# COMMENTS ON CONVENTIONAL TERRESTRIAL AND QUASI-INERTIAL REFERENCE SYSTEMS

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ABSTRACT. After commenting on certain definitions related to both the terrestrial and celestial (quasi-inertial reference systems (CTS and CIS) to clarify terminology, the geodynamic requirements for such systems are reviewed. This is followed by a discussion of certain problematic aspects of the two systems. The article concludes with a list of required actions aimed to assure that the reference system issue is resolved early. The list is proposed for the joint IAG/IAU working group to be established in accordance with the Colloquium resolution printed elsewhere in this volume.

## PREFACE

The authors were asked to review the Colloquium at the closing session and summarize the major conclusions. In this article, in order to save space, only those ideas are elaborated on which either are not discussed in the review articles of the authors elsewhere in this volume, or which require further elaboration. For this reason the reader should consult these articles first, otherwise this paper may appear to be a collection of somewhat disjointed thoughts.

## 1. COMMENTS ON TERMINOLOGY: IDEAL AND CONVENTIONAL REFERENCE SYSTEMS AND FRAMES

In order to clarify some of the conceptual aspects of various reference systems and frames, we propose to assign specific meanings to terms that have been used somewhat inconsistently in the past.

The purpose of a reference frame is to provide the means to materialize a reference system so that it can be used for the quantitative description of positions and motions on the earth (terrestrial frames), or of celestial bodies, including the earth, in space (celestial frames). In both cases the definition is based on a general statement giving the rationale for an ideal case, i.e., for an *ideal reference system*. For



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example, one would have the concept of an ideal terrestrial system, through the statement that with respect to such a system the crust should have only deformations (i.e., no rotations or translations). The ideal concept for a celestial system is that of an inertial system so defined that in it the differential equations of motion may be written without including any rotational term. In both cases the term "ideal" indicates the conceptual definition only and that no means are proposed to actually construct the system.

The actual construction implies the choice of a physical structure whose motions in the ideal reference system can be described by physical theories. This implies that the environment that acts upon the structure is modeled by a chosen set of parameters. Such a choice is not unique: there are many ways to model the motions or the deformations of the earth; there are also many celestial bodies that may be the basis of a dynamical definition of an inertial system (moon, planets, or artificial satellites). Even if the choice is based on sound scientific principles, there remains a part of imperfection or arbitrariness. This is one of the reasons why it is suggested to use the term "conventional" to characterize this choice. The other reason is related to the means, usually conventional, by which the reference frames are defined in practice.

At this stage, there are still two steps that are necessary to achieve the final materialization of the reference system so that one can refer coordinates of objects to them. First, one has to define in detail the model that is used in the relationship between the configuration of the basic structure and its coordinates. At this point, the coordinates are fully defined, but not necessarily accessible. We propose to call such a model *conventional reference system*. The term "system" thus includes the description of the physical environment as well as the theories used in the definition of the coordinates. For example, the FK4 (conventional) reference system is defined by the ecliptic as given by Newcomb's theory of the sun, the values of precession and obliquity, also given by Newcomb, and the Woolard theory of nutation. Once a reference system is chosen, it is still necessary to make it available to the users. The system usually is materialized for this purpose by a number of points, objects or coordinates to be used for referencing any other point, object or coordinate. Thus, in addition to the conventional choice of a system, it is necessary to construct a set of conventionally chosen (or arrived at) parameters (e.g., star positions or pole coordinates). The set of such parameters, materializing the system, define a *conventional reference frame*. For example, the FK4 catalogue of over 1500 star coordinates define the FK4 frame, materializing the FK4 system. Another example is the BIH Conventional Terrestrial Frame, whose pole is the origin of the polar motion derived (and published) by the BIH, and whose longitude origin is the point on the equator of the above pole, used by the BIH for deriving UT1. This frame materializes the BIH Conventional Terrestrial System (CTS), which itself is defined by the FK4 frame, Newcomb's constants of precession and obliquity, Woolard's series of nutation, and by all the assumptions made regarding the reference coordinates of the participating observatories and their relative weights, etc.

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Another way of defining the CTS for the deformable earth is through the time varying positions of a number of terrestrial observatories whose coordinates are periodically reobserved by some international service. The frame of this CTS could then be derived from the changing coordinates through transformations containing rotational (and possible translational) parameters. These transformation parameters computed and published by the service would then define the frame of the system. The service, as part of the system definition, thus would have to make the assumption that the progressive changes of the reference coordinates of the observatories do not represent rotations (and translations) in the statistically significant sense. This mode seems to be the consensus for the establishment of the future CTS frame.

It is also necessary to point out that celestial reference systems may be defined *kinematically* (through the positions of extragalactic radio sources), or *dynamically* (through the geocentric or heliocentric motions of artificial satellites, moon, planets). Stellar systems, such as the FK5, are hybrid. Furthermore, approximations must be introduced in the model so that it is not true to say that these systems are realizations of an ideal inertial system. This is why it is appropriate to use the term conventional "quasi" inertial system (CIS) as a common term for all such celestial systems. The corresponding frames would be defined by either the adopted positions of a set of radio sources (kinematic frame) or the adopted geocentric or heliocentric ephemerides (dynamic frames), all serving the materialization of the CIS with greater or lesser success (accuracy).

## 2. COMMENTS ON THE CONVENTIONAL TERRESTRIAL SYSTEM (CTS)

### 2.1 Geodynamic Requirements

Geodynamic requirements for reference systems may be discussed in terms of global or regional problems. The former are required for monitoring the earth's rotation, while the latter are mainly associated with crustal motion studies in which one is predominantly interested in strain or strain rate, quantities which are directly related to stress and rheology. Thus for these studies, global reference systems are not particularly important although it is desirable to relate regional studies to a global frame.

For the rotation studies one is interested in the variations of the earth's rotational rate and in the motions of the rotation axis both with respect to space (CIS) and the crust or the CTS. The problem therefore is threefold: (1) to establish a geometric description of the crust, either through the coordinates of a number of points fixed to the crust, or through polyhedron(s) connecting these points whose side lengths and angles are directly estimable from observations using the new space techniques (laser ranging or VLBI). The latter is preferred because of its geometric clarity. (2) To establish the time-dependent behavior of the polyhedron due to, for example, crustal motion, surface loading or

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tides. (3) To relate the polyhedron to both the CIS and the CTS. For the global tectonic problems only the first two points are relevant although these may also be resolved through point (3).

In the absence of deformation, the definition of the CTS is arbitrary. Its only requirement is that it rotates with the rigid earth, but common sense suggests that the third axis should be close to the mean position of the rotation axis and the first axis be near the origin of longitudes. An arbitrary choice, such as the one presently defined by the BIH-published polar coordinates and UT1, free from the complications introduced by the CIO definition, is appropriate.

In the presence of deformations, particularly long periodic or secular ones, the definition is more problematical, because of the inability to separate rotational (and translational) crustal motions of the crust from those of the CTS. For example, a westward drift of all observatories cannot be distinguished from a secular change in the rotation,and neither can the secular motion of the pole be separated from plate tectonic motions. This is why the consensus seems to be the CTS described in Section 1. If such a system is adapted, the secular type motions mentioned above will be absorbed in the future CTS, by definition. Residuals with respect to such a CTS will provide estimates of relative motions between stations, i.e., of the deformations.

One geophysical requirement of the reference system is that other geophysical measurements can be related to it. One example is the gravity field. The reference frame generally used when giving values of the spherical harmonic coefficients is tied to the axes of figure of the earth. This frame should be simply related with sufficient accuracy to the CTS as well as to the CIS in which, for example, satellite orbits are calculated. Another example is height measurements with respect to the geoid.

The vertical motions may require some special attention, because absolute motions with respect to the center of mass have an immediate geophysical interest and are realizable. Again, if the center of mass has significant motions with respect to the crust, such a motion will be absorbed in the future CTS, if defined as suggested above. At present there is no compelling evidence that the center of mass is displaced significantly at least at the decade time scale.

Apart from the geometrical considerations the configuration of observatories should be such that (1) there are stations on most of the major tectonic plates in sufficient number to provide the necessary statistical strength, (2) the stations lie on relatively stable parts of the plate so as to reduce the possibility that tectonic shifts in some stations will not overly influence, at least initially, the parameters defining the CTS frame.

## 2.2 The Future CTS

There is little doubt that the terrestrial reference frame presently adopted and tied to the CIO is of very little practical use because of its insufficient accessibility. Further, the astronomical observations currently used to maintain this and other frames (i.e., those of the BIH and the IPMS) should be replaced by methods which are not tied to the direction of the vertical but rather to directions tied to the crust. Such methods are the laser observations to satellites and to the moon, and VLBI. Portable systems can establish the polyhedron(s) discussed earlier, while permanent stations at suitably chosen locations would become the observatories for the maintenance of the CTS.

The repeatedly determined coordinates of the observatories by means of the above-mentioned techniques, suitably corrected for those variations which are due to well-established (especially periodic) deformations, will serve as the basis of the future CTS.

The definition of the CTS frame could have a similar form proposed by Guinot in this volume: The pole of the conventional terrestrial frame (CTP) is the origin of the polar motion derived by a future international service. The first axis of the frame (CTO) is the point on the equator of the CTP used by such a service for deriving UT1. In these derivations the assumption is made that the progressive changes of the reference coordinates of the observatories contributing to the determination of the earth rotation (position of the instantaneous rotation axis and UT1) do not represent statistically a rotation (and a translation).

Until the new system becomes operational, the above definition could be adopted for a specified existing service (BIH or IPMS), even if the coordinates of some of the contributing observatories are the astronomical latitudes and longitudes. An early adoption of such a definition would reduce the present confusion about the CTS described by Mueller in this volume. Possible alternative computational schemes for the determination of such future CTS parameters are also described there and also by Richter in this volume.

# 3. COMMENTS ON CONVENTIONAL QUASI-INERTIAL SYSTEMS (CIS)

## 3.1 Conceptual Considerations

Since the definition of such systems may be based on dynamical properties of the solar system as well as on the kinematics of extragalactic sources, we are led to distinguish between two kinds of quasi-inertial systems:

a) *Conventional kinematical systems*, based on the assumption that the proper motions of some celestial bodies have known statistical properties. In the case of extragalactic sources, it is postulated that remote galaxies have no rotational component in their motions.

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b) *Conventional dynamical systems*, based on the theory of the motion of some bodies in the solar system constructed in such a way that there remains no rotational term in the equations of motion.

If, in the framework of Newtonian mechanics, both definitions are equivalent, this is no more true in the theory of general relativity. A dynamical system of coordinates is a local reference that is locally tangent to the general space-time manifold. In contrast, the celestial system defined by the apparent directions of remote objects is a coordinate system that is subject to relativistic effects such as the geodetic precession. Even if this is being suitably corrected for, there remains a basic difference between the concept, and this is another good reason to use the terminology "*quasi-inertial*" to characterize both celestial and dynamical systems.

It is now well agreed that the best future CIS will be based on the position of extragalactic radio sources. But even if such a system is due to play a major role among conventional quasi-inertial systems, there may be great advantages, in some cases, to use a dynamical system. This is the case, for instance, when artificial satellites are used to monitor the earth rotation. This is why we are led to propose a certain hierarchy among these systems and give to the CIS based on extragalactic radio sources a role of a *primary system*, a role which is presently played by the FK4 System and will be played, during the interim, by the FK5 System before the VLBI based system is really set up and made available. Other systems, and in particular all the conventional dynamical systems, will have to be connected to the primary system in order to give consistent results.

## 3.2 Conventional Quasi-inertial Reference Frames

The actual availability of the systems is obtained through their realization in the form of reference frames. This materialization can be done in two different ways so that one can distinguish between two kinds of reference frames:

a) *Stellar reference frames*. The fiducial points are presently stars. Even if it is expected that they will be extragalactic radio sources in the future, it will still be necessary to provide connections to stellar catalogues, so that the celestial system be made available to optical instrumentation.

b) *Ephemeris reference frames*. In such frames, one or several moving objects are used as the materialization of the system (e.g., the GPS). The theory supporting the corresponding reference system provides the apparent ephemeris of the objects as a function of time and the observed successive positions are the fiducial points needed to refer the observations to the system.

It is to be noted that there is not a bi-univocal correspondence between both types of frames and the two sorts of quasi-inertial systems.

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For instance, the FK4 System is dynamical, while the FK4 Frame is stellar.

### 3.3 Origin of Quasi-inertial Frames

Astronomers have always used the equator as a fundamental plane of the coordinate system, and the origin was the equinox, although in studies of celestial mechanics, ecliptic coordinates are preferred. But none of these fundamental planes appears necessary in a purely celestial reference system. Since the point of the origin has been hotly debated, let us analyze the problem.

If a dynamical system is based on the motion of planets, the ecliptic plays a privileged role and, naturally, the ecliptic is used in the definition of coordinates. Since equatorial coordinates are preferred to ecliptic for obvious instrumental reasons, the ecliptic becomes the natural origin of right ascensions. When the dynamical system is geocentric, the natural reference plane is the Laplace plane whose position depends upon the relative magnitude of the perturbations. For the moon, the solar effects are dominant and, practically, the Laplace plane is the ecliptic and, again, the equinox is the natural origin of equatorial coordinates. In the case of artificial satellites presently used for earth dynamics, the perturbations due to the earth flattening are predominant so that the Laplace plane is the equator. The equator is, therefore, the natural fundamental plane, but the origin may be arbitrary. This explains why the mean equinox at a given epoch is used and not the true equinox.

Similarly, the choice of the equinox in the FK4 series is justified by the fact that they are dynamical systems based upon planetary theories. However, in the construction of the corresponding stellar frame, the difficulty of maintaining the theoretical origin is so serious that one is led to distinguish the dynamical equinox which defines the origin of the system and the catalogue equinox which is the origin of the frame. In practice, the actual origins of the FKn reference frames are purely conventional and are not the dynamical equinox.

This situation will become even more conspicuous for frames derived from conventional celestial systems. Even if, for the sake of continuity, the origin and the fundamental plane of a celestial system should be close to the equinox and the equator, they should be conventional points defined only by the realization of the corresponding frame. Otherwise, it would be necessary to introduce a complex dynamical model to define the origin at the expense of introducing inaccuracies in the system and an uncertainty in its realization by the frame. In practice, the solution might be analogous to the present situation for the terrestrial longitude system. One would establish an international organization that would provide the coordinates of radio sources in the conventional celestial frame, taking into account eventual changes in the number and position of the reference sources, due, for instance, to the disappearance or motion of quasars.

### 3.4 Origin of Terrestrial and Geocentric Ephemeris Frames

Finally one should realize that the problem of the geometric origin of the CTS frame is linked with this topic of its comparison with a geocentric ephemeris frame. The center of mass of the earth is directly accessible to dynamical methods and is the natural origin of a geocentric satellite-based dynamical system. But, as such, it is model dependent. And, unless the terrestrial reference frame is also constructed from the same satellites (as is the case in various earth models such as GEM, SAO, GRIM), there may be inconsistencies between the assumed origin of a kinematically obtained terrestrial system and the center of mass. A time-dependent error in the position of the center of mass, considered as the origin of a terrestrial frame, may introduce spurious apparent shifts in the position of stations that may then be interpreted as erroneous plate motions. To avoid this problem the parameters defining the CTS frame should include translational terms as suggested in Section 2.2.

## 4. CONCLUDING COMMENTS

From the discussion it is obvious that a number of actions are required to assure that the reference system issue is resolved early and that uniformity is assured by means of international agreements. These, not necessarily in order of importance, are the following:

*Re CTS:*

1. Selection of observatories whose catalogue will define the CTS.
2. Initiation of measurements at these observatories.
3. Recommendation on the observational and computational maintenance of the CTS (e.g., permanent versus temporary and repeated station occupations, constraints to be used).
4. Decision on how far and which way the earth deformation should be modeled initially.
5. Plans and recommendations for the establishment of new international service(s) to provide users with the appropriate information regarding the use of the CTS frame.

*Re CIS:*

6. Selection of extragalactic radio sources whose catalogue will define the CIS.
7. Improvement of the positions of these sources to a few milliseconds (arc).
8. Final decision on the IAU series of nutation and to assure that it describes the motion of the Celestial Ephemeris Pole.
9. Early completion of the FK5 and revision of astronomical equations due to the changed equinox (e.g., transformation between sidereal and Universal times).
10. Extension of the stellar catalogues (FK5 and later Hipparcos) to higher magnitudes.
11. Connection of the FK5, and later Hipparcos, reference frames to the CIS frame.

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12. Assure that all dynamical (planetary, lunar and satellite) ephemerides are referenced to the CIS.
13. Plans and recommendations for the establishment of a service that would be in charge of the maintenance of the CIS frame.

It is hoped that the proposed joint IAG/IAU Working Group will consider these items during their deliberations.

As a summary, the following figure shows the hierarchy of the conventional and quasi-inertial reference systems discussed, including examples of possible connections between them. The heavy boxes indicate the CTS and those CIS-s which are the most important ones from the points of view of orientation and origin definition. The heavy lines indicate the connections between these systems. It should be noted that though in some cases it may be possible to theoretically derive the transformations between two systems (e.g., those based on the motion of the moon and the planets), the result would not be of high accuracy because of the dependence on the model used, i.e., due to the degradation of the materialization of the systems. The connections through the observations shown actually result in transformations between the various frames, but this is exactly what the users need. For more details, see the authors' articles elsewhere in this volume.

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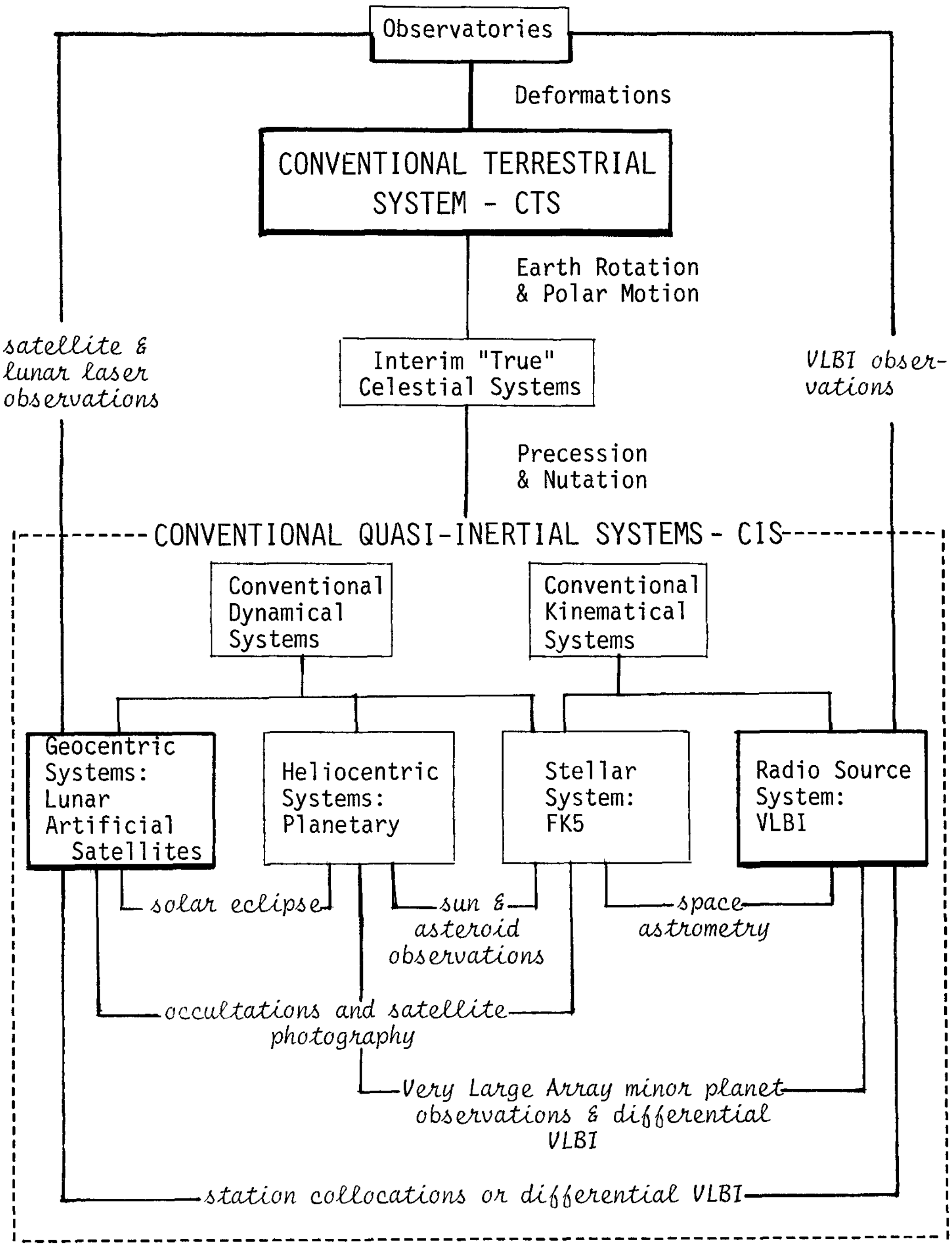


Conventional Terrestrial and Quasi-inertial Reference Systems with Examples of Possible Connections.

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