History of development of selenodesy and dynamics of the Moon in Kazan

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Abstract

The brief history of development of heliometric and positional observations of the Moon in Kazan university and Engelhardt Astronomical Observatory from the end of the last century till now days is given. All aspects of research of a figure, rotation and gravitational field of the Moon are considered as well as other close to them questions.

1. Heliometric observation of the Moon

The research work of the figure and rotation of the Moon in Kazan State University started more than a hundred years ago. In 1894 privat-docent A.V.Krasnov just returned from Gettingen where he was sent on by professor D.I.Dubjago, the director of the Astronomical Observatory of Kazan University at that time, who insisted for acquainting with a technique of study of lunar physical libration (Lunar Phusical Libration -- LPhL) by a heliometr and Krasnov began systematic observations by the Repsolds heliometer which was transferred to Kazan from Peterburg Academy of sciences about 1874.

From 1895 till 1898 A.V.Krasnov carried out 112 measurements of the Mesting A crater and 50 - of Procl and Aristarch craters relatively to points of the Moon limb. These observations marked the beginning of Kazan heliometric series of observations of the Moon in particular and fundamental lunar investigations in Kazan in general.

Owing to transfer in Warsaw University on a position of head of the astronomical ·bservatory A.V.Krasnov had no time to reduce his obsrvations. It was made by A.A.Nefedyev [41] only in 1955.

The assistant A.A.Mihaylovsky carried out 58 measurements of the Mesting A crater in 1900-1905 forming the second Kazan series, which was reduced by the assistant Breslavl observatory M.Volkel [67] in 1907 and by I.V.Belkovitch [1] in 1935. In 1905 heliometer was sent to Repsolds firm in Hamburg for preventive repair.

In 1908 the instrument returned in Kazan and was established in the country Engelhardt Astronomical Observatory (EAO).

After A.A.Mihaylovsky changed the place of the work observations of the Moon on the heliometer have been continued by magistr of astronomy of Warshaw University T.A.Banahevitch. In 1910-1915 he made 130 precision observations of the Mesting A crater. They formed the third kazan heliometric series which was processed by A.A.Yakovkin in 1928 [29].

In 1915 T.Banahevitch went in Tarty (Derpt) in astronomical observatory. A.A.Jakovkin continued observations of the Moon. In 1916 he began to form the fourth series of heliometric observations. In 15 years he carried out 251 measurements of the Mesting A crater.

A.A.Jakovkin was the first kazan astronomer, who worked up reduced heliometric observations of the Moon [31], [32] himself.

Then the follower of A.A.Jakovkin -- I.V.Belkovitch carried out for heliometric observations of the Moon more than 17 years (1931-1948). He made 247 measurements of Mesting A crater and results of working up published in 1949 [3]. After his untimely death in 1949 the lunar investigations were continued by A.A.Nefedyev.

Being the post-graduate student, he began to take an active part in observations. In 38 years he, as astronomer-observer formed two series of heliometric observations of the moon including about 400 measurements of Mesting A crater.

Thus the scientific workers of kazan observatory and EAO sunce 1895 till 1958 received by heliometer Repsold seven series of heliometric measurements of the positions of Mesting A crater relatively points of limb of the Moon.

The processing of heliometric observations for researching the LPhL is the most difficult work in astrometry. It is not surprising that first heliometric observations were not processed by the observers themselves. Some German astronomers, who had begun to research rotation and figure of the Moon before, were involved into that work.

Only in 1928 A.A.Jakovkin managed to process the series of Banahevich independently. A.A.Yakovkin and I.V.Belkovitch improved the methods of process of the heliometric observations. In particular, I.V.Belkovitch offered fundamentally new way of determination of parameter f showing up the duality of the solution, the parameter f has two significances about 0.62 and 0.71. The first is closer to the significance of f received later on basis of space observations [2].

Omitting the details we note that "If professor D.I.Dubjago by his more than thirty-years activity in organization of heliometric observations laid the foundations of Kazan school of investigations of rotation of the Moon, the merit in erection of a building on that foundations belongs to professor A.A.Yakovkin, who improved far the theory of reduction of the heliometric observations of the Moon" [10].

We notice also that A.A.Jakovkin was the first who stated the theory of LPhL in Russian. The technique of reduction of the heliometric observations created by him surpassed other methods in all respect. For example, the method of Naumann published considerably later, essentially was not as precise as the method of A.A.Jakovkin

Table1.
Kazan heliometric series of observations of Mesting A crater

nn	observer	years	N	the author of processing
1	Krasnov	1895-1898	112	A.Nefedyev [41]
2	Mihaylovsky	1900-1905	58	Volkel [2], Belkovich [1]
3	Banahevitch	1910-1915	130	Yakovkin [29]
4	Yakovkin	1916-1931	251	Yakovkin [31], [32]
5	Belkovich	1931-1948	247	Belkovich [3], Ju.Nefedyev [45]
6	Nefedyev I	1938-1945	143	A.Nefedyev [40]
7	Nefedyev II	1946-1958	267	Ъ.Nefedyev [42], Ju.Nefedyev [45]

N -- numbers of observations of crater Mesting A.

Sh.T.Habibullin made a great contribution to improvement of the method of processing of the heliometric observations. His method based on analysis of the higheest harmonics in series of LPhL in term of longitude provides one-valued determination of parameter f [10] in contradistinction to the methods of Bessel-Wihman and K.Koziel, which gave dual solution to parameter f.

In 1955-1957 by this method Sh.T.Habibullin rereducted six heliometric series [9] received in 1895-1945. In contradistinction to the previous authors magnitudes of parameters of LPhL obtained by him are close to results got in 60-70 years on the basis of space and laser observations of the Moon.

In 1972-1978 G.M.Stoljarov carried out another process of all Kazan heliometric series. In general he considered 1112 measurements of Mesting A crater obtained by six observers in 1895-1958. He used new methods of reduction (Sh.T.Habibullin, K.Koziel, Schrutka-Rechtenschtamm) and new dynamic parameters of the Moon and its ephemeride j=2 [63].

A number of investigations with the aim to improve a method of reduction of the heliometric measurements and to rereducte some series of observations were made by Ju.A.Nefed'yev [12].

We should note works of Sh.T.Habibullin [15] and of S.G.Valeev [16] on determination constants LPhL of 36 heliometric observations of Gartvig in ’ rtu (Derpt) in 1884-1885 and accordingly of 157 heliometrical measurement of Gartvig in Bamberg in 1890-1915.

2. Ground-based and space photography of the Moon

In EAO photographic observations of the Moon were carried out for solving three problems: study of rotation of the Moon, the mapping of the near lunar suface and its marginal zone, establishment of a uniform scale of the ephemeris time.

In 1949 I.V.Belkovich constructed special horizontal astrograph with coelostat and additional mirror. The objective of the telescope was doublet photographic aplanat which diameter 20 чm and focal length 8 m.

Because of untimely death I.V.Belkovich did not carry telescop to a working condition. It was made by Sh.T.Habibullin [10]. Three photographic images of the Moon received on the plate of size 13x18 cm. The stellar fields were photographed on separate plate for determination of the scale. Three images of the Moon were used to determine the orientation of the plates. That sufficed to research the LPhL.

In 1949-1952 Sh.T.Habibullin obtained several dozens of plates of the Moon. From which 40 plates were chosen to research LPhL. Constants of LPhL f were calculated by two methods: of Bessel-Wihmann and Koziel. The results of reduction of photographic observations of the Moon confirmed suitability of this way to study the rotation of the Moon.

The study of non-uniformity of rotation of the Earth and establishment of a uniform scale of ephemeris time became one of urgent problems of astronomy and geodinamic in a middle XXth century. For the solution this problem in 1953 the american astronomer W.Marcowitz offered the special dual-rate moon-position camera, which allows to photograph the Moon and stars simultaneously.

In 1958 such observations were begun in EAO on refractor Zeiss with doublet photovisual objectiv (D=148 mm, f=2580 mm). The camera of a type Ђ rkowitz was made under the management of N.D.Kalinenkov. During 1958-1961 by the employee EAO N.G.Rizvanov were obtained 435 plates of the Moon with stars. As a result of their reduction the corrections of ephemeris time for the next epoch were determined: 1958.25, 1959.61, 1960.43, 1961.37 [50].

In order to develop the Moon by a space-rocket equipment it was necessary to prepare cartographical maintenance of its near side surface. That is why the problem of determination of selenocentric coordinates of the lunar objects became years one of major in selenodesy in 60-70.

That was perfectly obvious that large-scale star-callibrated lunar photographs would more correspond for solving the problem. Unfortunately, to get such photographs was very difficult technically. That is why observers took photographs of the Moon without stars on large-focus telescopes. Thus there were dificultes with determination of their scale, orientation and zero-point.

First large-scale star-callibrated lunar photographs were obtained on horizontal telescope in EAO by N.G.Rizvanov in 1964. For this purpose the telescope was modernized [51] and several dozens of plates were obtained. Then on their basis the astronomer of EAO S.G.Valeev made some selenodetic investigations [65].

Later the observations of the Moon with stars by the horizontal telescope were made with the camera of N.F.Bistrov [27]. In 1970 telescope was transfered to mountain station of the region of Zangesur ridge. During 1970-1975 years about 1000 photographs of the Moon with background stars were obtained. At that stage the work was carried out together with Institute of Space Researches ЂS USSR [8].

A number of selenodetic problems was resolved on the basis of these observations. For the first time in selenodesy the catalogue of selenocentric coordinates of 264 craters was constructed by referencing to stars, that is "by the absolute method" [25], [52]. The catalogue of selenodesic positions of 120 craters was constructed on the basis of coordinates of 10 craters determined on its measurements relatively to stars by EAO heliometer [47]. A cycle of works on was accomplished to study the figure of marginal zone of the Moon [28]. Parameters of physical libration [7] were determined. The maps of the marginal zone of the Moon related to the centre of its mass [49] were made. Determination of orientation of axis of the ellipsoid of inertia of the Moon was carried out [56].

Some works on determination of the ephemeris time and its application for the analysis of the selenodedic basic systems of coordinates were made on basis of plates of the Moon, obtained with 16" refractor with focus length of 3750 mm [65].

The lunar surface mapping on space photographs of the Moon basis were carried out in 70-80 years together with Institute Space Researches ЂS USSR. The determination of the topographical characteristics of the surface of far side and of a marginal zone of the Moon was made on photographs from spacecraft "Zond-6,-8", transferred for this purpose in EAO from Institute Space Researches AS USSR. The most attention was given for studying the region of the sea East [62].

A number of the selenodedic researches is executed by S.G.Valeev on the basis of ground-based and space photographs of the Moon [66]. He developed the method of regression analysis for solving the problems of photographic astrometry and selenodesy.

N.G.Rizvanov [54] gives history of development of a photographic method of the observations in selenodesy and provide a general idea of photographic astrometry [53].

3. Theory of rotation of the Moon

The most significant theoretical investigation of rotation of the Moon is undoubtedly the work of Sh.T.Habibullin "The Nonlinear theory LPhL of the Moon" [13]. The author solved the problem of nonlinear fluctuations of rotation of the Moon by methods of N.Њ.Љrylov, N.N.Bogoljubov and N.G.Malkin.

The nonlinear theory in case of a resonance (f=0.622) gives the steady solution in contrast to the linear theory. In the intervals which are far from the resonance, the nonlinear theory does not reveal essential refinements in comparison with the linear theory, but more authentically describes so called "free libration".

In the article of Sh.T.Habibullin [34] was shown that free libration of the Moon was not more than 0.3".

Ju.A.Chikanov [4] constructed tables of coefficients of the trigonometrical expansion of LPhL components. In this case he put that LPhL components depended not only on paramete f, but also on inclination I. Similar investigations were carried out by D.Eckhardt, A.Migus and M.Moons.

Sh.T.Habibullin and Ju.A.Chikanov [18] in details considered the problem of lunar free libration and Eilerian movement of its poles, that is free libration.

Sh.T.Habibullin [15] gave the analysis of systems of the selenographic coordinates and developed the theory of precession and nutation of the axis of rotation of the Moon.

In works [16], [17] Sh.T.Habibullin executed fundamental investigation of movement of sattelite relatively to the centre of mass in the central Newtonian field of forces. In the first article oscillatory movements were studied at synchronous movement when the axial and orbital angular speeds were in ratio 1:1. The decision was obtained in the form of series of Lindshtedt. In second article three special case of plane movements of a sattelit round the centre of mass on the elliptical orbit were considered: movement of almost spherical satellite on the almost circular orbit, movement of almost spherical satellite on an appreciably extended orbit, movement of the flattened satellite on an almost circular orbit. The canonical transformations were executed with the help of the elliptical functions Jakobi.

K.S.Shakirov [60] studied the question of influence of the internal structure of the Moon to its rotation. The model distinguished from absolutely solid body was considered.

4. Selenodesic system of the coordinates and geometrical figure of the Moon

The employees of EAO carried out original researches of the figure of the Moon on the heliometric and photographic observations basis.

Analysing the heliometrical measurements of Mesting A crater A.A.Jakovkin opened dependence between radius of disk of the Moon and optical libration in latitude, this is so called "effect of Jakovkin" [30]. He stated the hypothesis that on the spherical Moon near its southern pole there was an additional layer and its visible thickness changed depending on as far its southern hemisphera was opened.

I.V.Belkovich studied a figure of the Moon by considering separately radiuses determined by heliometric observations of the east and western marginal zone of the lunar disk. He established that radius of east margin of the Moon is 0.14 "was more than the western one and the radiuses of east and western margin of a lunar disk variously depended on optical libration in latitude, that is the limb of the Moon at different significances of optical librations had the different form [3].

Sh.T.Habibullin gave the theoretical substantation of lunar cartography in the article [42].

A.A.Nefedyev constructed maps of the marginal zone of the Moon [43] on the basis of 5630 altitudes in the marginal zone obtained by heliometric measurements. In this fundamental work the solution of the problem about the zero surface from which the altitudes on the Moon should be measured was found. F. Hayn, T. Weimer and C.B. Watts solving the similar problem question left this opened. Ju.A. Nefedyev improved those maps taking into account the "effect of Yakovkin" [46].

L.I.Rakhimov constructed on basis of measurements of more than 40000 points of limb on 127 large-scale star-callibrated lunar photographs the maps of marginal zone of the Moon for the first time referred to a centre of its mass [49]. These maps should be considered as the most authentic among all other maps of altitudes in marginal zone of the Moon.

Except for measurements of Mesting A crater with the purpose to study LPhL with heliometr Repsold at EAO the observations of a number of craters were carried out for determining there selenodesic coordinates.

In 1970-1975 A.S.Mamakov executed 468 measurements of 32 craters relatively to Mesting A crater. He made improvement and investigation of a instrument for the increase of accuracy of results. In particular, method of measurements of positional angles and angular distances Mesting A - crater" was developed. As a result for the first time a system of selenodesic coordinates in 32 craters independent in scale and orientation was constructed on heliometric measurements [39].

In 1975-1985 Ju.A.Nefedyev made 1500 measurements with the purpose of determination of the selenocentric coordinates of 10 craters by referring to stars. Thus for the first time it was constructed of the completely independent system coordinates of 10 craters [43].

Results of the comparative analysis eight main selenodesical systems of coordinates are given in work [24].

A method of analysis of accuracy of selenodesic basic systems discussed in the article [55] by direct comparison coordinates of crater from catalogues with its measured coordinates on large-scale star-callibrated lunar photographs.

N.G.Rizvanov investigated a geometrical figure of the near side of the Moon on large-scale star-callibrated lunar photographs [25]. The radii - vectors of points of a lunar surface were determined with selenocentric coordinates craters from the catalogue [52]. The objects of the catalogue were grouped in areas. The average values of their heights determine the absolute heights of appropriate areas. It turns that relief of a surface of the Moon on a data of the catalogue [52] to the north from parallel of +10 degrees up to 2 km below a standard level determined on other ground-based observation of the Moon. This effect was confirmed by the analysis photographs of the Moon from spacecraft "Zond-6,-8" and other space experiments.

Relief of lunar near side with data of six selenodesic catalogues constructed on ground-based observations was investigated [20]. The analysis of a physical surface was made by means of the expansion of the absolute heights of craters in terms of spherical functions. The gipsometric map was received with data of the catalogue of I.V.Gavrilov. With results of expansion of heights of all six catalogues in terms of spherical functions is constructed averaged approximative ellipsoid. Comparison of results of research with data of other work is made. M.I.Shpekin [61] on the basis of the analysis of photographs of the Moon from spacecraft "Zond-6,-8" gave the quantitative description of a region of the sea East. For this purpose he determined selenodesic coordinate of 72 craters and measured 17 profiles of the limb. It is shown that the difference of heights in a researched region consists about 10 km, the heights of mountain reach 4.6 km, depth of marine sites - 4.8 km.

It is separately possible to allocate work of K.S.Shakirov on determination constant of LPhL and coordinates of crater Mesting A in relation to a centre of mass of the Moon [59]. He reduced 89 meridian observations of Mesting A crater carried out in Greenwich observatory in 1952-1954 and alongside with parameters of LPhL three-dimensional coordinates of Mesting A crater relatively a centre of the figure of the Moon are received. He for the first time in the world showed that the centre of mass of the Moon is located on 3.3 km closer to the Earth relative to centre of its figure.

5. Interpretation of space experiments, methods of the observation from a surface of the Moon

Sh.T.Habibullin and Ju.A.Chikanov carried out a cycle of works on interpretation of trajectory measurements of a gravitational field of the Moon from spacecraft. Results of determination of parameters of LPhL g' and f on a basis data of measurements from lunar artificial satellites are resulted in the article [21]. A problem on values of coefficients of expansion of potential of the second order C20, C22 was considered on a data of expansion of a gravitational field of the Moon [22]. Determination of a figure and anomalies of force of gravity of the Moon made with results of trajector measurements of lunar artificial satellites and problem of determination of a figure selenoid, construction of a map gravitational anomalies, and equation of a surface of the moon was considered sequentially in the article [19].

Sh.T.Habibullin found relationship between coefficients of expansion of potential and relief with series of spherical functions for some models of the Moon [56]. He has considered the homogeneous Moon, case of radial distribution of density, model of Laplas and model of the Moon with heterogeneous crust.

The cycle of works on determination of parameters of selenopotencial with a data of tracking low lunar artificial satellite was carried out by R.A.Kasheev [36]. Gravitational potentials of the Moon and Mars are studied in the article [37]: results of modelling of the second derivatives of gravitational potentials are discussed as well as some aspects of planning satellite gradientometric measurements near to the Moon and Mars. R.A.Kasheev applies the probable approach to the analysis of accuracy of the description of a gravitational field of the Moon [35]. It is made conclusion about insufficiency of accuracy of existing models of a gravitational field of the Moon. The work [38] is devoted to a problem of inter satellite tracing in problems of planetary gravimetry. The case of measurement of relative radial velocity in a system two close orbital satellites and the case of measurement of radial acceleration in a system of two satellites located on different altitudes was considered.

Sh.T.Habibullin and A.N.Sanovich [26] developed a method of equal altitudes for determination of coordinates of a point of observation from a surface of the Moon. S.S.Peruansky [48] considered a problem of determination of coordinates of a point of observation on a surface of the Moon by a method of close altitudes.

6. Observations of lunar occultations.

The registration of moment of occultation of stars by the Moon is a tradicional theme in EAO. The observatons up to 1982 were carried out visually. A number of employees EAO received significant series of observations. The results are published, mainly, in the EAO editions, in the Information issues of Astrometrical Commission of Astronomical Counsul AS USSR NoNo 14-19, in the Information issues on occultations of stars and planets by the Moon issued by astronomical observatory of Kiev university, in Catalogue of observation of occultations of stars by the Moon for the years 1943 to 1971, Royal Greenwich Obs. Bull.1978, No 183, Catalogue of observation of occultations of stars by the Moon for the years 1972 to 1980, Royal Greenwich Obs. Bull. 1982.

Since 1982 the registration of moments of occultations of stars by the Moon is made by a photoelectric method. V.B.Kapkov and R.R. Shaimukhametov received 63 registrogramms of moments of occultations of stars by the Moon and one occultation of a star by asteroid Pallada [33], [57]. The diameters of 12 stars are determined [34], [58]. On the basis of reducing of

8562 observations of occultations of stars by the Moon are constructed maps of marginal zone of the Moon [6], [5]. The position of a centre of mass of the Moon was determined with ephemeride of the Moon j=2.

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