CONCEPTS OF REFERENCE SYSTEMS

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ABSTRACT

With the atomic clocks and VLBI catalogues of extragalactic sources, the theory-independent references for both space and time will be quasi ideal in their underlying principles (non-rotation of very distant objects, constancy of the frequencies associated to atomic transitions). The paper is an attempt to clarify the role of these natural references with respect to those which are implicitly defined by the dynamical theories.

The example of time is discussed, since it already gave rise to serious difficulties, but similar problems may occur about the space references. Such complexities are suprising: one could have expected simplifications from the use of references which are not entangled with theory. Some suggestions are made for the use of these natural references.

INTRODUCTION

The general principles of the definition and realization of references in space have been discussed by Mueller (1981) and Kovalevsky and Mueller (1981) (This last paper will be denoted by KM in the following). While being largely in agreement with these authors, I will present the subject under a slightly different light and extend the discussion to the references for time. As far as possible, I will use the terminology proposed by KM.

In the history of astronomy, the references for the dynamics have long been considered as naturally given by the mean duration of the day and the star directions.

But, after some decades of investigations, we observed around 1950 the triumph of the method which consists in deducing the time from the dynamical study of orbital motions. However, rapidly (1955) the atomic

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clocks have brought the possibility of coming back to a reference which is independent of dynamical models.

There are no such clear-cut changes for the space references. Nevertheless, the determinations of the precession constant by dynamical methods, after the first applications in 1950, gradually improved, and were used at least as a confirmation in the adoption of the new conventional value of the precession constant in the IAU (1976) System of Constants. But, in space, the adoption of references also free from theory can be expected from the VLBI observations of extragalactic sources.

The aim of this paper is to discuss the concepts which are at the basis of our reference systems (and reference frames), and to draw the attention on the importance of the present evolution. Some suggestions will be made to avoid the confusion of concepts which leads to difficulties, as shown recently by discussions on the time scales to be used for dynamics.

CONCEPTS AND REALIZATIONS

The realization of references, which are available for practical use (conventional reference frame), requires two necessary phases (a) and (b), and a phase (c), which can be sometimes omitted.

(a) The conception of the reference consists in defining the class of phenomena that are supposed to be appropriate for providing the needed reference frame. It is a quasi-philosophical problem ; but, in general, it does not present itself as a choice to be made. The quality of the realization, which will be considered in (b), often imposes a particular concept. That is the reason why the importance of the concept is under-estimated. { In the metrology of basic physical quantities, the concept is almost always ignored, because the nature or the precision of the measurements does not let any choice, but in principle, the concept exists. For example, we could wonder whether the unit of mass should be defined by consideration of gravitation or inertia } .

After the selection of the concept, KM considers a next stage which is the definition of an ideal reference system (the conventional reference system). This stage, in my opinion, is not always clearly separated from the realization in (b), and I am afraid that, using the KM terminology, it could lead to a confusion between "Conventional Reference System" and "Conventional Reference Frame". { Many authors already use "Conventional Terrestrial System" for what should be "Conventional Terrestrial Frame" } .

(b) The realization consists in giving the means of referring the measurements to an unique reference which agrees as well as possible with the underlying concepts of (a). In the usual metrological

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terminology, it is the primary reference (the "Conventional reference frame" in KW) which can have quite different forms, according to the quantity under consideration : definition, procedure, material system, etc.

(c) The secondary references are globally in accordance with the primary reference, but their use may be easier or more precise in some domains (in general of restricted temporal or spatial extent).

The pragmatic aspect of the choice of the concepts, mentioned in (a) should be somewhat detailed. It is a legitimate desire that, when one measures a quantity with respect to a reference, the main part of the uncertainty come from the measurement method and/or of the indetermination of the quantity to be measured ; ideally, the contribution of the reference itself should be negligible.

The uncertainties arising from the reference are of two kinds

- the lack of precision refers only to the quality of the reading of the reference. For instance, for the International Atomic Time TAI, this defect is of the order of 0.2 μs.

- the lack of accuracy refers to the non-conformity of the primary reference to the underlying concept. In the same example of TAI, the inaccuracy, in the present state of art, could be of the order of $2 \times 10^{-14} (t-t_o)$ or 0.6 μs y^{-1} x n years, the time being reckoned from a date where TAI coincides with a time scale established by adding ideal SI seconds.

In a broad sense, we will designate by metrological quality of a reference a relative notion referring to the level of the above uncertainties. The best metrological quality is evident when the uncertainties of both types are smaller. If it is not the case, the accuracy is often the most important criterion. For equal metrological qualities, the choice of concept would be delicate. But it does not seem that this choice has been the subject of explicit discussions. The more or less conscious transitions from one concept to the other have been dictated by large differences of metrological qualities.

NATURAL AND DYNAMICAL REFERENCES

Generalities

The two concepts which in turn prevailed are those of natural and dynamical references.

(a) A possible concept is to believe that there exist in the nature, some phenomena or some objects, which give us directly the needed references, without any dynamical theory.{In space, KW use the terms "kinematical references" ; I prefer the adjective natural which also applies for time }.

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More precisely, that means that if one wishes to make the dynamical study of a material system observed with respect to this reference, one has, of course, to find the dynamical model appropriate to the reference. But there should not be the need of a theory concerning other phenomena which would affect the reference itself (with the omission of non-critical or unavoidable corrections, such as aberration corrections).

(b) In the concept of dynamical references, one adopts a priori a model of mechanics and gravitation which is applied to a material system. Neglecting here the errors due to the modeling of forces, the integrations, the choice of numerical initial conditions, an ephemeris is obtained, which is then perfect in the framework of the adopted theory. This ephemeris gives coordinates P as a function of time (t) :

$$P = f(t)$$

Thus both the references in space and time are implicitly defined by the theory and materialized by the ephemeris and the observation.

At first sight, it does not appear possible to get simultaneously both the references in space and time. In fact, time is not critical for obtaining space references free of rotation, by analysis of the observation of planets. The dynamical approach is viable, but delicate and difficult, because of the inter-dependence of P and t and of the sensitivity to theories, models, integration and values of numerical constants.

We will briefly remind how these two concepts were applied.

Time references

From the antiquity to the middle of the 18th century, the mean duration of day has been considered a priori as constant, and the time scale based on this standard of duration, the mean solar time, was quite evidently a natural time scale to which was attributed the virtue of uniformity. After Euler's demonstration (1736) of the constancy of the speed of the Earth's rotation, one can dwell on the statute of the mean solar time : natural or dynamical ? The answer is of little importance. The true implementation of a dynamical time scale has appeared with the Ephemeris Time toward 1950. However, shortly afterwards, in 1955, was born another natural time scale, the atomic time, of which a particular realization, called later the International Atomic Time TAI, was conventionally adopted. The TAI has metrological qualities superior by far to those of the Ephemeris Time. The uncertainties of its reading and its inaccuracy are negligible for all the uses which can be made in dynamical astronomy.

Space references

The primary reference has always been a selection of stars of which positions and proper motion are given. We will consider only the residual speed of rotation of this system which is linked to the value adopted for the precession constant.

Until 1983, Newcomb's value of the precession constant was conventionally in use. However, other estimations were available long before and it was possible, whenever needed, to apply corrections. Therefore, we have to consider the concepts for the best evaluations of the speed of precession.

Since Copernic, the directions of stars give a natural non-rotating reference in space. Neither the treatment of proper motions as purely random, nor the kinematical consideration of the galactic rotation (1930), prevented the stellar system of being a natural reference.

The first significant contributions to a dynamical reference in space, through the determination of the constant of precession by study of the planetary motions, appeared toward 1950 (Brouwer, 1950, Clemence, 1950). This method, progressively improved, has become an important confirmation in the IAU choice for the precession constant in the IAU (1976) system.

The return to a purely natural system, by optical observations of extragalactic nebulae, the proper motions of which being assumed negligible, does not seem to have brought sufficient results. But, since a few years, VLBI opens new possibilities and it is generally admitted that the future primary space reference will be a catalogue of positions of radiosources, the secondary references being catalogues of star positions and proper motions, the link being made with bodies radiating in radio and optical domains. When this new primary reference will be adopted ? Probably during the decade 1990-2000.

The parallel evolution of time and space references

Figure 1 shows schematically and approximatively the evolution of the concepts for time and space references. It is quite remarkable that the dynamical methods have occurred almost simultaneously in both domains. But the return to natural references was much faster for time.

The return to a full natural system, with excellent metrological qualities will not bring us back to the situation of the first half of the 20th century. At this epoch, the inadequacy of the available natural references was known or suspected, but they were no means to palliate them. The lack of confidence in these reference and the progress due to the dynamical method did not prepare to the new situation where the natural primary references will be quasi-ideal.

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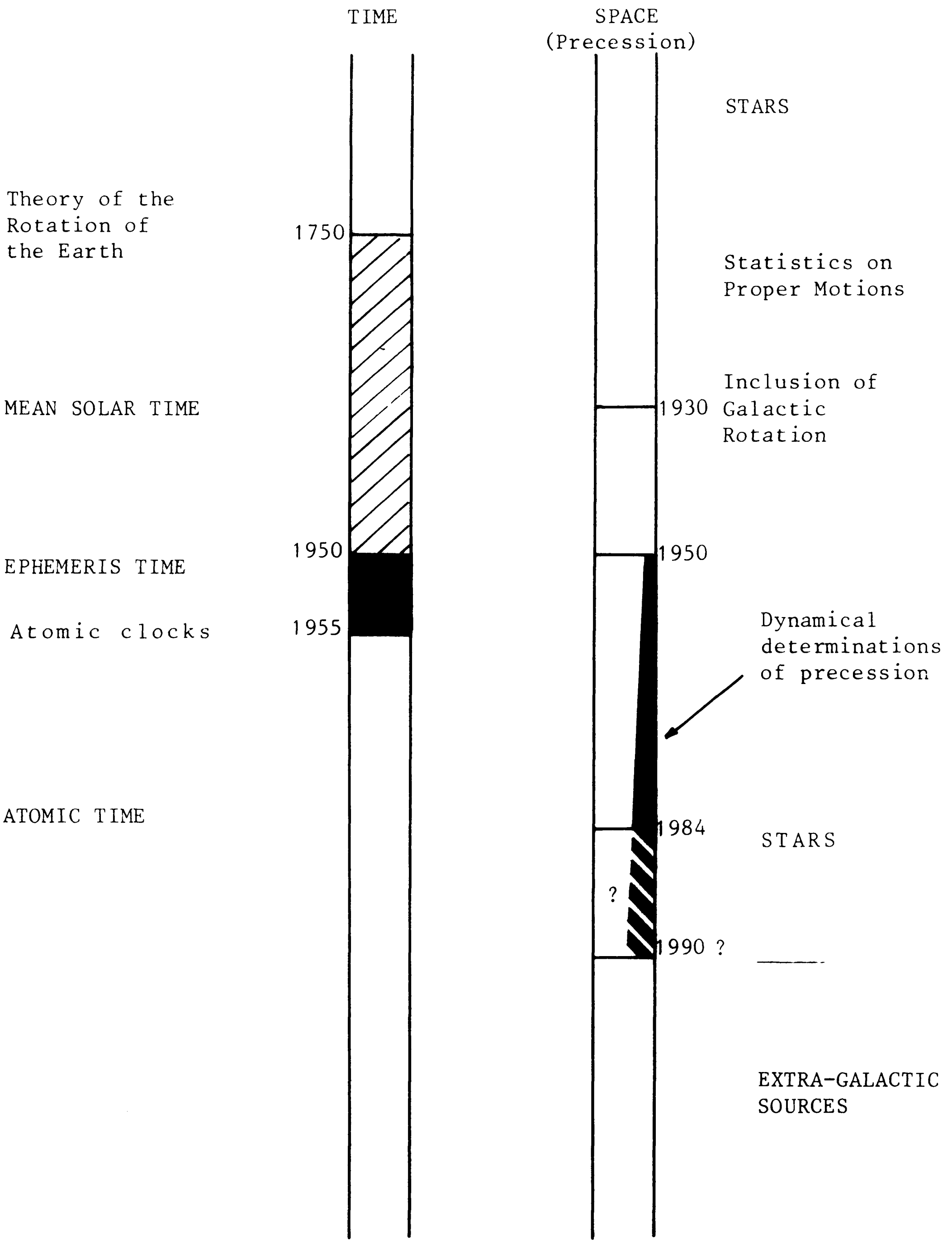

Fig. 1 - Dates of appearance of the references with the best metrological properties (their use in retrospect is sometimes possible). In black are the dynamical references.

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THE USE OF NATURAL REFERENCES

The natural references for time given by the atomic clocks being already available since more than two decades, it is interesting to observe how the atomic time is used for dynamics, in order to foresee what should be done (or should not be done) for space.

The example of time

Several atomic time scales already existed in 1958, starting in 1955, which have been used, as soon as available, to study the Earth's rotation irregularities. The use in the dynamics of the solar system was not considered so fast ; this may be explained by the long duration of the observational series to be studied.

The discussions on the time scales for the dynamics officially started within a working group of IAU Commission 4 created in 1970. They were difficult and misunderstandings persisted until the adoption in 1976, of IAU Recommendation 5. This recommendation and its explanatory notes have been almost immediatly considered as ambiguous by some parties (Seidelman et al. 1983). The discussions should be resumed, although there was a consensus for not doing so before a few years of reflexion.

(a) The atomic time was first considered as a secondary reference for the Ephemeris Time, thus keeping the concept of dynamical time. The relationship hasbecome

$$TE = TAI + 32.184 \text{ s.}$$

(b) At the beginning of the discussions within the IAU working group, it was proposed to take TAI as argument of the ephemerides. But later , it was judged better to define an ideal atomic time, by counting ideal SI seconds. In order to make clear this distinction, a time offset between TAI and the ideal time was decided. In one of its interpretation (the one which corresponds at the best with the wording), Recommendation 5 (1976) is in agreement with the above views ; thus it should mark the transition from a dynamical reference to a natural reference.

(c) The time-like argument in the development of the dynamical equations cannot be submitted to other constraints than fixing its phase and the duration of its scale unit at some instant. It cannot coincide permanently with the ideal time of (b) and still less with TAI. That is the reasons of the criticisms of Recommendation 5 (1976) or of attempts to an interpretation somewhat in contradiction with its wording.

(d) The problem of the time reference is further complicated by the distinction to be made between several proper times and coordinate-times, and also by the necessity of using observations made before the creation of the atomic time.

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The transition from a dynamical primary reference for time to a natural one does not appear as straightforward. Each dynamical development implies its own references for time and space, to which an unique primary reference, whichever be its basic concept, cannot be substituted. The discussion which was due to the availability of atomic time, could have taken place as well on the subject of Ephemeris Time, which was a primary reference, therefore unique, based on the Sun's longitude. TE should have been also distinguished from the time argument of the various ephemerides.

It is possible to establish rules to limit, as far as possible, the deviation between the various time like arguments of theories. But it is a different problem to make use of a primary reference. Recommendation 5 (1976) is ambiguous because it fails to distinguish these two problems.

Space references

It is surprising to observe that we are much less meticulous for space references. There exists a recognized primary reference, the FK5 (previously the FK4) and it is understood that the geocentric ephemerides should be expressed in this system. We do not feel any need of indicating by some special notation that the positions given in the ephemerides are referred to a system of reference implied by the theory. This is in contrast with the non-acceptance that TAI be the time argument of the ephemerides. The notion of dynamical equinox is used by specialists, but it has no official definition.

However, difficulties similar to those encountered for time can be foreseen when precise positions of extragalactic sources will be available.

SUGGESTIONS

The following suggestions should avoid misunderstandings for the use of natural primary references having metrological qualities such it is not needed to improve them by dynamical methods. For time such a reference already exists : TAI. The future reference for space (geocentric or barycentric) will be denoted by E.

Primary reference in space (reference system and conventional reference frame)

Ideally, the primary reference should have no rotation with respect to the directions of extragalactic sources. Let be X_i (i=1,2,3) the reference axis. Their choice is free, they are therefore implicitly defined by the coordinates attributed to a set of sources which realize the primary reference E (the conventional reference frame of KW). For practical reasons, X_3 could be close to the rotation pole at some instant,

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and X_1 close to the corresponding equinox. However the suggestion implies that there should be no further adjustments in order to improve the coincidence with the pole and the equinox. The improvement of E, due to better measurements of the angular distances between the sources or a better knowledge of the source structure, should be made with the statistical condition that there should be no rotation in the average.

Rotation of the Earth

The orientation of the Celestial Ephemeris Pole axis in space should be given explicitly by two coordinates in the primary reference E. The developments of the precession and nutation should be expressed as a function of TAI.

The origin in the instantaneous equator should be a non-rotating origin, deriving from the direction of X_1 of E, in such a way that the instantaneous system has no component of rotation around the polar axis (Guinot, 1979). This condition can be maintained without ambiguity, when readjusting the conventions which describe the position and motion of the pole.

Concerning the Universal Time UT1, one should distinguish between primary and secondary definitions. The primary definition should express, once for ever the linear relationship between UT1 and the measure of the arc between the non-rotating origin and the projection of the longitude origin of the Conventional Terrestrial System CTS on the instaneous equator. {Improvements of the CTS should also be made without global rotations around the polar axis}. The secondary definitions are specific to the various techniques of measurement. They should be conceived in order to align the UT1 values with those of the primary definition.

Ecliptic

In a similar way, the motion of the pole of ecliptic should be described by two parameters in E. A non-rotating origin on the ecliptic could be defined.

It is further suggested to avoid the use of mixted quantities referred to both the pole of ecliptic and the pole of rotation, such as the equinox. These two poles may not be needed simultaneously and they are known with very different accuracies. It appears sounder to deal with them separately. For instance, the pole of ecliptic is not required for studying the Earth's rotation, except for small terms where a very rough estimate is sufficient.

Definition of the role of the ephemerides

In the assumptions made previously, where TAI and E are quasi-ideal references, the ephemerides should be considered as predictions of motions with respect to (TAI, E). They would thus fulfil the prac-

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tical needs for positions, since the references are available. The deviations between "observed" and "predicted" positions would be the basis of theoretical refinements and of researches in cosmology.

This suggestion means that the theoretical efforts should tend to express the ephemerides in the (TAI,E) system. This should be indicated by using TAI and the E coordinates as notations in the published and disseminated tables.

However, it does not exclude rules to unify as far as possible the time scales and coordinates implicit in the theories.

As an example, a possible application in the domain of time is shown thereafter, since there are already ambiguities.{In fact, most of the following text has already been written in preparatory documents of the IAU Recommendation 5 (1976)}.

It is recommended that

1 - the distinction be made between the primary time reference TAI and the time-like arguments of dynamical studies,

2 - the ephemerides give the prediction of the positions at instants dated in TAI.

3 - the relationship between TAI and the time-like arguments of dynamical studies be established using the assumption that TAI is equivalent to an ideal time-scale obtained by adding ideal SI seconds, at sea level.

4 - the following rules be applied in order to unify the time-like arguments of dynamical studies :

(a) at the instant of 1977 January $01^{d}00^{h}00^{m}00^{s}$TAI, the value of the time-like argument for equations of the apparent geocentric motions be 1977 January 1, 0003725 d exactly,

(b) the unit of this time-like argument be a day of 86400 SI seconds at mean sea level, at the above instant,

(c) the time-like arguments for equations of motions referred to the barycenter of the solar system be such that there be only periodic variations between these time scales and that for apparent geocentric motions.

CONCLUSION

Fundamental astronomy has been optimized since centuries in order to conform with instrumentation (meridian astronomy) and to simplify the computations, but at the cost of obscuring the principles.

We have now arrived at a point where this optimization is of secondary importance, compared with the need of clarifying the concepts and principles. The numerous difficulties, contradictions, misunderstandings which appeared when preparing the IAU decisions on the time scales (UT1, ET, TDB, TAI,...), on the pole, on the constants, show that the complexity reached a level such as even the specialists do not understand fully each other.

The major argument of this paper is that the existence of references, which are independent of dynamics, could give the possibility of clarifying and simplifying the fundamental notions. It is important to use the few years until the adoption of space references attached to extragalactic sources, to investigate this possibility.

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Discussion:

EICHHORN: There is no reason to continue using the ecliptic, the invariable plane is dynamically founded and the problem of its motion is **identical** to that of the motion of the ecliptic. One might even abandon the equator system which is based only on the Earth's kinematic peculiarities which has nothing to do with the stars. The galactic system would be more appropriate for dealing with stellar problems.

YE: There are problems with the new definition of UT1 as adopted at Patras. First, the definition in terms of Greenwich mean time depends on the value of a constant which is subject to revision in the future. Second, used for the FK5 it refers to a different system. Even though old and new UT1 are continuous at a certain epoch, they do not form a homogeneous series. The concepts are very complex and prone to be easily misinterpreted by the users. We thus propose a new conceptual definition of UT1 as an angle proportional to the

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rotation of the Earth with appropriately specified numerical constraints for Greenwich noon and for the rate.

MURRAY: I think that it is most important to define the reference system for space and time from a strictly relativistic standpoint, making a clear distinction between what is local, in the sense of the proper time and ephemerides for the terrestrial frame, and what is dynamical and coordinate dependent, such as the ecliptic.

TELEKI: What is, in your opinion, the necessary accuracy for the definition of the conventional reference frame?

GUINOT: Over the whole sphere, 0''.001. This will acommodate VLBI observations.