EPHEMERIDES AND CELESTIAL MECHANICS

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When solving some abstract problems in mechanics related to the dynamics of bodies and systems, the notion of an inertial frame of reference is introduced in an apparently clear and natural way by simply drawing its coordinate axes and then paying no further attention to the system of reference which is then taken for granted. If we turn, however, towards investigations of the real stellar and planetary world, or as Sir James Jeans put it, " . . . to the Universe around us," we immediately face the question of how to practically construct a useful and obvious model of the inertial frame of reference sufficiently close to reality.

An answer to this question is given by Ephemeris Astronomy which is a unique branch of astronomical science dealing with the well known astronomical almanacs published annually. It is these astronomical annuals, such as *Astronomiceskij Ezhegodnik SSSR*, the *Astronomical Almanac*, the *Apparent Places of Fundamental Stars*, the *Nautical Almanac and American Ephemeris*, the *Connaissance des Temps*, the *Japanese Ephemeris*, and the *Indian Astronomical Ephemeris*, that fix by their fundamental ephemerides at any epoch (a moment of physical time) a definite space-time model of the inertial frame of reference. This model serves as the basis for all exact science dealing with space and time measurements and especially for positional astronomy.

Fundamental astronomical observations have served, and are still serving, to establish the conventional equatorial coordinate system. These observations have been used to compile catalogues containing positions and proper motions of stars, so that stellar catalogues, along with an adopted numerical value of the precession constant, geometrically define a stellar (sidereal) frame of reference. It is with respect to this stellar, kinematic, frame of reference that the positions of other stars, as well as of the Sun, Moon and major and minor planets, have been determined.

Celestial mechanicians integrate, either analytically or numerically, the differential equations of motion of celestial bodies to construct theories of lunar and planetary motions, and to obtain solutions, using

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e.g., analytical methods, as functions of time and several arbitrary constants. In order to make these solutions represent the actual motion, i.e., to give the coordinates and velocity components of relevant celestial objects in the past, present and future in the form of ephemerides, the celestial mechanician should evaluate these arbitrary constants on the basis of the very same observations. With the advances in the methods and techniques of observation, e.g., the development of direct, radar and laser ranging to planets and to the Moon, respectively, the accuracy of the determination of these arbitrary constants has been increased considerably and therefore, that of the astronomical ephemerides.

Now, returning to the equatorial and ecliptic systems of reference, it is evident that they are defined and provided respectively, by the Earth's diurnal rotation and heliocentric orbital motion relative to the stellar frame of reference. Hence, following R.L. Duncombe, P.K. Seidelmann and T.C. Van Flandern, one should distinguish not only between the dynamical and catalogue equinoxes, but also between the dynamical frame of reference and the frame of reference defined by a particular star catalogue, e.g., by the fundamental FK5 catalogue, although both of these systems are usually called by the same name as equatorial ones. Celestial mechanics, as in the case of theories of the motion of the Sun, Moon, and major and minor planets, also provides for the theory of the Earth's rotation around its axis, giving an exact description of the precession and nutation of the Earth's rotation axis, so that the basis of the astronomical method of time measurement is defined. Hence in this way the space component of the astronomical model of the inertial frame of reference is complementary to the space-time system of coordinates, and the ephemerides published in the astronomical almanacs mentioned above, may be considered as a real implementation of this system.

Things are not quite so simple, however, because of the transition from Newtonian dynamics to General Relativity which has led to cardinal changes in the point of view of the very notion of a frame of reference as the space-time continuum. Newtonian dynamics were adopted for planetary theories by Le Verrier and Newcomb, and were used in the issues of the *Astronomical Almanac* before the issue for 1984 (for the *Astronomiceskij Ezhegodnik SSSR* before 1986). In those years, the relativistic equations of motions were introduced for the Sun, the Moon, and major planets, as well as for some massive minor planets. The concepts of coordinate time and proper time were also introduced.

Historically, the rotating Earth was replaced as the time standard due to irregularities in its diurnal rotation rate discovered by N.M. Stoyko. It was first replaced by another time standard founded on the Earth's heliocentric orbital motion, which is reflected by the transition from *Universal Time* to *Ephemeris Time* as the time argument in the ephemerides which was called, by G.M. Clemence, the *Newtonian Time*. Due to progress in physics, a more efficient, practical realization of a uniform time system, *Atomic Time*, has been developed. This has been accompanied also by the perfection and refinement of the theory of the perturbed diurnal rotation of the Earth. This involves the introduction of more correct

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geophysical models of the Earth's interior structure in both their mathematical and physical aspects. For example, the interaction between various compound layers, such as the mantle and the core, are taken into account, and the parameters of these models are better fitted to actual observations.

As one of the essential parts of the general problem of Ephemeris Astronomy, the problem related to constructing a consistent system of astronomical constants and geodetic parameters may be considered. That is, celestial mechanics, being the science of studying the motion of gravitationally interacting mass-points through theoretical astronomy (which when combined with celestial mechanics is known as *Dynamical Astronomy*), is making profound use of results obtained by celestial mechanics to study the motions of finite bodies. These results, a particular example being the theory of equilibrium figures of celestial bodies, provide theoretical relationships between a certain part of these constants and parameters which permit one to speak about the consistency of the system.

Major alterations in the theoretical foundations of astronomical ephemerides follow general progress in astrometry and in celestial mechanics, directly affecting the system of astronomical constants. Thus, before new sets of lunar and planetary theories such as DE 200/LE 200, VSOP-82 and ELP-2000, came into existence, very extensive work had to be done to establish the new IAU System of Astronomical Constants (1976, 1979), and to build up the new IAU Theory of Nutation (1980), based upon the more perfect geophysical model of the Earth developed by Gilbert-Dziewonski and J. Wahr

On the other hand, in view of the planned introduction of the FK5 system equinox (to which the dynamical equinox of DE 200/LE 200 is the closest) into astronomy in general and into astronomical ephemerides in particular, the expression for UT1 in terms of Greenwich Mean Sidereal Time has been redefined.

In this way the modern astronomical frame of reference has so far been established and "incarnated" by the fundamental ephemerides of both the *Astronomiceskij Ezhegodnik SSSR* and the *Astronomical Almanac*. Of course as of now one cannot speak about having in hand the frame of reference with the catalogue equinox of the FK5 system since the systematic differences between the FK5 and the principle catalogues, such as the GC and N30, are not yet known. The complexity of establishing a unique system of reference by any method, kinematic or dynamic, is confirmed by the fact that even the determination of the position of the equatorial plane by using samples from one and the same catalogue of star postions yields, as was shown by H. Eichhorn, various frames of reference depending upon the sample selection. The same kind of intricacy may be illustrated by the discrepancies in the coefficients of the obliquity as well as of the expansions of the precession parameters computed on the basis of DE 200/LE 200 and VSOP-82, even though the arbitrary constants entering the VSOP-82 were determined by means of numerical DE 200 data. Such discrepancies could be caused by certain differences in reduction algorithms. This fact

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shows itself, for instance, in the definite variability of results obtained in the reduction to apparent place if performed in accordance with the algorithms recommended by K. Yokoyama for the treatment of observations made during the MERIT campaign, or if performed with those adopted for reduction computations at some astronomical institutions.

The dependence of astronomical ephemerides on celestial mechanics, or more precisely, on dynamical astronomy is also illustrated by frames of reference connected with the Moon and planets, i.e., on selenographic and planetographic coordinates. The same is true also for the satellites of major planets. The classic selenographic system of reference may, in particular, be mentioned which is defined by the Cassinian equator and the first radius of the Moon. The orientation of this frame of reference with respect to the ecliptical coordinate system is defined in terms of the Moon's mean orbital elements. Recently, the correct solution based on a strict treatment of Euler's equations of the Moon's axial rotation has defined the new, selenodetic coordinate system with its axes directed along the principle inertia axes of the Moon's body to which positions of lunar surface points as well as those of the Moon's artificial satellites may be referred. Actually, the ephemerides of the Moon's physical libration parameters are referred to this frame of reference, thus describing the perturbed axial rotation of the Moon as that of a body of finite dimensions and of a complex shape. An even more striking example of this dependence is presented by the problem of constructing an astronomical frame of reference with the Laplacian plane chosen as the fundamental one. This is due to the very high "sensitivity" with respect to the planets' masses.

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