over the northern terrestrial hemisphere which was accepted at X IAU General Assembly in 1958. However, in the early seventies of the last century this task was still not completed because by that time only three observational catalogues formed following this programme had been finished. In view of this fact at the Belgrade Observatory the General Catalogue of Latitude Stars [16] was compiled. It used the data of several observational catalogues obtained between 1929 and 1972. These catalogues had different numbers of common stars, but their declinations were determined more accurately than those used earlier by Boss in forming his General Catalogue (GC). This catalogue (IKŠZ) was compiled without pretensions to play the role of the catalogue foreseen by the IAU resolution, but to replace it temporarily until at all observatories which took part in the realization of this programme the observational data were collected and a final result as a new catalogue of declinations of latitude stars given in a unique system was obtained.

The values of declinations and proper motions for the IKŠZ stars were obtained on the basis of 36 000 positions of different accuracy where the rms error of a single determination was on the average about $\pm 0.35''$. The star positions in the observational catalogues were determined from on the average four measurements so that it can be said that the declinations and the corresponding proper motions in this catalogue were determined from on the average 36 measurements. Since a part of the material collected for the treatment was given in the FK3 system, the first step was to convert all the observations given in FK3 into the corresponding FK4 ones, after which a further treatment of observations took place.

The rms error in declination in IKŠZ is $\varepsilon_\delta = \pm\ 0.06''$, that of proper motion $\varepsilon_\mu = \pm\ 0.005''$. The mean observational epoch in this catalogue containing 3895 stars is 1954.55. All the positions given in the catalogue are referred to the equinox, equator and epoch of 1950.0. No matter to the relatively short period in which the observations were collected (about 40 years), a circumstance with unfavorable influence on the accuracy of proper-motion determination, the

catalogue at the given moment had the most probable values of declination for stars used in the latitude measurements. The catalogue made possible to reduce significantly or eliminate the shortcomings and problems arising due to bad star positions in a catalogue from which stars were selected for the programme of latitude observations.

The Belgrade Catalogue of Double Stars served as a frame in the obtaining of preliminary derived positions for DS-Programme stars [17]. The programme, foreseeing observations of double stars proposed following an initiative of M. S. Zverev and accepted in 1958 at X IAU General Assembly, had as its objective determination of right ascensions, declinations and proper motions for visual double stars of small separations which at that time was important to stellar astronomy, especially to the studying of galactic structure in the solar neighborhood. These stars were observed as early as about 1930 by L. Courvoisier with the Meridian Circle of the Babelsberg Observatory and their positions were published as the corresponding appendix in each of the 15 volumes of the AGK2 Catalogue. By the end of the eighties several observational catalogues had been completed and as a material for obtaining preliminary positions in this general catalogue the results collected at observatories in Kiev, Kharkov, Odessa, Moscow and Kazan were added to the Belgrade Catalogue.

In this preliminary general catalogue which contains the positions of the DS-Programme stars right ascensions are given for 930 stars and declinations for 1225 ones. The coordinates of a star were derived if its data had been given in at least two observational catalogues and they were calculated for the equinox and equator of 1950.0 and for the epoch of the observations. The mean epoch of observations is 1982.91 in right ascension and 1983.19 in declination. The rms position error in the general catalogue is $\varepsilon_\alpha \cos\delta = \pm\, 0.019^s$, i. e. $\varepsilon_\delta = \pm\, 0.27''$ (right ascension and declination, respectively).

By comparing the star positions from this catalogue with the observations done by Courvoisier the proper motions of these double stars could be approximately deduced. It should be noted that in the determination of the proper motions there is a special difficulty which should be taken into account, the orbital motion of the components.

4 Conclusion

Thanks to the possessing of the instruments for fundamental astrometry (Large Transit Instrument, Large Vertical Circle and Large Meridian Circle) which were mounted in the early sixties of XX century at the Astronomical Observatory in Belgrade in this field of astronomy there was a very intensive activity for quarter century. It resulted in eight observational star catalogues, two general catalogues and in a large number of positions for the Sun, Mercury and Venus on the basis of which it was possible to calculate the corrections in the reference-

frame orientation for FK4, i. e. FK5. To be specially mentioned are: Catalogue of declinations the latitude programme stars, Catalogue of NPZT programme stars, Catalogue of double stars, Catalogue of positions of 290 stars situated in the vicinity of radio sources and General catalogue of latitude stars. All of them at the given moments were important results of the international cooperation between the Belgrade Observatory and other ones and give its contribution to the establishing of the modern reference frames.

With regard that the HIPPARCOS Catalogue, as the most accurate international celestial reference frame valid today, contains the FK5 stars within the error limits of this catalogue and that it is linked to the positions of extragalactic radio sources, it can be accepted that some grains obtained at the Belgrade Observatory are woven in the coordinate grid of celestial bodies used as a *metrological* frame in modern astronomy.

References

[1] B.M. Ševarlić (1968) *Publ. Obs. Astron. Belgrade* **14** 11.

[2] S. Sadžakov, D. Šaletić (1972) *Publ. Obs. Astron. Belgrade* **17** 1.

[3] W. Fricke, H. Schwan, T. Corbin (1991) *Fifth Fundamental Catalogue, Part II. The FK5 Extension – New Fundamental Stars, Veröff. Astron. Rechen-Institut Heidelberg* **33** 1.

[4] S. Sadžakov, D. Šaletić, M. Dačić (1981) *Publ. Obs. Astron. Belgrade* **30** 1.

[5] W. Fricke, H. Schwan, T. Lederle (1988) *Fifth Fundamental Catalogue, Part I. The Basic Fundamental Stars, Veröff. Astron. Rechen-Institut Heidelberg* **32** 1.

[6] S. Sadžakov, M. Dačić(1990) *Publ. Obs. Astron. Belgrade* **38** 1.

[7] S. Sadžakov,M. Dačić, Z. Cvetković (1991) *Astron. J.* **101** 713.

[8] S. Sadžakov, M. Dačić, Z. Cvetković (1992) *Bull. Astron. Belgrade* **146** 1.

[9] S. Sadžakov, M. Dačić, Z. Cvetković (1996) *Bull. Astron. Belgrade* **153** 1.

[10] S. Sadžakov, M. Dačić, Z. Cvetković (1997) *Bull. Astron. Belgrade* **155** 3.

[11] S. Sadžakov, M. Dačić (1989) *Bull. Astron. Astrophys. Suppl. Ser.* **77** 411.

[12] M. Mijatov, G. Teleki, Dj. Bozhichkovich, V. Trajkovska (1991) *Bull. Obs. Astron. Belgrade* **143** 1.

[13] M. Dačić, S. Sadžakov, Z. Cvetković (1995) *Bull. Astron. Belgrade* **151** 81.

[14] I. Vince, M. Dačić, Z. Cvetković (1996) *Proc. 18th SPIG, Kotor, September 2–6, 1996* 524.

[15] I. Vince, M. Dačić, Z. Cvetković, N. Popović, P. Jovanović (1998) *Proc. 19th SPIG, Zlatibor, August 31–September 4, 1998* 667.

[16] S. Sadžakov (1978) *Publ. Obs. Astron. Belgrade* **24** 1.

[17] Z. Cvetković (1992) *Astron. Astrophys. Suppl. Ser.* **96** 191.