THE NECESSARY PROCEDURES TO REACH AN AGREEABLE REFERENCE FRAME
–COUNTER-PROPOSAL TO THE CIRCULAR LETTER N°4 OF KOVALEVSKY–

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ABSTRACT The procedures are summarized in order to obtain a reference system which is available at the present moment and in the near future for the astronomical purposes. The target of the present discussions is the IAU General Assembly to be held in the summer of year 1991, in order to find out an agreeable result there. Discussions beyond this are postponed to a further occasion.

Introduction

Reviewing the voluminous Circular Letter n°4 of Kovalevsky to Subgroup on Coordinate Frame and Origin (SgCFO), dated July 17, 1990, on the very delicate problems, I feel nevertheless some difficulties to accept these proposals as they are. I have here made the modifications and / or counter-proposals and comments, respectively, as follows:
section 1. corresponds to the original section 2.1 (G1); section 2. to section 2.2 (G2); section 3. to section 3.1 (R1); section 4. to section 3.2 (R2); and section 5. to section 4. The reason(s) why I have made the counter-proposals may be found in the comments, which are arranged as the second subsection of each section. Each subsection is further divided into several subsubsections in some cases.

In the following, I have used the abbreviations: A for Aoki, and K for Kovalevsky.

1. Recommendation on the Definition of the Reference Frame to be Aimed (G1)

1.1. PROPOSAL

I have proposed the expression of the line element in the form that it gives the time-like argument instead of the original form which give the space-like argument. The concrete expression was given in a letter to K, September 20, 1990.

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1.2. COMMENTS

1.2.1 *Conceptual / Conventional Definition.* To my opinion, the discrimination between the conceptual and conventional definitions is not clear (For some details, connecting to the CEP, see A 1990, Appendix B) . Therefore, I have chosen the wordings "definition to be aimed" and "definition to be realized or realizable" instead. For I don't prefer, in particular, the usage of "conventional" in the meaning of "which should be avoided".

1.2.2 *Reference Frame / System.* The usage of "reference frame" and "reference system" by Kovalevsky seems not to be recommendable. See A 1990, Appendix A. Also see the arguments by Eichhorn 1990.

1.2.3 *Form of the Line Element.* The original expression of the line element is given to be applicable for the barycentric system of the solar system, as well as in order to cover the local systems, such as the geocentric system. However, according to my opinion, the latter case is derivable from the former, and it is not necessary to give it. Instead, I think it is necessary to give the expression of the potential function in a more explicit form, in order to avoid a possible confusion.

2. Constraint Recommendation (G2)

2.1. PROPOSAL

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considering
a) the necessity to define a barycentric coordinate system centered at the barycenter of the solar system, a geocentric coordinate system centered at the barycenter of the earth, and the terrestrial coordinate system,
b) the desirability that the coordinate system be linked to the best physically realizable references in time and space, and
c) that the theory of general relativity is appropriate to describe the reference frames,

recommends

1. that it is urgent to research whether the coordinate system without rotation considering only the masses within the solar system conforms with that of the whole universe or not,
2. that the geocentric coordinate system is constructed so as to be tangential [in other words, in such that its time coordinate is selected to be the proper time at the geocenter (which is the origin of the coordinate system) given by the line element of the basic coordinate system for which the mass of the earth is omitted and its spatial coordinates to be perpendicular to its time coordinate at the origin], but of which the so-called *geodesic or relativistic precession* is discarded, in order to be a natural coordinate system.
3. that the relation between the geocentric coordinate system and the terrestrial coordinate system should be accounted for the rotation of the earth and for the attracting force arising from the mass distribution within the earth, and

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4. that in order to be parallel in average between the time reading of the coordinate time in the barycentric coordinate system of the solar system and that realized on the (timely averaged) geoid of the terrestrial coordinate system, the units of time arguments are selected to be

$$[s_T] = (1 - 1.55050 \times 10^{-8})[s_B], \tag{1}$$

where $[s_T]$ is the time unit of the terrestrial coordinate system, identified with the SI Unit, and $[s_B]$ is the time unit of the barycentric coordinate system.

2.2. COMMENTS

2.2.1 *Natural Coordinate System.* It is not yet sufficiently established that the quasar system links to the non-rotating system in the dynamical sense. For detail, see A 1990, Appendix A (in which I have discussed that the so-called "ideally quasi-inertial system" should be replaced by the natural coordinate system), and section 6.2 (in which I have discussed the (supposedly apparent) motion of 3C273B).

I think it is necessary to add the last clause in the item 2. of the Recommendation beginning with "but." See a discussion on the geodesic precession in A 1990, Appendix A.

2.2.2 *Barycentric, Geocentric, and Terrestrial System.* I think it is necessary to give the relations among the barycentric, geocentric, and terrestrial systems in a clearer and more concrete expression than the original text.

2.2.3 *Scaling of the Time Argument.* I still have the opposite opinion against to abandon the present convention of scaling the time argument.

The main reason of my opposition is that the existing planetary ephemerides in terms of TDB are to be neither excluded nor re-calculated, and for the sake of continuity it is necessary to have these ephemerides also in the future. The similar opposisions are expressed by people of JPL, such as Lieske, Dickey, Williams, and Standish.

The numerical value given in eq.(1) comes from Fukushima et al. 1986.

3. Recommendation on Reference Frames to be Aimed (R1)

3.1. PROPOSAL

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considering
a) that the reference frame should be still defined to be referred to the mean equator and equinox of the fundamental epoch of J2000.0 (say),
b) that the catalogue to be realized should include objects being well coordinated and emitting any electromagnetic wave available for the astronomical purposes, and

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c) that this catalogue should be an extension of the presently existing FK5,

recommends

1. that an international working group be set up, in order to select the appropriate candidate objects for constructing the reference coordinate system, consisting of members of Commissions 4, 8, 19, 24, and 31, and other pertinent experts, with consultation of Commissions 5, 33, 40, and all the pertinent (or relevant) institutes;
2. and that its subgroup collect all the observational data of their positions and principal characteristics available and compile the positions, in particular, with respect to the reference frame defined above, as early as possible, so that the new fundamental catalogue serves as a continuation and/or an extension of the FK5.

3.2. COMMENTS

3.2.1 *On the Definition of Reference Frame.* I have a strong objection to *define* the reference frame [the reference system, in Kovalevsky and Mueller(1981)'s sense] by a set of quasar system. The reason is that we do not know whether the quasar system represents the ideal system which is considered in Recommendation G1. (See A 1990, sections 2 and 4). Wielen comments " If we would *define* the coordinate system at J2000.0 implicitly by a set of quasar positions, how should we improve this list by further observations?")

De Vegt argues that VLBI uses objects [quasars] which stem from a class displaying most variable astrophysical properties and which in addition are poorly understood; and further argues that this could have a serious impact on the longterm usability of this object class (change of spatial structure and emission strength). Murray comments " We know from experience that even in the best fundamental catalogues there are individual and systematic regional errors. How can we be certain that VLBI catalogues do not have analogous errors, albeit on a small scale?"

The problem depends on the accuracy obtained or obtainable. When we have the more accuracy, we have to take the more care of it. I have a common opinion that the reference frame should be defined by the mean equator and equinox at some epoch, say J2000.0. We should not change this conventional principle as was stated by Murray.

3.2.2 *A Working Group.* As was discussed by de Vegt in his letter to K. on 23.05[*sic*].90, the IERS group has interest only on the quasar positions. However, the objects, to be coordinated, are not restricted only to the radio sources. Therefore, the IERS to which the original proposal refers has been replaced by an international working group, according to his suggestion.

4. Recommendation on the (Conventional) Reference System to be Realized (R2)

4.1. PROPOSAL

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considering
a) that the new conventional celestial barycentric reference system to be realized should be as closely as possible to the existing FK5 reference system as referred to J2000.0, and
b) that it should be accessible to astrometry[-rist] in visual wavelengths as well as in radio wavelengths,

recommends

1. that the position of the extragalactic sources given in the catalogue representing the reference system be computed for the epoch J2000.0 using the presently adopted value of precession and nutation,
2. that a great effort be developed in intercomparison of reference systems of all types between them and particularly with FK5 and extragalactic reference systems,
3. that all types of observing programs be undertaken or continued in order to link to a catalogue of extragalactic source positions to the best catalogue of star positions, in particular FK5 and HIPPARCOS catalogues with the accuracy of these catalogues, and
4. that the Ox axis of the spherical coordinates of the conventional celestial reference system be as close as possible to that of the FK5, equinox J2000.0, and that the principal plane be as close as possible to the mean equator at epoch J2000.0.

4.2. COMMENTS

4.2.1 *Designation of the Fundamental Epoch.* J2000.0 is employed here for the designation of fundamental epoch, in accordance with the IAU recommendation 1976, instead of J.2000 of the original text.

4.2.2 *Reference System / Frame.* Exchanges between "reference system" and "reference frame" are taken place. As for the reason, see section 1.2.2.

4.2.3 *What is the Best Value?* I have changed "the best available values of precession and nutation", in item 1. of the original text. The reason is as follows:

(i) It is very hard to accept the statement which gives an allowance to use the best value for the precession constant instead of the presently adopted constant, since the meaning of the "best" will depend on each researcher's judgment. In fact, we cannot separate the precession from nutation, even using the very accurate VLBI observational data presently available (For detail, see A 1990, section 4.3.)

(ii) Moreover, it is unusual in the history of the IAU to give such an allowance without specifying the value to be used of an important astronomical constant. If this would take place, we would not be able, afterwards, or at least it would be very difficult to follow up what value some person actually used.

(iii) Schwan in his letter to K, 30 August, 1990, stressed that "We should therefore make the extrapolation to J2000 with the IAU standard values because a frequent change in the constants is very unconvenient[in-] and even dangerous if different observations are to be compared (see also my [Schwan's] letter of 28 May 1990)." De Vegt, in his letter to K, 23.05[sic].90, gave a similar opinion.

4.2.4 *Reference System to Which the Motion is Described.* There was some confusion and misunderstanding on the "motionless." In fact, in the past, there were some quasar catalogues without mentioning their mean observation dates explicitly, according to Walter 1990, probably from a reason because the quasar system is "motionless." They were, I think, coming from a bad practice. We don't know exactly the precession constant; therefore, the reduced position for each obserevation epoch using an adopted precession constant is not necessarily fixed. After assemling such data, we can separate the precession constant statistically in such a way that the precession refers to the mean position of ensemble of the observed objects. This convention has been applied since the days of Bessel. It is very important to notice that the method does not depend on whether the objects do move or not. In other words, it is not pre-requested that the ensemble is motionless or not. It is still valid for quasar system, albeit the degree of accuracy is much higher than the stellar case. Yet, I am afraid that there is a misunderstanding on this point. It is important to recall that we should always mention something to which "the motion" is referred. In fact, Smith asked "but relative to what [the motions of quasars are measured]?" It is a tautology and trivial, as is easily understood, to say that the quasar system is motionless with respect to the quasar system.

4.2.5 *Dynamical Reference System.* There is another kind of reference system which is called dynamical. This reference is based on the dynamical solution of the members of the solar system. Such a system should be connected with the statistically obtained quasar system. Presently the link is not so tight because of the lower accuracies in the optical observations of the sun and the planets than radio range observations. However, I have a hope for a time when sufficient observational materials of the so-called millisecond pulsars are collected, since the analysis of these materials is expected to be able to afford the orbital motion of the earth with respect to the radio source system. See, for more detail, A 1990, section 3.

4.2.6 *The necessary Steps.* It is not yet established whether the apparent differences in orientation among various VLBI catalogues at a level of milli-arcsecond (mas) are really due to the nutation offsets depending on the selected reference days, respectively, (A 1990, section 4.3) or due to the other systematic errors involved in the reduction analysis. In fact, during a discussion with me when Ma visited Japan, he recognized that a presently compiled catalogue, such as Ma et al. 1990, depending on the reference day, is a catalogue with tentative character. Therefore, the steps to be taken are as follows:

(i) To establish observationally the offsets of the nutational coefficients at least for the short periods (equal to or less than one year), by excluding any contamination caused by the other effects.
The subgroup on nutation has decided not to adopt new nutation series for the time being since the theoretical consistency is not yet obtained. But we may obtain observationally a tentative nutation series for the components including the so-called out-of-phase components [See, e.g., Herring et al. 1986] at least with periods of or less than a year.

(ii) To obtain theoretically the real causes of the offsets on the well-established internal constitution of the earth.
The terrestrial reference coordinate system should be referred to the so-called Tisserand mean axes (see Munk and MacDonald 1960, p. 10f.), which is defined in such that the total angular momentum of the earth referred to this coordinate system is zero. However, this is not yet accomplished, because the observation sites are scanty on the earth's surface, and because we have to use a modeling of the motion of crustal plates, e.g., such as given by Mister and Jordan 1978.
We do not know the modeling of plates, on which the observatories reside separately, is altogether correct, because of the scanty number of the observatories. The present practice may lead us thus to a divergence in the definition of reference coordinate systems among the different networks depending on the different choice of the VLBI observation sites.

(iii) Upon completing the above steps, we may have the quasar positions with respect to the *adopted reference system*, not on the basis of day by day but of year by year. It is not recommendable to analyze the quasar positions using a reference day discussed by Ma et al. 1990 [Also see Sovers 1990], because the quasar catalogue reduced to a fundamental epoch such as J2000.0 depends on the reference day, since the adopted values are not so accurate that they do not represent the orientation of the earth in space.
This means that the reference coordinate systems, to which such catalogues are referred, may be their own tentative reference systems but do not represent the unique reference system. According to Ma's opinion, the quasar positions are sufficient if they are expressed in a relative sense. This may be true as far as we consider only the quasar observations, but this does not mean that such a treatment produces the reference coordinate system to which the every astrometric observations should be referred.

(iv) Then we have the separation of the precession from the nutation if the observational materials are accumulated at least for a score of years or more.
Note that the present situation, on the contrary, is not sufficient. Note that it has a merit to separate precession from nutation, because the precessional motion is considered as if the earth is solid, while the amplitude ratio of the deformable earth to the solid earth for a nutation component depends on its period [See A 1988, section 5.] Thus the theoretical nutation amplitude can be easily treated, if each component of the nutation is separated from the precession.

It is not yet accomplished so far, however, to separate the precession from the nutation in the VLBI observations at the mas level because sufficient data are not yet available only from the decade observations. It needs at least 18.6 years to separate fully the precession from the nutation component associated with the nodal motion of the moon, in such a degree that this is comparable with the highest order of magnitude for the accuracy presently obtained.

(v) And then we can test whether the quasar system is connected to the dynamical system expressed in the relativistic theory discussed in Recommendation G1.
As was discussed in A 1990, Appendix A, we do not know so far that the extragalactic system represented by quasar system is rotation-free or not, because this is given only kinematically. We should have a test by the dynamical system, namely, by the natural coordinate system. [I still oppose the expression "ideally quasi-inertial", because this is very misleading.] We know that the optically observed data are not sufficiently accurate, but we may expect radio observations of millisecond pulsars and/or artificial proves traveling through the solar system with much accuracy within a decade or so [as was discussed in a letter by Williams to K, February 1].
This does not mean, however, that the terrestrial optical observations are obsolete, because the optical observations have their own long history and the separation of precession from the proper motion system of the galactic objects has been made using the optical observations. We have to do, therefore, many works such as coordinating radio sources within the FK5 system before we could construct the reference frame.
Note that the precession of order 0."1 / century is not yet known even from the VLBI observations. Moreover, the quasar observations are not all the observations in the field of astrometry. We should take also care of the optical observations hitherto obtained and to be observed in future. Also we should keep in mind that the FK5, e.g., has much more objects in number than those of the quasar system so that we can coordinate easily the other objects referred to the former catalogue. Without such a catalogue, we cannot compare the positions directly with quasar system because the quasars generally have only their very weak optical counterparts so as to be observable for comparison.

(vi) Finally when all these steps would have been well done, then we could know whether the quasar system is really rotating or not.
I have heard, however, from Ma that it would take quite a lot time if we want to compile and to combine all the material such as of Crustal Dynamical Project (CDP), International Radio Interferometry Survey (IRIS) and Deep Space Network (DSN) obtained from the different networks and different purposes, although the techniques used in the VLBI observations are almost the same. What we should do right now is, however, to reduce the quasar positions to J2000.0 by using the adopted precession and the adopted nutation series *mutatis mutandis* [with alternations if necessary] for the short periods given by the above analysis. The reduced positions thus obtained can be at least free from the uncertainty of the nutation series of period one year or less, and could represent a common catalogue.

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Note, however, that the reference frame is dependent on the adopted precession and adopted nutation series at the highest degree of accuracy, because we do not know the exact precession nor nutation series beyond the observation accuracy of its date. [See, for detail, A 1988, section 6.] This implies that the reduced positions to a fundamental epoch are not necessarily constant but are subject to a proper motion referred to the adopted precession constant. This situation could not be avoided at any historical dates and will not be able to be altered for the future, as long as we observe celestial objects from the surface of the earth, because the precession and the nutation are not given *a priori* but they should be given from the observations depending on the orientation of the earth.

It should not be considered it as a degrade to use the precession and nutation. Also one should not be reluctant by the degrade (uncertainty) limited by the adopted precession and nutation series, but one should determine them by observations themselves, because the terrestrial observations anyhow depend on the precession and nutation.

Unless these steps are taken, I think we cannot have a unique or the unified celestial reference system proposed up to the mas level acceptable among those who have interest in the present issue. Make haste slowly!

5. Recommendation on the Relation between the Tentative (Conventional) Terrestrial and Celestial Reference Coordinate Systems

5.1. PROPOSAL

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considering
the present situation of the realized celestial reference coordinated systems,

recommends

that the relation between the (spatial) terrestrial reference system mentioned in Recommendation G2 and the presently realized (spatial) celestial reference system be given by

$$[\mathrm{TRS}] = W R_3(\hat{\phi}) N P [\mathrm{CRS}]. \tag{2}$$

The mathematical symbols employed here denote as follows: [TRS] and [CRS] are the vector representations of the spatial terrestrial and celestial coordinate systems (in three dimension), respectively;
W, N and P are the wobble, nutation and precession matrices given, respectively, by

$$W = R_2(-x_\mathrm{p}) R_1(-y_\mathrm{p}), \tag{3}$$
$$N = R_1(-\epsilon_A - \Delta\epsilon) R_3(-\Delta\psi) R_1(\epsilon_A), \tag{4}$$

and

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$$P = R_3(-z_A)R_2(\theta_A)R_A(-\zeta_A), \tag{5}$$

where x_p and y_p are the terrestrial polar coordinates in the left hand coordinate system usually employed, $\Delta\epsilon$ and $\Delta\psi$ are the nutation series given in Seidelmann 1982, and $\epsilon_A, z_A, \theta_A$,and ζ_A are the components of the precession quantities given by Lieske et al. 1977, together with the rotation matrix R_1 being defined as

$$R_1(x) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos x & \sin x \\ 0 & -\sin x & \cos x \end{pmatrix} \tag{6}$$

for any dummy angle x, and the other matrices being obtained by cyclic permutations of the coordinates; and $\hat{\phi}$ is the true Greenwhich Sidereal Time defined by

$$\hat{\phi} = \mathrm{GMST} + (\Delta q)_{\mathrm{per}}, \tag{7}$$

where GMST is the Greenwich Mean Sidereal Time, which has a relation with the UT1, given in Aoki et al. 1982 and endorsed by the 18th GA of IAU (Resolution C5),and $(\Delta q)_{\mathrm{per}}$ is the equation of equinoxes in wider sense and given by

$$(\Delta q)_{\mathrm{per}} = \Delta\psi \cos\epsilon + 0.''00264 \sin\Omega_{☊} + 0.''000063 \sin 2\Omega_{☾}, \tag{8}$$

with $\Omega_{☾}$ being the mean longitude of the lunar node.

5.2. COMMENTS

5.2.1 *Where Should the So-called Non-Rotating Origin (NRO) be Discussed?* Objection against the transfer of discussion introducing the so-called NRO to the IERS. It is quite curious and ironical that Capitaine and myself have a common opinion that it is the task of the subgroup, as was discussed by Capitaine, notwithstanding our opinions on the problem itself may be quite different from each other.

5.2.2 *Demerits of NRO.* According to my opinion, the so-called NRO has demerits as follows:

(i) This Origin is only locally inertial (namely as far as the rotation of the earth is concerned) but moves with respect to space even to the right ascension direction, against its naming, and is very misleading: For example, we can easily know that after a complete revolution of the precessional motion (26,000 years), the right ascension (RA) of the NRO increases by an amount $360° \cos\epsilon$, while an object at the equinox at the beginning will recover the same RA or increase 360° after the same period, so that the NRO moves $360°(\cos\epsilon - 1)$ with respect to space in this period. In order to make clear this fact, I prefer the departure point (or the local inertial direction) on the moving equator, to the NRO, as the naming, according as the usage of celestial mechanics. In case of the nutational motion of 18.6 years, this amount is estimated to be −0.72 mas per period, which is not negligible for accurate determination of the sources. Besides, we have the periodic motion given by the last two terms of the right hand side of eq.(8). See also A 1989.

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This phenomenon can be explained mathematically from the fact: a direction on a tangential plane to a sphere of the unit length cannot keep its original direction when the plane contacts without sliding and local rotation around the contact point and returns to the the starting point of contact. The change or difference of the direction during this route is equal to the area described by the normal of the tangential plane on the unit sphere. In other words, the tangential plane is only local and does not represent the direction in the original space.

(ii) The difference between usual RA and the instantaneous ascension (IA, which is the RA direction coordinate referred to NRO, according to Guinot[1979]'s naming, although I dislike this naming), is nothing but the RA of the NRO and is completely calculatable, if one adopts a precession constant. In this meaning, the choice of two ascensions does not make any difference mathematically and has no merit. [See Aoki, S. and H. Kinoshita 1983.]

(iii) Moreover, the fixing the coordinates at the beginning and the continual prolongating the position of the NRO by integration, which CGS (1986) intend, has a demerit, because we cannot have any recovering procedure when once we have committed errors which would be serious at later times, however they might be slight at the standards of the beginning, if we do not have a room for adjustment procedures such as the equinox correction. To abandon such a degree of freedom for adjustment procedures is, I think, to loose the relation to the fiducial point at the beginning.

5.2.3 *Equinox Correction.* Incidentally, it should be noted that the neglection of the equinox correction ΔE (or the correction to the fiducial point) already takes place in the formulation given in IERS Annual Report, for the year 1988. Correctly, the fourth line of equation (3) should read

$$\Delta \mathrm{d}\psi = \mathrm{A2}/\sin\epsilon = -(\mathrm{A3} - \Delta E)/\cos\epsilon$$

(with the signs taken in ERRATUM), instead of $\Delta \mathrm{d}\psi = \mathrm{A2}/\sin\epsilon = -\mathrm{A3}/\cos\epsilon$, since the difference A3 in orientation can be interpreted as to include generally the difference of RA of the fiducial points in comparing catalogues not only the difference in the offsets implicitly taken in precession and nutation. A similar error is found in Arias' letter to K, October 26, 1989. If this or similar erroneous formulations are widely spread, the influence is very serious.

5.2.4 *Current System.* Anyhow, my recommendation stated above is a confirmation of the currently adopted or to be adopted with a slight but important modification [see section 5.2.5] from my stand-point.

Now, the expressions adopted here are taken from those given in Aoki, S and H. Kinoshita 1983, and A 1988, except for the notations.

5.2.5 *Amelioration.* An important amelioration of the relation between the Greenwich True and the Greenwich Mean Sidereal Time adopted here is an introduction of "the equation of equinoxes in wider sense" which differs from "the equation of equinoxes $= \Delta\psi \cos\epsilon$" currently adopted, by the amount coming from the last two terms of the right hand side

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of eq.(8). The terms with similar numerical coefficients were discussed by Woolard (1953), but the astronomical circle has not yet formally adopted these terms.

As for the light deflection and aberration due to the relativistic effect through the gravitational field of the solar system, which is not discussed here, see IERS (or Merit) Standards.

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