COMMENTS ON THE TERRESTRIAL POLE OF REFERENCE, THE ORIGIN OF THE LONGITUDES, AND ON THE DEFINITION OF UT1

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ABSTRACT. The definition of a terrestrial reference pole (TRP) and of a Terrestrial Longitude Origin (TLO), by fixing the stations coordinates of an adopted network seems unrealistic. It is proposed that TRP and TLO be the realized origins of some specified service working in accordance with some stated principles. It is also proposed to clarify the definition of UT1 and to base it on some physical properties.

INTRODUCTION

A terrestrial reference system (T_o) is defined by the center of masses T of the Earth, an arbitrary axis Tz_o, and another axis Tx_o in the plane perpendicular to Tz_o. For practical reasons, Tz_o is chosen close to the terrestrial rotation axis. When it is needed to relate a terrestrial direction to space fixed directions, the common practice is to use the coordinates of the pole in both the Earth and space reference systems, and the value of an angle around the rotation axis, which is conventionally linked to UT1. Therefore the coordinates x and y of the pole and UT1 (designated as the Earth rotation parameters, ERP, in the following) should refer to (T_o).

We are presently far from this ideal situation, the main reason being that the ERP are determined by instruments which use, as a terrestrial reference, not a direction linked to the body of the Earth, but the vertical. Thus the coordinates of the stations which determine the ERP, which should be the primary reference for geodetic networks, cannot be used for accurate purposes.

A number of other defects also affect the present system for referring the ERP. Although, under the instigation of Markowitz (1968), an attempt was made to define a realizable polar origin, known as the Conventional International Origin, CIO, by specifying station coordinates, observational and computational procedures, strictly speaking, this origin will be lost, because some of the stations of the Interna-

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tional Latitude Service (ILS) which realize it, will close. On the other hand, no precise definition of the origin of the longitudes was given. This origin should be a point on the equator of CIO, so that the prime meridian should pass through a given point of the old Greenwich Observatory ; in practice, this condition is not realizable and the adopted origin is implicitly linked to the longitude system of the Bureau International de l'Heure (BIH).

Thus, we are faced to a number of problems.

(a) Since precise terrestrial coordinates are obtained by methods which refer to the body of the Earth, and not to the vertical, the method for determining the ERP should also refer to the body of the Earth. Even if more precise, the classical astronomical methods could remain a good tool for geophysical studies concerning the Earth rotation irregularities, and for interpolation, but could not satisfy alone the geodetic needs.

(b) The choice of the coordinates of the stations which determine the ERP is a difficult task, in particular because fixed coordinates cannot be acceptable, in the long term.

(c) As the ILS network will be dismantled before the official organization of new networks for measuring the ERP, an interim reference pole is needed to replace CIO.

(d) A decision is also desirable for an interim definition of the longitude origin.

(e) A somewhat independent problem is the definition of UT1, which, to my opinion, should be re-considered.

These problems are most difficult. I do not pretend to have made their exhaustive study. I only offer some comments, as a modest contribution to their solution.

FRAMES OF REFERENCE FOR THE EXISTING EARTH ROTATION SERVICES

Concerning problems (b), (c) and (d), the consideration of what has been accomplished by existing services might provide some guidance, and we will briefly summarize it.

The ILS solution

The ILS network consists in 5 stations observing latitude. The observations are solved for 3 unknowns : the two coordinates of the pole and an auxiliary quantity, the z-term. The 5 initial latitudes define the CIO.

Three stations would have been geometrically required. The redundancy is nevertheless acceptable because of the simple dependence of the pole

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errors on the measurement errors at the stations: the proportionality. Therefore, if there are linear latitude drifts at the stations (non common), there is a linear drift of the CIO, which is not too serious. However, this property is obtained at the cost of some limitations.

The linear dependence on station errors requires a specific method of computation. It is made possible by the linear relationship between the pole coordinates and the local latitudes, by the properties of the least squares method, and by the fact that fixed weights for the observed data are adopted, in spite of their variable quality and amount. It therefore requires averaging the observed data over long intervals (one month) to smooth out the effects of the weather,and forbids fine time resolution and rapid service.

The BIH solution

The BIH method of computation of the ERP, adopted in 1967 (BIH, Rapport Annuel pour 1967 ; Feissel, 1980) was devised with the aim of using all existing measurements, to have short averaging time (5 days), and to allow a rapid publication of the ERP. This requires that any subset of observational data should lead to the same solution, except for the effects of the random errors. It was thus necessary to maintain at any time a coherent system of initial longitudes and latitudes. This was accomplished by an algorithm giving predicted values of the systematic corrections to the initial coordinates.

In this algorithm, the coordinates are revised every year by applying a new set of corrections. It is done in such a way that, in the yearly average, there is no systematic change of the ERP when using the old or the new corrections. Therefore, the BIH algorithm realizes the condition that the variable initial coordinates bring no rotation in the BIH reference system for the ERP, although this has never been explicitly said.However, when realizing this no-rotation condition, the stations receive weights, according to their observation uncertainties, which is questionable.

The IPMS solution

The International Polar Motion Service uses the same observational data as the BIH, but processes them independently. First,fixed initial coordinates were used, with some exceptions (Yumi, 1975). But, in a recent revision (Yumi, 1980), variable coordinates have been adopted. The general principle according to which the variations are obtained is not given.

The DMA Doppler solution

The Doppler solution for the pole coordinates by the Defense Mapping Agency (see, for instance, Oesterwinter, 1979) uses fixed reference positions of the Doppler stations. However, it was found by Anderle (1978) and by McLuskey (1979) that station residuals in latitude,

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longitude, and height have significant variations. Although the results are derived from an all-weather observing network, and that it can be expected that each 2-day pole position is derived from the data of the quasi-complete network, one can wonder whether a constantly coherent system of stations positions would improve the results, especially when poor conditions of reception occur. This raises again a question about the principles which should govern the choice of the zero of the adopted rate corrections.

Comparisons between the origins of the existing services

Different methods have been used for maintaining the pole and the longitude origin. Nevertheless it is interesting to compare these origins and their relative rates : it will give an idea of the size of the drifts which can occur, due to the different effect of the plate motions and/or to other causes. In these comparisons, the following series are used

ILS : revised results (Yumi and Yokoyama, 1980).

IPMS : revised results (Yumi, 1980),
1967-1978, solution from time and latitude, with τ,
1962-1978, solution from latitude only.

BIH : BIH Global solution, BIH Ann. Rep. for 1978, D-68 to D-76 and BIH Ann. Rep. for 1979, D-79.
The intervals 1967-1978 and 1962-1978 are considered, the results for 1962-1966 being less accurate than the following ones.

DMA : the latest results available in the BIH files and used in the BIH Ann. Rep. for 1979. Results prior to 1972, which were obtained by a different method are not used.

The results of the comparisons are given by Table I.

Interim definition of the origins for the pole and the longitudes

The BIH pole is not as close to CIO (the ILS pole) as the IPMS pole, probably because it was adjusted to CIO over a shorter interval : 1964 - 1966. However, the BIH pole, which was realized several years before the IPMS pole and which is still available with slightly shorter delays, is generally adopted as the current reference for geodetic purposes.

There is no observable relative drift of the IPMS and BIH poles since 1967 -at the level of 0".0007 per year (2cm y^{-1}), one sigma. The drift of these two poles relative to CIO might be of the order of 0".001 per year (to be compared to the drift of the ILS mean pole towards America by 0".003/year).

The IPMS and BIH systems for UT1 show a small relative drift, which might be due to the effect of different weighting, combined with the stars proper motion errors.

Table I. Difference between the Earth rotation parameters by various services :
Service - BIH = A + B (T - 1975.0)
Units are : 0".001 for x and y, 0.0001s for t = UT1. The variations B are yearly rates.

Services	Interv.	A_x	B_x	A_y	B_y	A_t	B_t
ILS - BIH	62-78	36 ± 4	-0.2 ± 0.9	-2 ± 3	1.0 ± 0.5		
	67-78	39 ± 4	2.3 ± 1.3	-4 ± 3	-0.2 ± 0.8		
IPMS(L) - BIH	62-78	29 ± 2	-0.3 ± 0.3	2 ± 2	1.1 ± 0.5		
	67-78	29 ± 1	0.0 ± 0.4	1 ± 3	-0.4 ± 0.7		
IPMS(L+T,τ) - BIH	67-78*	30 ± 1	0.3 ± 0.3	3 ± 2	0.0 ± 0.6	-8 ± 3	-1.9 ± 1.0
DMA - BIH	72-79	-15 ± 2	-1.6 ± 0.6	-2 ± 3	1.6 ± 1.1		

* Interval 1967-77 for UT1.

The pole of the satellite Doppler system has a drift with respect to IPMS, ILS and BIH, but still slow.

We can conclude that the IPMS and BIH poles are equally acceptable as the "official" reference pole, in replacement of CIO, until modern networks be operational, and that the dismantling of the ILS network would have no adverse consequences. However if it is planned to instal new optical instruments, such as PZT's, their location on the international ILS parallel would be much better than a location "at random" .

CONSIDERATIONS ON THE REFERENCES FOR THE FUTURE EARTH ROTATION NETWORKS

The evolution of the services processing the data of the optical astronomy is, to many respects, exemplary. The initial plan of the ILS, based on geometric properties, is being abandonned and replaced by a statistical solution which allows taking advantage of instrumentation progress. But, for decades, valuable observations were not used to derive polar motion for fear of spoiling the ILS system.

In the future organization of the measurements of the ERP, one could be tempted to rebuilt an ILS, i. e. to freeze a technique and a network so that the origin could be defined by a set of adopted coordinates. Such an organization would not be realistic. No technique appears much superior to others, and competition between techniques will continue. On the other hand, for a given technique, it should be possible to profit from theoretical developments, instrumental improvements, and increased participation. The organization of new networks should be flexible enough to allow this progress without loosing the reference frame. This leads to the following considerations.

(a) Ideally, the coordinates of the observing stations measuring the ERP should be "absolute". They should belong to a worldwide homogeneous system, representing the real shape of the Earth, which should define both the reference system for geodesy and for the ERP. Leaving in the station coordinates some foreign quantities which appear in the data processing (to use them as a "garbage box") should be avoided. An example is the mixing of the longitude and right ascension errors.

(b) Fixed coordinates of stations, or even variable coordinates according to some conventionally adopted model of plate motions, cannot be convenient, in the long term, for the operation of a network determining the ERP. The evolution of the network (in particular, closing of some stations, changes of weighting station data on account to instrumental modifications, and variable influence of each station in the global solution for the ERP due to meteorological effects and failures) requires that, at every instant, the station coordinates constitute a coherent system. This is also needed for a correct evaluation of the random uncertainties. I suggest that the corrections to the initial coordinates be established in accordance with the condition that they should bring no rotation in the reference system for the ERP obtained by the considered network.

(c) The above "no-rotation" condition cannot be strictly specified. In principle, if the station motions were random, following a common distribution law, non-weighted averages of the motions should be considered. However, the systematic effects due to plate motion and the anomalous local effects prevent one from giving precise rules. I suggest that the conventionally adopted frame of reference for the ERP be the one realized by the service in charge of the final evaluation of the ERP, working in accordance with the general "no-rotation" condition. An example of such a definition already exists for the International Atomic Time, TAI. The 15th General Conference on Weights and Measures adopted the following text (non-official English translation from French)

> "The International Atomic Time is the time coordinate established by the BIH on the basis of the readings of atomic clocks operating in various establishments, in conformity with the definition of the second, time unit of the SI".

A possible definition of the reference frame for the ERP is given in the Conclusions.

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DEFINITION OF UT1

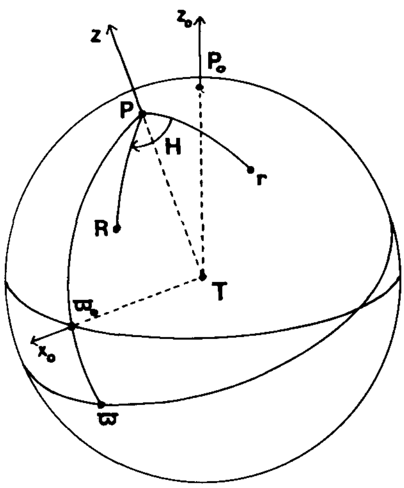

Fig. 1

Let us represent directions by points on a celestial sphere accompanying the Earth rotation (fig. 1). P_o is for Tz_o; $\bar{\omega}_o$, for Tx_o; P for Tz, the instantaneous rotation axis (more precisely P is the newly defined celestial Ephemeris Pole). One needs to know the angular position of (T_o) around Tz. This can be accomplished by giving the angle $H = r\hat{P}R$, as a function of TAI, where Tr is a known direction in (T_o), and TR a known direction in a space non-rotating reference system.

In practice r is ϖ_o, and R is ♈ the mean equinox of date, H being then known as the Greenwich Mean Sidereal Time, GMST. Let us investigate the reasons of these choices.

The necessity of having the Earth reference on the equator is clear. Thus, when P moves, as it remains close to P_o, the $P\varpi_o$ meridian has no appreciable rotation around the Pz-axis : GMST is independent of the polar motion in (T_o). The origin of the longitudes in the instantaneous system (T) can be defined as the intersection ϖ of $P\varpi_o$ with the instantaneous equator.

The choice of the space reference ♈ is traditional. As ♈ does not move uniformly on the equator, GMST is not proportional to the sidereal rotation of the Earth. This has no importance for geodetic applications since the observed relation GMST/TAI would satisfy the needs. However, for geophysics, one requires the departure of the Earth rotation from uniformity. Both the geodetic and geophysical needs are fulfilled by

- the UT1/TAI relation (obtained from measurements),
- the UT1/GMST relation (conventional),

where the latter relation should ensure the proportionality of UT1 to the sidereal rotation of the Earth.

Equivalently one can define a fictitious point moving on the equator, the Mean Sun MS, in such a way that UT1 be equal to the hour angle of MS from the prime meridian, + 12h, and that UT1 be proportional to the sidereal rotation of the Earth. But this definition has no operational usefulness since the position of the celestial bodies are referred to ♈, not to MS, which rapidly moves among the stars.

Guinot (1979), using the concept of a non-rotating origin on the mean equator of date, has found that the proportionality of UT1 to the sidereal rotation was not ensured neither by the current UT1/GMST

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relation, nor by the proposed relation in conjunction with the adoption of the IAU (1976) System of Constants.

In order to clarify the concept of UT1, and to extend the definition of UT1 to possible non-rotating systems of reference in space, in which the equinox could not be determined, the following broad definition is suggested.

"UT1 should be an angle proportional to the sidereal rotation of the Earth, the coefficient of proportionality being chosen so that 12 h UT1, in the long term, remains approximatively in phase with Greenwich Noon. In some applications, UT1 can be considered as a non-uniform time scale."

To implement this definition, one could use the appropriate UT1/GMST relation (Aoki and Kinoshita, 1980).

However, I believe that, even in the case of classical determinations of UT1 by optical observations of fundamental stars, it would be better to define explicitly a non-rotating origin (NRO) on the true equator. In case of changes of conventional equator and ecliptic, the NRO can be transferred on the newly adopted equator using the non-rotation condition. Thus, if we call θ the hour-angle of the NRO from the prime meridian, a fixed linear relation UT1/θ could be adopted, not affected by revision of constants and ensuring the continuity of UT1 in phase and in rate, when these revisions occur.

The NRO could be made available through a γ/NRO relationship. As the initial NRO should be chosen conventionally, as γ, and as the subsequent position of γ is obtained from conventionally adopted series and the position of the NRO is rigourously computable, the relation γ/NRO would be exactly known permanently. But Guinot (1979) believes that it would be preferable to use the NRO instead of γ for referring star positions. This more general use is not discussed in this paper.

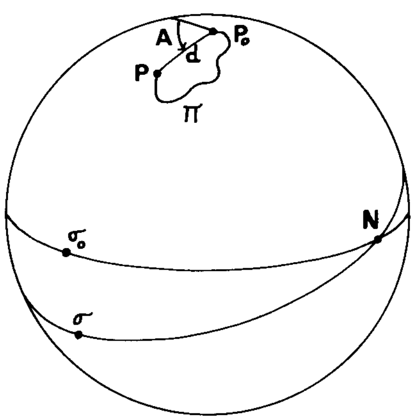

Fig. 2

The position of the NRO is computed in the following way. If P_0 and P are two positions of the pole on the non-rotating celestial sphere at dates t_0 and t, A and d are the polar coordinate of P from P_0 (fig. 2), A being reckoned from a fixed direction in space, σ_0

and σ are the NRO at t_0 and t, π is the path of P, and N is the ascending node of the equator of P on the equator of P_0, it is easily demonstrated that:

$$s = \sigma_0 N - \sigma N = \int_{\pi} (\cos d - 1)\, dA .$$

The effects of the nutation, which should be included in π, are not entirely negligible, since they are of the order of 0".0001 per year.

CONCLUSIONS

We summarize the main suggestions of this paper

(a) The primary methods for determining the Earth rotation parameters should use, as terrestrial reference, directions tied to the body of the Earth -not the vertical. This is needed for expressing these parameters in a worldwide geodetic network.

(b) The definition of the Terrestrial Reference Pole,TRP, and the Terrestrial Longitude Origin, TLO, could have the following form.

> The TRP is the origin of the polar motion derived by XXX. The TLO is the point of the equator of TRP used by XXX for deriving UT1. In these derivations, the assumption is made that the progressive changes of the reference coordinates of the stations contributing to the determination of the instantaneous pole, and of UT1 do not represent statistically a rotation.

XXX represents the future officially designated service for issuing the values of the Earth rotation parameters. But, provisionally, such a definition could be used for a specified existing service, even if the coordinates of the observing stations are the astronomical latitudes and longitudes.

(c) The definition of Universal Time UT1 should be based on a physical property : UT1 should be proportional to the rotation of the Earth in space. The explicit definition of a non-rotating origin on the true conventional equator would help in realizing this definition.

REFERENCES

Anderle, R.J. : 1978, NSWC/DL Techn. Rep. 3884, Dahlgren Virginia, Naval Surface Weapons Center.

Aoki, S., and Kinoshita, H. : 1980, submitted to Celestial Mechanics.

Feissel, M. : 1980, Bull. géod., 54, pp. 81-102.

Guinot, B. : 1979, in D.D. McCarthy and J.D. Pilkington (eds) "Time and the Earth's Rotation", IAU Symp. 82, pp. 7-18.

https://doi.org/10.1017/S0252921100081173 Published online by Cambridge University Press

Markowitz, Wm. : 1968, in Wm. Markowitz and B. Guinot (eds), "Continental Drift, Secular Motion of the Pole, and Rotation of the Earth", IAU Symp. 32, pp. 25-32.

McLuskey, D. : 1979, Report presented at the 17th IUGG General Assembly, Canberra.

Oesterwinter, C. : 1979, in D.D. McCarthy and J.D. Pilkington (eds), "Time and the Earth's Rotation", IAU Symp. 82, pp. 263-278.

Yumi, S. : 1975, Ann. Rep. of the IPMS for the year 1973, Central Bureau of IPMS, Mizusawa.

Yumi, S. : 1980, Ann. Rep. of the IPMS for the year 1978, Central Bureau of IPMS, Mizusawa.

Yumi, S. and Yokoyama, K. : 1980, Results of the International Latitude Service, Central Bureau of IPMS, Mizusawa.