JOINT COMMISSION MEETINGS

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

1. FOR MILLIARCSECOND OR BETTER ACCURACY

Chairman and Editor: P.K. Seidelmann

Supporting Commissions:

4, 7, 8, 19, 24, 31, 40

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

"FOR MILLIARCSECOND OR BETTER ACCURACY"

P. K. SEIDELMANN
U S NAVAL OBSERVATORY, WASHINGTON, D C 20392

INTRODUCTION

The accuracies being achieved in astrometry, celestial mechanics, Earth Orientation, ephemerides and time have been improving significantly in recent years.

The introduction of the improved astronomical constants, ephemerides, time scales and nutation as adopted from 1976 to 1984 has had the desired effect of permitting the investigation of systematic effects at precisions of an order of magnitude better than previously possible.

Therefore, there have been many developments in observational data, in theories, and in astronomical computations that have promised, or claimed, to deliver accuracies of a milliarcsecond or better.

Working Groups had been established with interrelationships in their scopes of activities. It did not appear that any of the working groups were prepared to present final recommendations that would be generally accepted.

As a result a number of commissions requested that there be a Joint Commission Meeting, or a Joint Discussion, on the general topic of milliarcsecond accuracy. The IAU Executive Committee asked me to organize a Joint Commission Meeting involving commissions 4, 7, 8, 19, 24, 31 and 40. That meeting, and these resulting proceedings, are designed by means of a series of invited papers to give the background and status of observational, theoretical, and computational efforts necessary to achieve milliarcsecond or better accuracy. It was hoped that these presentations would provide an overall background of the considerations and current status to be considered by the working groups on the use of the millisecond pulsars, nutation, astronomical constants and reference systems.

Achieving milliarcsecond accuracy, requires significant improvements in many different areas. The breadth of the disciplines involved in these accuracy improvements is indicated by the number of commissions sponsoring Joint Commission Meeting 1. Considerations that in the past were negligible now have to be included. This means that people working in one discipline are required to include the latest knowledge, techniques and constants from another discipline.

These are a number of issues which need to be considered as accuracies of a milliarcsecond or better are being sought by different techniques. The following issues were drafted as a basis for the papers.

1). Are we achieving accuracy or precision?

D. McNally (ed.), Highlights of Astronomy, Vol. 8, 465–499.

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

2). Are the theories and computational procedures consistent with observational accuracies?

3). Do the anticipated observational accuracies require new levels of accuracy in theories?

4). Do the anticipated accuracies of the future require fundamentally new methods of proceeding in astronomy?

5). How do we ensure that there are not systematic errors in a type of observation or computation?

6). Is our knowledge, understanding and application of relativistic theory sufficient for current observational and theoretical activities?

7). Are the old divisions between physics, astronomy, geodesy and mathematics causing barriers to achieving accuracy improvements?

8). Can we have a single definition of a reference system and practical realizations thereof for terrestrial and celestial coordinates that satisfy all requirements?

9). Is the accuracy of the reference system satisfactory for the accuracy of observations and theories?

10). Are radio and optical based reference systems consistent, compatible and equivalent?

11). Should there be IAU adopted constants, reference frames, and theories?

12). Should there be IAU adopted values of constants in some cases and best estimates in other cases?

13). Are the constants sufficiently accurate for the theories and observations?

14). Are inaccuracies of constants, theories, or observations in one area limiting the accuracies which can be achieved in another area?

15). Are we making approximations based on past accuracy requirements that are no longer satisfactory for the present?

16). How can we ensure documentation and consistency in constants, reference systems and computational procedures for different theories and observations?

The presentations were to provide an interdisciplinary overview of the considerations and current status on important observational, theoretical, and computational subjects involved. These presentations then provided an introduction to the Working Group reports which followed. The following list

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

of presentations were given by the indicated speakers.

Observational accuracies

Radio Interferometry*	K. J. Johnston
Current and Potential Accuracies of Optical Interferometry	M. Shao
Lunar Laser Ranging	P. Bender
Millisecond Pulsars	J. H. Taylor

Theoretical Developments

Relativistic Framework for Precision Astrometry*	I. I. Shapiro
New Nutation Theory	H. Kinoshita
Earth Models	J. Wahr
Non-rotating Origin	N. Capitaine
Procedures for Accurate Origin	S. Aoki

Computational Considerations

The Mean Motion in Modern Planetary Ephemerides	E. M. Standish
Determination of Earth Orientation	M. Feisel
Apparent Place Computations	B. Yallop
Galactic Coordinates	C. A. Murray
Review of Current/Future Catalog Accuracies	H. Schwan

Working Group Reports

The Use of Millisecond Pulsars*	D. Allan
Nutation	R. L. Duncombe
Astronomical Constants	B. Morando
Reference Systems	J. A. Hughes

The same speakers provided the following written summaries of their presentations and working Group Reports. The asterisks indicate the cases where summaries have not been received.

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

Reports of the working groups reflect the results of the discussion that took place during the IAU and to that extent, are improved versions of the reports presented at the General Assembly.

The recommendation of the Working Group on Nutation was judged not acceptable for high precision requirements, unnecessary for lower precision needs, and not consistent theoretically. Therefore, it was not adopted by the Commissions.

During the discussion of the Working Group reports it became evident that the working groups' reports were not ready for adoption at this General Assembly. Rather, more effort and discussion were required. The Scientific Director of the U S Naval Observatory extended an invitation for a meeting to be held in 1990 at the U S Naval Observatory on this general subject.

The Resolution C2 as follows was drafted and adopted by the IAU General Assembly:

Commissions 4, 7, 8, 19, 20, 24, 31, 33 and 40

noting the proliferation of Working and Study Groups which deal with various matters of concern to these Commissions;

recognizing the necessity of considering such matters carefully along with the inevitability of scientific interrelationships among them;

thanks the Chairperson and Members of the Working Groups on Nutation and Astronomical Constants for their efforts; and

recommends that the Working Group on Reference Systems (WGRS) be continued as an intercommission project and that it concern itself with Nutation, Astronomical Constants, Origins, Reference Frames and time;

that appropriate Study Groups be formed as required and that the current chairman continue in office, and that Commissions 4, 7, 8, 19, 20, 24, 31, 33 and 40 and the IAG be invited to appoint members;

that the International Astronomical Union support the efforts of the Intercommission Project by providing funds for travel of members to attend the Working Group meetings;

that the WGRS produce a draft report with specific recommendations at least six

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

months before the General Assembly;

that close ties be maintained between the International Astronomical Union, as represented by the WGRS and the Geodetic Community, as represented by the IAG/IUGG;

that a close liaison with the IERS be continued.

Thereby, the Working Group on Reference Systems was continued and its purview broadened to specifically include the questions of nutation, astronomical constants, time and the origins.

Current Status of Optical Interferometric Astrometry M. Shao

Traditionally built for astrophysical research, such as stellar diameter measurements, the success of radio interferometry in making extremely accurate astrometric measurements has motivated the recent work in optical interferometric astrometry. Interferometric astrometry at optical wavelengths can be divided into 3 categories, very narrow field astrometry (double stars), narrow field astrometry (a few degrees), and wide angle astrometry (1 radian).

The technique most widely used in milliarcsecond (mas) double star astrometry is speckle interferometry where separations of stars can be measured with accuracies slightly better than 1 mas. The major source of error is in the calibration of the effective focal length of the telescope. Long baseline interferometers can also be used to measure the separation of double stars with the potential of much higher accuracy because of the higher resolution of the longer baseline and the ability to accurately measure the baseline vector. The Mark III Interferometer has measured the diameter of large stars (>0.010 arcsec) with accuracies of 0.1 mas for one night. Interferometric techniques work best for stars separated by less than 5-10 arcsec.

In narrow field astrometry, the Mark III is currently the only interferometer making such measurements. With the addition of several subsystems such as a laser metrology system to measure siderostat bearing errors, an internal white light metrology to measure the thermal drift of the delay offset, and the use of two color astrometry, a precision of 3-4 mas rms have been demonstrated for six stars in an 8 degree field. These preliminary results must be verified with a much larger data set. However, the precision is almost competitive with ground based photoelectric long focus astrometry with much smaller fields of view.

The Mark III was built as a prototype wide angle astrometric instrument. Instrumental systematic errors are most severe in wide angle measurements. Our measurements in 1986 showed repeatability of a night's observation to be 50 mas in declination using a 12 meter N-S baseline. In 1987, we added a second E-S baseline that had a 5 meter E-W component and the night to night repeatability of 50 mas in DEC and about 60 in RA. Averages of about a dozen nights of data would give a formal error of 20 mas for the 20-30 stars observed over a range of 45 deg in DEC and 10 hrs in RA. In 1988, we moved the E-S baseline so that it had a 10 meter E-W component. More important, we refined the software so that two color astrometry was now an operational system, using two colors for atmospheric correction and three colors for central fringe identification. In addition we installed a system of 12 laser interferometers for siderostat monitoring and the white light delay offset measurement system. Currently we have night to night repeatability of 20-25 mas in the relative position of stars that cover a DEC range of 55 deg and 12 hrs in RA. The formal error for an average of 6-10 nights of data will then be in the 10 mas range. It should be noted that the narrow and wide angle numbers represent precision, since we lack the large data sets needed to demonstrate accuracy. Optical interferometry compared to other astrometric techniques is in its infancy and we expect that progress towards higher accuracy will continue and accelerate as more people and resources migrate to the field.

Lunar Laser Ranging: P. Bender

The lunar laser ranging data through 1983 was obtained almost completely with the 2.7 m telescope at the McDonald Observatory. Some additional measurements were made with this telescope in 1984 and 1985, but most of the data from 1984 on has come from 3 other instruments. These are the 1.5 m telescope at the Claern-CERGA Observatory in France, the Multi-Lens Telescope at the Haleakala Observatory on Maui, and the 0.75 m. telescope at the McDonald Observatory. The most prolific producer of lunar range data has been the CERGA station, which also has done an excellent job of obtaining ranges to the Apollo 11, Apollo 14, and Lunakhod 2 reflector packages, as well as the Apollo 15 site.

The length of the observing period which goes into forming one range normal point varies considerably, but is roughly 20 minutes. From 1976 through 1983 both the precision and the accuracy of the normal points was typically 15 to 20 cm. The precision was improved to roughly 5 cm by 1987, with the accuracy being somewhat worse because of limitations in the calibration procedures. However, recent improvements have been dramatic. By the spring of 1988, all 3 stations had demonstrated repeatabilities for their best range normal points over periods of 4 hr or more of 2 cm. During the IAU General Assembly Dr. Christian Veillet reported that more recent analyses at CERGA and at the USNO gave better than 1 cm normal point repeatabilities. The accuracy is currently estimated to be 2 or 3 cm, but plans are to make major efforts to improve this to 1 cm in the next year or two.

Almost all of the scientific results so far from lunar ranging have been based on the earlier data with roughly 6 to 20 cm accuracy. Most of the analysis work has been carried out by the following organizations: JPL; MIT; the Center for Astrophysics; the USNO; the University of Texas; and CERGA. Major objectives of the work have been: the determination of the Earth's rotation and nutation, in conjunction with VLBI and

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

Satellite laser ranging measurements; the continual improvement of the lunar ephemeris for use in planetary ephemeris development work; and studies of lunar interior properties from measurements of the lunar librations.

One important gravitational physics test from lunar ranging is a negative result for what is called the Nordvedt effect. This result shows that the gravitational self-energy of the Earth behaves in the same way as other forms of energy in determining the gravitational interaction of the Earth with the Sun. However, if energy and momentum conservation are assumed and preferred frame theories are not considered, the lunar ranging results provide an accurate determination of the parameter ß in the Robertson-Walker metric. The accuracy currently is about 0.15%, which is roughly an order of magnitude better than has been obtained from the precession of perihelion for Mercury. Tests of the geodetic precession of the lunar orbit predicted by De Sitter in 1916 based on general relativity also have been reported recently by the Center for Astrophysics and JPL groups, with 2% accuracy. And finally, a combination of the secular acceleration of the moon from lunar ranging with determinations of ocean tides on the Earth from satellite laser ranging provides confirmation that the Newtonian gravitational constant G is not changing with time.

Astrometry of Millisecond Pulsars — J. H. Taylor

Soon after the discovery of the first millisecond pulsar it became clear that this class of objects would provide unusual opportunities for high-precision astrometric observations. Even for the longer-known class of "ordinary" pulsars, timing observations had yielded celestial position measurements with accuracies at the <0.1" level. Since the uncertainty in pulsar time-of-arrival measurements tends to be a fixed fraction (typically 10^{-4} to 10^{-3}) of a period, millisecond pulsars obviously afford even better possibilities. Consequently, it is not surprising that early work on PSR 1937+21 yielded position measurements with precision at the milliarcsecond level (Davis et al 1985), or that more recent work (Rawley, Taylor, and Davis 1988, and unpublished results) have improved these measurements by a further factor of 8. Millisecond pulsar timing observations are already accomplishing astrometry at the 0.1 milliarcsecond level.

Precision is one thing, and absolute accuracy another. The intrinsic reference frame underlying the analysis of pulsar timing data is that of the planetary ephemerides. In current practice, this means the reference frame of a model solar system fitted to a large archival data base of optical and radar observations, numerically integrated to construct the tabular ephemerides. Celestial coordinates quoted in this system have real meaning, and clear definition - but obviously a different definition from, for example, FK5 positions. Some of the ramifications and difficulties relating the reference frames have been discussed by Becker et al. (1986).

About a year ago Rawley, Taylor & Davis (1988) were surprised to discover that Arecibo Observatory timing data on

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

PSR 1937+21 revealed that this pulsar has remarkably small proper motion in the planetary reference frame. Galactic rotation should contribute a proper motion of -5mas/y in galactic longitude, but the observed rate was only -0.6 ±0.3 mas/y. If the planetary reference frame is truly inertial and thus non-rotating, as our ephemeris-oriented colleagues very reasonably insist, then the peculiar velocity of PSR 1937+21 must have just the right magnitude (about 85 km/s) and direction to cancel most of the contribution from galactic rotation. Further results on this and other millisecond pulsars are steadily accumulating, and it will be of considerable interest to see whether special values of peculiar velocity will be required to explain them. In any event, millisecond pulsar timing observations promise to provide some of the most accurate astrometric data available over the next few years.

References:

Backer, D.C., Fomalont, E.B., Goss, W.M., Taylor, J.H., & Weisberg, J.M., 1986, Astron J., 90, 228.

Davis, M.M., Taylor, J.H., Weisberg, J. M., & Backer, D.C., 1985, Nature 315, 547.

Rawley, L.A., Taylor, J.H., & Davis, M.M. 1988, Astrophys. J., 326, 947.

Preliminary Results of Reconstruction of Nutation Series of the Rigid Earth

H. Kinoshita & J. Souchay

At present for the orientation of the Earth in the space, we have an observational accuracy of a millaircsecond by VLBI. The accumulated 8 years of VLBI observations clearly show the systematic and periodic residuals, which indicate that the present IAU nutation series should be revised. Recently Kubo (1986) compared the IAU nutation series with numerical integration and found long periodic systematic deviations. The order of these systematic deviations from the theory is of a milliarcsecond. On the other hand we are going to achieve an accuracy of submilliarcsecond by VLBI and other high precision techniques in the near future. Consequently, a nutation theory with an internal precision better than 0.1 milliarcsecond is necessary to be compatible with the observational accuracy.

The present internationally adopted nutation series are based on Kinoshita's rigid theory (1977) and Wahr's non-rigid theory (1981) that uses the Earth model 1066A (Gilbert and Dziewonski, 1975). Wahr's theory gives a ratio of the nutation amplitude for the non-rigid Earth to that for a rigid Earth model. Therefore, we have to improve both a rigid theory and a non-rigid theory.

For a rigid theory, we have to: 1) Adopt more precise orbital theories of the Moon and the Sun for the computation and disturbing functions (for example ELP2000 for the Moon and VSOP82 for the Sun). The present rigid theory (Kinoshita 1977) adopts Brown's theory for the Moon and Newcomb's theory for the

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

Sun for the calculation of the disturbing function by these two bodies. 2) Take into account the direct torques from planets. 3) Take full account of second order effects such as the disturbing potential due to J3 and J4, interactions among nutation, coupling effects between the rotational motion of the Earth and the orbital motion of the Moon.

Among these three items the most important one is the second order coupling effect between the rotation of the Earth and the orbital motion of the Moon. Kinoshita's theory (1977) is not complete in this respect, which was pointed out by Kubo (1982). In order for a theory of nutation to be complete up to the second order, we have to treat the rotation of the Earth as a dynamical system with six degrees of freedom (3 for rotation and 3 for orbital motion) instead of a restricted problem with three degrees of freedom (the orbital motions of the Moon and the Sun are given and only the rotation of the Earth is to be solved.)

The preliminary corrections to the nutation amplitudes with argument Ω and 2Ω (Ω is the longitude of the node of the Moon) arising from the coupling effect mentioned above are:
nutation in longitude: $0.00007 \sin\Omega + 0.00121 \sin 2\Omega$ (1)
nutation in obliquity: $0.00069 \cos\Omega - 0.00024 \cos 2\Omega$. (2)
where the unit is arcsecond. These numerical values of (1) and (2) may change after taking account of other effects mentioned above. We have already finished calculations related to items (1) and (2) above. The difference in the nutation amplitudes due to the change of planetary theories and Moon's theory is of order 0.1 milliarcsecond and the contribution from direct planetary torques is also of order 0.1 milliarcsecond.

References:

Kubo, Y. 1986 Proceedings of the Nineteenth Symposium on Celestial Mechanics, Kinoshita, H. and Nakai, H. editors, 78-81.
Kinoshita, H. 1977 Celest. Mech. 15, 277.
Wahr, J. 1981, Geophy. J. Royal Astr. Soc. 64, 705.
Gilbert, F. and Dziewonski A.M.: 1975 Phil. Trans. Soc. London A278, 187.
Kubo, Y. 1982 Celest. Mech. 26, 97-112.

The Effects of the Earth's Non-Rigidity on Nutation J. Wahr

Recent VLBI nutation results (Herring, et al, 1986) disagree with the current IAU nutation series at the milliarcsecond level. Studies of this problem have demonstrated that there are certain properties of the Earth that geophysicists do not presently understand well enough to allow them to predict the nutation for a non-rigid Earth accurate to the sub-milliarcsecond level. This is good news for geophysicists, because it implies that the VLBI results can be used to constrain those properties. But, it is bad news for those astronomers who only want to be able to accurately remove the nutation from their data.

Some important features of the real Earth that are not

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

is more adapted for deriving UT1, polar motion and the celestial pole coordinates than the classical transformation involving the equinox, in which the precession and nutation motions are coupled with the Earth rotation.

REFERENCES

Capitaine, N., Guinot, B., Souchay, J., 1986, Celest. Mech. 39, 283.

Capitaine, N., Guinot B., 1988, in The Earth's Rotation and Reference Frames for Geodesy and Geodynamics, A.A. Babcock and G. A. Wilkins ed. D. Reidel Publishing Company, 33.

Guinot, B., 1979, in Time and the Earth's Rotation, D.D. McCarthy and J.D., Pilkington ed, D. Reidel Publishing Company, 7.

Guinot, B., 1981, in Reference Coordinate Systems for Earth Dynamics, E.M. Gaposchkin and B. Kolaczek ed, D. Reidel Publishing Company, 125.

<u>Procedures for Accurate Origin</u> S. AOKI

RELATION BETWEEN CELESTIAL AND TERRESTRIAL REFERENCE SYSTEMS

In the previous paper (Aoki 1988b) we have solved the equations of rotational motion of a rigid Earth up to the second order. The results are summarized as follows: (i) the forced oscillation of the polar position in space is expressed with the celestial ephemeris pole (ii). The remaining part includes nutation and Oppolzer terms multiplied by wobble. (iii) The Greenwich apparent sidereal time (GAST) is expressed in the form, GAST-GMST + (q)p where (q)p called the equation of equinoxes in the wider sense, includes the additional terms, $0.00264 \sin\Omega$, + $0.000063 \sin 2\Omega$, besides $\phi \cos\epsilon$. (iv) The relation between GMST and UT1 is given by eq. (13) of Aoki et al (1982).

DEMERITS OF NRO

The coordination using the Non-Rotating Origin (NRO) proposed by Guinot (1979) and restated by Capitaine et al. (1986) has following demerits; (i) the NRO is only locally inertial and moves with respect to space even to the right ascension direction, by $(\cos\epsilon-1)P_1$= 413"/ century on average (Aoki, 1988a). Even for an object near the equator, NRO moves by 0.00386"/century, by the second order effect of nutation (Aoki 1988b). (iii) The nutation with respect to NRO looks as if it includes out-of-phase terms (Aoki and Kinoshita 1983). (iv) The position of NRO is given by an indefinite integral. If we want to give it definitely, it depends on the initial position as well as the adopted precession constant. This reveals that the position of NRO, depending on its hysterisis, cannot be corrected if the NRO is chosen continuously across a changeover date in future. In other words, the NRO is theory-dependent (Aoki 1988a), whereas the equinox is observable (Aoki, 1988b).

References:

Aoki S. 1988a. in Proc. Japanese Symp. on Earth Rotation, Astrometry and Geodesy, pp. 196-206.
Aoki, S.: 1988b. Celest. Mech. in press.
Aoki, S., Guinot, B., Kaplan, G.H., Kinoshita, H., McCarthy, D.D. and Seidelmann, P.K., 1982. Astron Astrophys 105, p. 359-361.
Aoki, S. and Kinoshita, H., 1983 Celest Mech 29, 335-360.
Guinot B., 1979. IAU Symp No. 82, 7 - 18.
Capitaine, N., Guinot, B., and Souchay, J. 1986. Celest. Mech. 39 283-307.

The Mean Motion in Modern Planetary Ephemerides E. M. STANDISH, JR.

In 1984, Stumpff and Lieske illustrated an inconsistency of approximately 1"/cty which exists between three astronomical parameters: Fricke's (1972) correction to Newcomb's value of general precession in longitude, the mean motion of the Earth in modern planetary ephemerides and the rate of the apparent longitude of the Sun as given by Newcomb's Theory of the Sun (1898). Of course, at least one (if not more) of the three quantities could be in error. It is instructive to examine each.

Precession

It seems certain that Fricke's correction of 1.10"/cty to the Newcomb precession is correct, at least to within 20%. More modern determinations show 0.85"/cty from Lunar Laser Ranging, 0.90"/cty from VLBI at JPL and 0.80"/cty from VLBI at MIT.

Planetary mean Motion

Realistic estimates of the accuracy of the Earth's mean motion have been about 0.01"/cty - two orders smaller than the sought-for inconsistency mentioned above. These estimates have now been substantiated in two ways:

1) A comparison between the two independently created ephemerides, JPL's DE118 and MIT's PEP740, shows agreement for the Earth's mean motion of about 0.005"/cty.

2) An experiment was performed during which a change in mean motion of 1"/cty was artificially forced into the ephemeris for the Earth. A new adjustment was then made for all relevant parameters while keeping the Earth's mean motion artificially changed. The results show how badly distorted the solution becomes and are perhaps best illustrated by a comparison of the Viking Lander residuals in Figure 1 which shows a normal fit and the residuals in Figure 2 which shows the best possible fit with an artificially changed mean motion.

Newcomb's Theory

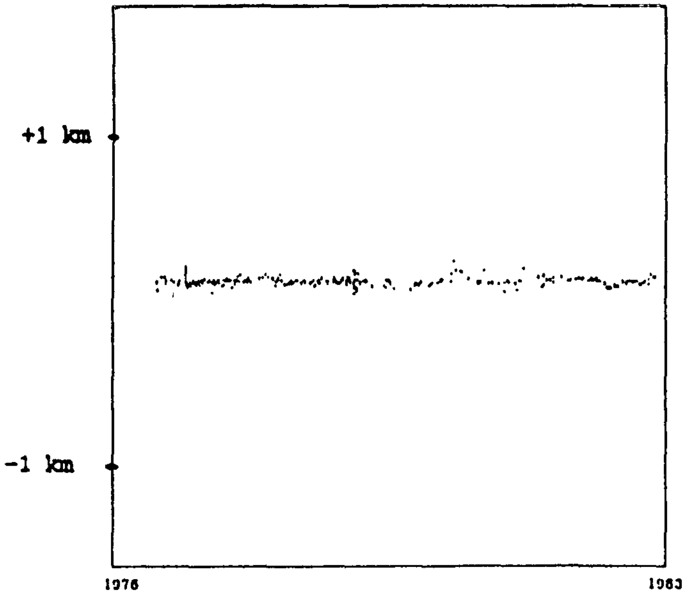
https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

The apparent longitude is given as a function of time, but it isn't clear exactly which time to use. Further, the theory is based upon 19th century observations, about which Fricke had the following to say. "It may be mentioned that absolute observations carried out before 1890 show not only a large scatter but also clear indications of neglected instrumental errors..."

Conclusion

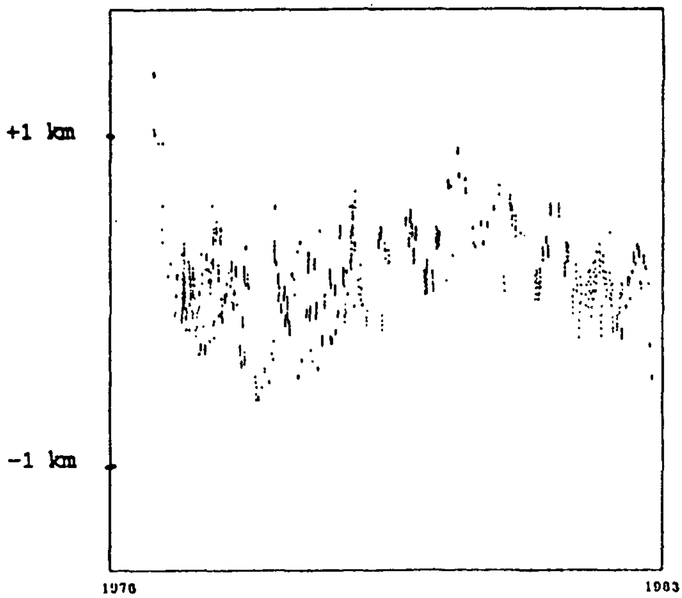
Newcomb's theory was a remarkable achievement and it is a credit that he was able to attain an accuracy of 1"/cty. However, one could hardly expect more.

Figure 1. Viking Lander residuals from a normal solution.



https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

Figure 2. Viking Lander residuals when the earth's mean motion is forced to fit a 1"/cty change to its normal value.



Determination of the Earth Orientation M. FEISSEL

The Earth orientation can be described by five parameters which provide the transformation between a reference frame attached to the Earth and a quasi-inertial reference frame, as a function of time. The parameters measured give the direction of the rotation axis in space (offsets in longitude and in obliquity with respect to a modelled direction), and in the Earth (x, y), and universal time (UT1-UTC). Due to the incomplete theoretical modelling of the Earth rotation irregularities, these parameters have to be monitored, for practical applications (e.g. space navigation) and for improvement of the theory. The main observation methods are Very Long Baseline Interferometry (VLBI), laser ranging to the Moon (LLR), and high altitude satellites (SLR), organized in permanent programs involving worldwide networks. From 1970 through 1983 they have progressively replaced the less precise optical astrometry method, which had been in use since the end of the 19th century. Global analyses of these observations over several years include, for each program, the computation of a terrestrial and celestial frame, of time series of the Earth orientation parameters, and other parameters pertaining to the body of the Earth or to specific aspects of the observing method. The celestial frame realized by VLBI is a set of coordinates of extragalactic compact radio sources; in the laser techniques, it is the ephemeris of the target, lunar reflector or artificial satellite. The terrestrial frame is in all methods a set of geodetic coordinates for the observing sites; the VLBI terrestrial frames include about 15 sites and

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

the SLR about 55.

The limiting factors to precision and accuracy of the analyses are in general at the milliarcsecond level or lower, e.g. tectonic plate motions (VLBI, LLR, SLR) precession-nutation models (VLBI, LLR) radio source structure (VLBI), lunar ephemeris (LLR); orbit perturbations by the oceanic tides prevent SLR from accurately determining UT1 for frequencies lower than 1c/80d; due to a sparse network (3 stations), LLR cannot determine polar motion. For the participation of analysis centers in the International Earth Rotation Service (IERS), a part of the models and astronomical or geodetic constants are unified, for the models and constants which are not known accurately enough, their improvement is pursued on the basis of the observations themselves.

The precision of the Earth orientation measurements is estimated by the analysis centers, which associate formal uncertainties to their results. The accuracy, or consistency, of these determinations can also be estimated through comparisons of the global results obtained independently from the different analysis centers for the same technique. Taking advantage of several time series of similar quality over several years. the long term consistency of results can also be evaluated. Various evaluations of precision and consistency are summarized in Table 1.

Table 1 - Precision and consistency of Earth orientation determinations Units : 0.001".

methods :	VLBI				LLR		SLR		
estimation (1984-1987)	sampl. time	celest. pole	terr. pole	UT	sampl. time	UT	sampl. time	terr. pole	UT
formal uncert.	1d	0.4	0.9	0.6	0.1d	4.5	3d	0.7	1.0
consistency of time series	5d	0.5	1.2	0.7	0.5d	4.2	5d	1.3	1.8
	1m		0.5	0.4			1m	0.5	1.0
	1y		0.2				1y	0.4	

The VLBI polar motion determinations have an error spectrum consistent with a white noise model. The VLBI series of UT1 as well as the SLR determinations of polar motion and UT1 have an error spectrum which is nearer to a flicker noise model, suggesting that some time dependent errors are present in the analyses at the submilliarcsecond level.

Other consistency tests can be performed with the help of closure equations which should be verified between the relative orientations of the individual reference frames and the biases between the corresponding series of Earth orientation parameters. The inconsistencies between two parallel solutions from the same method are at the level of 0.0002" for SLR and

0.002" for VLBI, probably due to the poor distribution of the VLBI network; the inconsistencies between SLR and VLBI independent solutions are at the level of 0.002".

In summary, while the long term inconsistency of the series of Earth orientation parameters is well under the milliarcsecond, the evaluation of their accuracy is presently limited to about 0.002" by the coverage of terrestrial networks.

References

BIH, 1988, Annual Report for 1987, Observatorie de Paris IERS, 1988, IERS Standards, Technical Note No. 1, (Ed. D.D. McCarthy).
Moritz, H., and Mueller, I.I.: 1987, Earth Rotation, Theory and Observation, Ungar.

Apparent Place Reduction B. D. Yallop

A procedure based on that published in the Astronomical Almanac, section B, is recommended. That procedure was intended to produce apparent places to 0.01". In most cases it may be used without modification to produce apparent places to mas.

For stars and extragalactic sources the main inaccuracy occurs at the start of the procedure which is to obtain a barycentric position and velocity of the object on the FK5 system at J2000.0. The FK5 catalogue itself contains standard errors of 0.02" in position and 0.7 mas per year in proper motion.

In general it will be necessary to include observations made in the FK4 system to produce final positions to mas precision. The FK4 system is non-inertial due to known errors in precession and the motion of the equinox. The transformation recommended by Aoki et al from FK4 at B1950.0 to FK5 at J2000.0 ignores second order effects of non-inertial motion, which produces errors of up to 5 mas in position and up to 13 mas per century in proper motion. Murray has taken fully into account the non-inertial motion and has shown that it is more logical to make the changeover from FK4 to FK5 at 1950 as Standish suggested originally.

The effect of removing the E-terms of aberration may still introduce inaccuracies in the positions and proper motions of catalogue mean places. The effect of these terms can only be properly eliminated from individual observations when the original procedure is known. This demonstrates the importance of using agreed standard procedures for apparent place reductions.

At the next stage of forming the mean place of a star at the epoch of date, Stumpff has pointed out that the calculation of space motion in the Astronomical Almanac is not rigorous. Observables are used instead of inertial quantities and the effect of light time has been ignored. Fortunately these effects are very small and are only important for nearby stars whose apparent motions are changing rapidly across the line of sight. The errors increase progressively with time so that they may become significant at the mas level only after several decades.

Several general relativity effects up to order μ/c^2 have been accounted for in the reduction procedure, because they do not exceed 0.1 mas. While photons are crossing the solar system, the Sun moves relative to the barycentre. This effect, which is estimated not to exceed 0.1 mas, has been ignored in the algorithm for solar light deflections.

The Transformation Between the Coordinate Systems of FK4 at B1950.0 and FK5 at J2000.0 — C. A. Murray

The essential changes in the fundamental coordinate reference system of FK5 relative to that of FK4 are (i) revision of the precession constants, (ii) correction for the zero point error in right ascension and its rate of change, (equinox correction and motion), and (iii) the adoption of J2000.0 as fundamental epoch instead of B1950.0. We are not concerned here with regional systematic errors.

Two matrix formulations of the transformation have been proposed, by Aoki et al. (1983) and by Standish (1982); these differ in the following two important respects. (a) The osculating epoch at which the coordinate axes in the two systems coincide is taken to be 1984 January 1 by Aoki et al. and B1950.0 by Standish. and (b) the equinox correction at a general epoch is applied in the reference frame of date by Aoki et al. and in the frame of B1950.0 by Standish.

We consider first point (a). The FK4 system is defined at B1950.0 by positions and proper motions in the catalogue, and it is these proper motions which were analyzed by Fricke (1967) in order to derive corrections to precession and equinox motion. It follows therefore that these corrections must be applied at this epoch. We assume, with both authors, that the proper motion system defined by FK5 is inertial whereas that of FK4 is not. This implies that a linear space velocity is represented by coordinates varying linearly with time in the FK5, but not in FK4. We can therefore calculate true coordinates at any epoch in the J2000.0 reference frame just from the positions and proper motions in FK5 (with radial velocity and parallax if necessary), but B1950.0 is the only epoch for which true coordinates are known in the FK4 system; it is therefore necessary to adopt B1950.0 as the osculating epoch.

On point (b) it is clear that the motion of the equinox obtained from proper motions is a rotation of coordinates about the pole of the B1950.0 frame. It is also evident that Fricke (1985) regarded the equinox corrections derived from observations of solar system bodies at successive epochs as being in the B1950.0 frame. Therefore, it is essential that the correction for equinox motion be applied in this frame. In the special case in which the precession is unchanged and the equinox correction does not vary with time, both coordinate systems are inertial and should differ only by a constant rotation; this follows from the formulation proposed by

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

Standish, but that of Aoki et al. depends on the epoch, which is absurd.

The main difference between the transformations formulated by Aoki et al. and by Standish are coordinate rotation of 0.005" at B1950.0 and a relative rotation rate of 0.013" per century, both about the direction to the vernal equinox. Since at least one of these transformations leads to a non-inertial coordinate system at the milliarcsecond level, it is important to arrive at a consensus as to which should be adopted. My own view is that Standish's formulation is correct with respect to both points.

References:

Aoki, S., Soma, M., Kinoshita, H., Inoue, K.: 1983, Astron. Astrophys. 128, 263.
Fricke, W.: 1967, Astron. J. 72, 1368
Fricke, W.: 1985 Veroff, Astron Rechen-Institut Heidelberg No. 31.
Standish, E.M.: 1982, Astron. Astrophys. 115, 20.

Review of Current/Future Catalog (Radio/Optical) Accuracies

H. Schwan

Considerable progress in the determination of the positions of celestial objects has been made in the recent years. In optical astrometry new fully automated and photoelectric meridian circles have come into operation (in La Palma, Bordeaux and Tokyo) which can perform about 100,000 observations per year for objects brighter than 13th magnitude with a precision of 0.15" to 0.20" for a single observation. Including such observations in addition to those made in the past with the aid of other meridian circles, astrolabes, vertical circles and transit instruments, we have achieved in the basic part of the FK5 (consisting of the classical 1535 fundamental stars) a systematic and individual accuracy of about 20 mas for the positions at the mean epoch (about 1950) and of 0.7 mas/year for the proper motions. Positions and proper motions of inferior precision will be derived for about 3000 new fundamental stars (the FK5 Extension) selected from the FK4 Sup and IRS list.

In the future the astrometry satellite HIPPARCOS will hopefully measure positions and proper motions of more than 100,000 stars brighter than 13th magnitude with a precision of 2 mas and 2 mas/year, respectively. The precision of these proper motions (which is comparatively low because of the short period of the mission) can be significantly improved by combining the HIPPARCOS measurements with existing ground based catalogues. A combination of HIPPARCOS with the Basic FK5, e.g., would provide proper motions with a precision of 0.4 mas/year. Optical Interferometry is a promising means to determine high precision positions. Based on experience at MIT, SAO and USNO one can expect an accuracy of 3 mas from one night for stars brighter than 12th magnitude.

The most precise positions have been obtained by means of VLBI measurements of compact extragalactic radio sources. The precision given in existing radio catalogues is typically better than 5 mas. Analyzing only objects with more than 100 observations, a precision of better than 1 mas had been achieved; in that case corrections to the 1980 IAU nutation series had to be included in the reduction procedure.

Future improvements in radio (and optical) astrometry will arise from an increased number of the measured objects, in particular in the southern sky, from improved techniques, from more instruments and therefore more base-line orientations, from more sophisticated reduction procedures and improved theories, and from the accumulation of more observing time per object.

Report of the IAU Working Group on the Theory of Nutation

R. L. Duncombe

The IAU Working Group on the Theory of Nutation comprises; N. Capitaine, T. Herring, G. Kaplan, H. Kinoshita, M. Rochester, J. Vondrak, J. Wahr, D. McCarthy with R. Duncombe as Temporary Chairman during the beginning phases of the work. The Working Group was formed in April 1987 and from that time on it has not been possible to assemble this group as a whole. Consequently all of the work has had to be done by correspondence. Helpful comments and contributions to the task of this Working Group have been received not only from within the group but also from other scientists who are actively engaged in problems concerning the Earth's nutation. This report draws heavily on contributions by N. Capitaine, J. Vondrak, V. Dehant, J. Dickey, T. Herring, and O. Sovers and C. Edwards.

The IAU 1980 Nutation Series are based on Kinoshita's (1977) rigid Earth Theory, using Newcomb's Theory for the motion of the Earth, Brown's Theory for the motion of the Moon and the IAU 1976 System of Astronomical Constants. These theoretical coefficients are modified on the basis of Wahr's theory (1981) in the ratio of the amplitudes of each circular nutation relative to a realistic Earth model and to a rigid Earth Model. This ratio is computed for an elliptical, rotating, elastic and oceanless, hydrostatically pre-stressed Earth with a fluid core. While this nutation series has proven adequate for many astronomical reductions, the introduction of high-precision VLBI, LLR, and SLR observing techniques has revealed some significant inadequacies. VLBI observations at the milliarcsecond level (or better) have indicated possible amendments to a number of terms in the nutation series from the 18.6 year term on down. To enable the systematic reduction, on a common basis, of VLBI, LLR and SLR observations, a new more precise nutation series is required.

To this end, the consensus of the Working Group indicates that it would be desirable to repeat Kinoshita's theory for a rigid Earth, using modern theories for the motion of the Earth and Moon, current values for the astronomical constants and including the effect of the planetary perturbations. To match the accuracy of the VLBI, LLR and SLR techniques this new rigid Earth theory should attempt to incorporate all known

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

contributions at the one tenth milliarcsecond level. In addition the Wahr theory should be redone, again attempting to incorporate all known contributions at the one tenth milliarcsecond level. N. Capitaine has pointed out that the amplitudes of the in-phase and out-of-phase components of nutation should include the contribution of the non-hydrostatic core flattening as well as the oceanic and anelastic effects which have been shown to be significant. She adds, however, that present models do not allow these effects to be derived at the sub-milliarcsecond level.

The tasks outlined above will clearly occupy the endeavors of this Working Group and others for the next triennium and possibly beyond. In the interim, it becomes necessary to take some action to provide standardized working coefficients for those terms where observations have clearly shown modifications to be desirable, to allow for systematic nutation reduction of VLBI, LLR and SLR observations. It is the consensus of this Working Group that these corrections should not be empirical (that is taken directly from the observations) but rather "adopted" values based on plausible modifications to present theory which produce corrections consistent with the observed results. It is a further consensus of this Working Group, that of the several terms shown by observation to need possible amendment, only the annual and semiannual terms are sufficiently verified to consider at this time. The working group consensus favors the "adopted" values of corrections to these terms given by the discussion of T. Herring (1987). These are for nutation in longitude annual term, in-phase +5.23 mas, out-of-phase +0.61, mas; semi-annual term, in phase +1.02 mas, out-of-phase -1.18 mas. For nutation in obliquity the corrections are: annual term, in-phase +2.08 mas, out-of-phase -0.24 mas; semi-annual term, in-phase -0.41 mas, out-of-phase -0.47 mas. Herring states that these "adopted" corrections to the "coefficients in the 1980 nutation series were obtained assuming that the semi-annual nutation corrections are due solely to an error in the prograde semi-annual circular nutation, and that the annual correction is due to an error in the retrograde annual circular nutation. These circular nutations are those which geophysically should be most affected by the fluid core, elasticity and the oceans. These assumptions are consistent within the observational uncertainties."

It is the consensus of the Working Group that these corrections be used, not as new constants, but as standardized working numbers to facilitate the uniform nutation reduction of VLBI, LLR, SLR and other observations, so that results from all techniques may be intercompared.

In concluding this report, I would like to thank those scientists, both within and without the Working Group, who have contributed so significantly to our task.

References:

Herring, T. 1987, private communication.
Kinoshita, H. 1977 Celest. Mech. 15 277
Wahr, J. 1981 Geophy J. Royal Astr. Soc 64, 705.

Report of the IAU Working Group on Astronomical Constants B. Morando

Setting up of the Working Group

The Working Group was created following Resolution C1 of the International Astronomical Union adopted at the General Assembly in New Delhi in November 1985. This resolution reads as follows:

"Commission 4, (Ephemerides), 7 (Celestial Mechanics), 8 (Positional Astronomy), 19 (Rotation of the Earth), 31 (Time) recognizing the importance of ensuring that the IAU system of astronomical constants is rigorously defined and is well suited to current applications,
invite the presidents of IAU Commissions 4, 7, 8, 19, and 31 to form a Working Group to serve in collaboration with the appropriate special study group of the International Association of Geodesy which will; 1) review current determinations of astronomical and geodetic constants, 2) provide for informational purposes the current best estimates of the values, accuracies and sources of these constants, 3) propose appropriate changes in the relevant definitions and values of the constants of the IAU system, 4) urge all authors to specify completely the values and accuracies, as well as the sources, of the constants used in their work and 5) submit a preliminary report in 1987."

The Working Group is composed as follows: Chairman; B. Morando (Bureau des Longitudes, France), Members; V. A. Abalakin (Pulkova Observatory, USSR), W. E. Carter (National Geodetic Survey, USA), H. Kinoshita (Tokyo Astronomical Observatory, Japan), J. Lieske (Jet Propulsion Laboratory, USA), J. Schubart (Astronomisches Rechen Institut, GFR), H. Schwan (Astronomisches Rechen Institut, GFR), P. K. Seidelmann (U S Naval Observatory, USA), E. M. Standish (Jet Propulsion Laboratory, USA), J. M. Wahr (University of Colorado, USA), G. Wilkins (Royal Greenwich Observatory, UK), B. Yallop (Royal Greenwich Observatory, UK), Ya S. Yatskiv (Kiev Main Observatory, USSR).

Philosophy for a system of constants

The activity of astronomy has broadened to such an extent that the various activities of astronomy encompass a broad spectrum of different types of constants. These range from geodetic constants to constants for physics, so it is difficult to draw a line and say that these are the constants for astronomy. At the same time the increase in knowledge has progressed at such a rate that the constant adopted today may not be satisfactory a year later.

On the other hand one of the principal requirements for utilizing observations from the past or for understanding the observations of today in the future, will be a requirement to know what constants and procedures were used for the reduction of those observations.

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

Thus if the need for the adoption of an apriori set of constants has lessened, it has become important to publicize the procedures that were used. The question of what procedures were followed includes the reference system used, in what order were the computations made, and what accuracy and weighing procedures were used. The need is for a means of comparing different results today and for documenting what was done. It might even be possible to have computer readable, updated files available almost immediately over some sort of telephone network with a monitoring group responsible for the contents of such a file. An archiving system would have to be associated with this by which one could retrieve previous files in order to determine how a given set of data has been processed.

In the past the IAU has regarded as one of its duties to provide conventional values of some astronomical constants considered as being especially significant. Such systems of constants were the 1964 IAU system of constants adopted at the Twelfth General Assembly and introduced in the ephemerides in 1968 and the 1976 IAU System of Constants adopted at the Sixteenth General Assembly and introduced in the ephemerides in 1984.

The difficulties of an adopted system of constants are exemplified by the system adopted in 1976. When ephemerides were subsequently fit to the observations, it became apparent that there was no way in the fitting process, to enforce upon the observations given values for some constants. For example, the value of the obliquity of the ecliptic determined by Newcomb could not and should not be used to fit modern ephemerides with the modern observations. Also between 1976 and 1984 a satellite of Pluto was discovered which indicated that the mass of Pluto was very different from the value adopted in 1976. To force such a mass of Pluto on the ephemerides would be a serious mistake. The process of fitting the ephemerides to the observations and solving for unknowns, such as the obliquity and the masses of the planets, results in a better fit and better ephemerides. So the apriori adoption of constants is inconsistent with the process of obtaining the best fit of the ephemerides to the observations. The values of some constants are improved, sometimes drastically, thanks to numerous and precise, mainly space borne, observations. These observations so frequently alter the values of the constants involved that it is impossible for a system of constants intended to last ten years to keep up with them. This is the case, for instance, for the radii of the satellites of the planets and it may become very soon the case for the masses of the minor planets.

This situation will inevitably remain for the future. The inadequacy of the current system of constants has, of necessity, led to the practice of different groups defining and adopting their own system of constants. Examples are the Merit standards and the standards of the International Earth Rotation System.

Special Issue: The astronomical units. The concept of the unit of length.

The 1976 IAU system gives a definition of the unit of time in the relativistic framework, but the unit of length is not clear, as in fact two different time scales exist each one being related to a specific frame. It is suggested that the SI second, and the SI meter in the 1976 IAU system should be understood as the barycentric second sB and the barycenter meter mB respectively. These quantities would then be related to the SI units sL and mL by the following relations:

$$sB = {}^{1}/_{n}\, S_L \quad m_B = {}^{1}/_{n}\, m_L \quad \text{where } n = 1 - 1.55051 . 10^{-8}$$

n is the mean value of the derivative of local time with respect to barycentric time. Then the day would be 86 400 barycentric seconds and the astronomical unit would be defined as the semi-major axis of a planet with a mass equal to zero having a mean motion equal to the Gauss constant. As a derived constant it would be equal to
$1.4959787014953416 \times 10^{11}$ barycentric meters. The velocity of light would have the same value in the local frame or in the barycentric frame. Some members of the Working Group, instead of defining the SI second in terms of the barycentric second, had rather use the local second which would have the advantage of being more accessible to time-service people and laboratory physicists. The definition of the unit of length remains so far linked to the two body problem in the frame of newtonian mechanics. It might be approached quite differently by defining first, as above, a second of coordinate time, the day being 86400 such seconds, and defining then the unit of length (the astronomical unit) by adopting a given value for the velocity of light expressed in astronomical units per day.

Another strong feeling of the Working Group has to do with the names given the time scales TDT and TDB which are deemed confusing and misleading. Proposals are made to drop the word "dynamical" from those names.

New approach to constants

In order to comply with resolution C1 of the IAU there is the need for communication between the IAU and the various organizations specifying constants. This includes the International Union of Geodesy, Codata and other such constant defining groups. The constants could be divided into the following groups:

1. Defining constants should be adopted and accepted as they are unlikely to change over a long period of time. First the unit of time would be clarified as explained in section 3. Then there are two possible solutions:

a - The unit of mass is the mass of the Sun and the unit of length is defined given the Gaussian gravitational constant.

b - The velocity of light expressed in astronomical units per day is a defining constant which defines the unit of length and the unit of mass is defined using the Gaussian gravitational constant.

The velocity of light in meters per second is now a defining constant of the SI system of units. It is then unnecessary to give it as part of an astronomical system of

units.
2. All the other constants would only be considered as part of a recommended set of values. This set would include a list of constants obtained as the result of the solution of fitting the ephemerides to observations. Such a system of constants would be some of the values underlying, for instance DE200/LE200. Also a list of best estimates of values needed for the multitude of purposes in Astronomy would be given. This list would include the masses of the minor planets and satellites, the equatorial radii of the planets, etc. The list of these constants could be revised on an annual or tri-annual basis.

The defining constants and the list of recommended values could be published annually in the national ephemerides.

3. In addition a set of procedures and computational algorithms should be suggested for use as applicable. Thereby astronomers could document their procedures and observational reductions by consistently including in publications a statement that the procedures and constants documented in a reference are utilized in this work. To provide a draft example of such a system of astronomical constants and procedures the following is put forth as an example.

- Suggested Procedures and Computational Algorithms are:
  (1) Planetary, Solar and Stellar Reduction as described in the national ephemerides.
  (2) Conversion of standard epoch B 1950.0 to J2000, from Standish, E.M., (1982) Astron. Astrophys, 115, 20-22 and from Aoki, S., Soma M., Kinoshita, H., Inoue, K., (1983) Astron. Astrophys., 128, 263-267.
  (3) IAU Theory of Nutation
  (4) Radiation Pressure Model of Merit Standards 1983, Appendix A4.
  (5) Ocean Tide Model of Merit Standards 1983, Appendix 6.
  (6) General Relativistic Terms for Propagation and Time, Merit Standards 1983, Appendix 12.
  (7) Radio Source Positions of Merit Standard 1983, Appendix 12.
  (8) FK5 Star Catalogue.

- Defining constants
  (1) Gaussian gravitational constant k=0.01720209895, the unit mass being the mass of the Sun.
  Alterative
  (1) Gaussian gravitational constant k=0.01720209895
  (2) Velocity of light c=173.14463331 au/day

Report Of The Working Group On Reference Frames

J.A. Hughes, Chairman

The following is an abreviated and edited version of the report of the Working Group as given at the General Assembly in Baltimore. The six recommendations of the group which are given here are slightly edited in order to agree with the exact wording adopted by the IAU as Resolution C1. The original report contained two additional recommendations which are essentially subsumed in Resolution C2 as adopted at the IAU General Assembly (GA), and which therefore, are not given here. The essential text of the report is unchanged.

The Working Group on References Frames (WG), was founded by Resolution C2 of the XIX GA held in New Delhi in 1985. The members of the WG and the Commissions which they represent are: B. Morando (4), J. Kovalevsky (7), H. Schwan (8), N. Capitaine (19), E. Roemer (20), C.A. Murray (24), I. Mueller (31), R. Wielen (33), K. Johnston (40) and D. McCarthy representing the IAG.

At the outset, it was anticipated that the matters listed in the founding document of the WG could not be completely and definitively addressed prior to this GA. Such has proved to be the case. On the other hand however, the WG has been very effective in stimulating discussions and promoting a wider awareness and deeper understanding of the essential issues which are involved in the matters of concern to the WG. Open discussions were held by the WG on three occasions: IAU Symposium 128, *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics,* Coolfont, West Virginia, October 1986; IAU Symposium 133, *Mapping the Sky,* Paris, June, 1987; IAU Colloquium 100, *Fundamentals of Astrometry,* Belgrade, September 1987. Discussions also took place during the XIX GA of the IUGG, Vancouver, August, 1987. A great deal of personal correspondence was also exchanged by those most interested in the matters with which the WG was charged, some relevant papers were given at various meetings and a few publications have appeared. As a result of this activity, a better informed membership of the IAU should be more capable of fully considering any resolutions regarding reference frames and time which may come before it.

The following report is divided into three sections, each dealing with a major area of concern to the WG. These sections are: Celestial Reference Frames; Terrestrial Reference Frames; and Time. The use of the word "Frames" rather than "Systems" appeared desirable to the Chairman of the WG. The recommendations of the WG appear in boldface type throughout the report.

Celestial Reference Frames

At the present time there exists only one generally acknowledged, global reference frame. This is the FK5 classical, optical system which, including the fainter stars added to the FK4 star list, contains a total of approximately 5,000 stars, (rather than 1535 stars as in the FK4).

The WG recommends that: (WGRF Recommendation No. 1)

In order to avoid a confusing proliferation of reference frames, the FK5 should be retained as the IAU reference frame at optical wavelengths for the present and immediate future.

As is generally known, progressions such as FK3 to FK4 and FK4 to FK5 were achieved by incorporating new observations into the predecessor system in order to improve it and thus generate a successor system. Efforts are now underway to refine this procedure by discussing all observations simultaneously and *ab initio*. These efforts will produce a successor to FK5 which, it is anticipated, will be superior to FK5 in both its random and systematic error characteristics.

The WG recommends that: (WGRF Recommendation No. 2)

In order to derive the maximum possible information from the accumulated, classical observations, and most especially from the fundamental observations, ab initio discussions of these latter observations should be encouraged and supported.

Current definitions of celestial reference frames at radio wavelengths make use of the extragalactic references provided by suitable objects, primarily quasars. Such references, when combined with interferometric astrometry, are *nonpareil* when applied to the determination of Earth Rotation Parameters (ERP) and Crustal Dynamics (CD) studies. Indeed, these programs have made the major contribution to the various radio reference catalogs currently available. It is now necessary to extend the use of such systems to astronomy in general. This must include extensions in wavelength, in applications, and in the classes of objects included in such systems. There are, of course, obstacles to be overcome if the full potential of this conceptually straightforward approach is to be realized. However, if the phenomena of precession, nutation and polar motion as well as the concepts of the ecliptic and the vernal equinox can be disconnected from the realization of a reference frame, and be regarded as simply describing various aspects of the Earth's complicated motions, then a great simplification will have been achieved. Of course all of the above phenomena and concepts are basic, and a knowledge of them is absolutely necessary. This knowledge will continue to be supplied by the classical, dynamical observations, radio astrometry and pulsar observations. However, it is now possible to consider these items in their proper context and to define a reference frame which is independent of them. Such independence will benefit not only the reference frame, but also aid in the study of the very phenomena from which the concept of a reference frame will have been freed. Essentially, observations will have been decoupled from the observing platform. As a result of this, the accuracy of the reference frame will become primarily dependent upon the precision and accuracy of the underlying measurements, and will have a minimal, non-critical dependence upon any companion theories.

The WG recommends that: (WGRF Recommendation No. 3)

The IAU should adopt a celestial reference frame based upon a consistent set of coordinates for a sufficient number of suitable extragalactic objects when the required observational data have been successfully obtained and appropriately analyzed. This reference frame should be based upon a common, simultaneous discussion of the observations using agreed upon conventions. This reference frame is likely to be

based, initially at least, exclusively upon radio astrometry, and transformations between this reference frame and the conventional celestial and terrestrial reference systems as well as the dynamical frame should be defined. The reference frame should be updated as required.

The wording of the above recommendation implies that a reference frame other than the Conventional Celestial Reference System should be adopted by the IAU. This is not necessarily the case, but could be the case. That is, the title, Conventional Celestial Reference System, is used by the ERP community in conjunction with a similar name for the adopted Conventional Terrestrial Reference System. The use of the modifier "Conventional", came into general use during the MERIT program, possibly due to the earlier use of the word in conjunction with the origin of the pole, i.e., the Conventional International Origin (CIO). The determination of ERP does not require a global distribution of sources nor a large number of them. The needs of the purely astronomical community are not adequately known at this time and therefore it is not possible to assert that the conventional system of the ERP/geodetic community will precisely fulfill the requirements of the IAU in general. On the other hand, ERP observations provide much of the data used to define the extragalactic radio frame and will perforce contribute greatly to whatever frame might be adopted. If the conventional system is ultimately adopted as it stands, then the transformation mentioned in the recommendation above becomes simply an identity.

In any event, the achievement of a general reference frame on a global basis, encompassing a range of both magnitudes and wavelengths, will not be easy, but the difficulties are primarily observational and not conceptual or theoretical. Indeed, great progress has already been made in the areas of ERP and CD and VLBI experiments in general. For example, an extragalactic reference frame which will serve as the initial system of the International Earth Rotation Service (IERS) was received by the Chairman of the WG as this report was being completed. This frame was compiled on the basis of four individual catalogs from the Goddard Space Flight Center, the Jet Propulsion Laboratory and the U.S. National Geodetic Survey. The compilation was carried out at the IERS (E.F. Arias, M. Feissel and J.F. Lestrade, *Bureau International de l'Heure Annual Report for 1987,* Observatoire de Paris), and includes 228 extragalactic, compact sources divided into primary, secondary and complementary sources depending upon geometrical and physical considerations as well as observational histories. Unfortunately, this reference frame contains no sources south of -45°, and of the 23 primary sources which define the directions of the axes, only 8 are in the southern hemisphere (between the equator and -29°). This points up the fact that even with the excellent ERP results, the distribution of well observed radio sources and radio interferometry baselines is far from ideal for the purposes of a global reference frame. Nevertheless great improvements are taking place. Indeed, since the formation of the WG, dozens of new sources have been observed, most recently many in the southern hemisphere. Thus the problem of sufficient coverage on a global basis, whatever coverage that may ultimately prove to be, is being addressed. At present the density and the distribution of radio sources necessary to provide an acceptable transformation between radio and optical systems depend primarily upon the homogeneity or isotropy of the optical system. If, for example, one had an optical catalog with relative coordinates of the stars at some epoch with the same accuracy as in radio catalogs, then merely applying a correction to the zero points could serve as the transformation for that epoch. The forthcoming HIPPARCOS catalog is intended to approach this ideal and will provide an excellent example regarding the matter of radio/optical transformations. If the HIPPARCOS system is successfully referred to an extragalactic frame, then the extension of this frame to magnitudes intermediate to HIPPARCOS stars and the quasars will follow through the use of astrographs and Schmidt telescopes. Imperfect proper motions complicate the situation of course, but the whole point of improving the reference frame is to provide a better standard coordinate system within which improved stellar motions, for example, can be determined. It is important to note that given an accessible extragalactic reference frame, optical reference frame positional observations would be freed of the burden of simultaneously determining the zero points of a dynamical system, the improvements to the assumed planetary orbits and the individual star positions. The emphasis could then be upon achieving isotropy and observing to fainter magnitudes. Questions involving source structure and any evolution thereof can only be resolved by repeated and carefully programmed observations.

The WG recommends that: (WGRF Recommendation No. 4)

The determination of the positions of radio sources at all possible wavelengths should be continued and accelerated so as to achieve the best possible all sky coverage and overall accuracy, while testing the suitability of candidate sources. The International Astronomical Union should encourage institutions to provide adequate time on appropriate instruments to ensure that the necessary astrometric observations are obtained.

The accessibility of an extragalactic reference frame to astronomers dealing with brighter, optical objects is of great concern to many and this question must be satisfactorily addressed. At the present time, as discussed above, the matter of accessibility really concerns the transformations, or links, between radio and optical reference frames. The identification and observation of galactic radio stars at both optical and radio wavelengths and in both optical and radio reference frames plays a crucial role in this area. Action is necessary if the full potential of the radio reference frame is to be realized.

The WG recommends that: (WGRF Recommendation No. 5)

The detection of radio stars and the determination of their positions and proper motions should be a major goal of astrometry.

The determination of optical positons and proper motions of stars with respect to extragalactic objects should be encouraged.

All applicable methods, particularly astrometry on large reflectors, should be used.

In the longer term, further progress will be possible only when an optical/IR reference frame is available which is comparable to the radio reference frame in accuracy and which is also based directly upon extragalactic objects. This implies a need for improvements in existing methods and the use of new techniques, especially interferometry and space astrometry, the latter perhaps also using interferometric techniques. Having independent radio and optical/IR reference systems of comparable accuracy will permit much more physically significant astrometric comparisons of objects. At present, with but few exceptions, transformations have been derived whose essential purpose is to improve optical systems by using the accuracy of the radio system. Even so it should be noted that significant research is being carried out, for example regarding stellar maser activity, using available astrometric data.

The WG recommends that: (WGRF Recommendation No. 6)

Optical and infrared astrometric interferometry should be developed vigorously for use on the ground and possibly later in space. The related efforts in imaging interferometry have astrometric implications and these developments should also be supported. In all cases the direct determination of the positions of extragalactic objects at optical/IR wavelengths must be a major goal.

Interferometric observations have provided absolute declinations and so-called "relative right ascensions." That is, observations contributing to reference frames based upon extragalactic objects do not automatically define a zero point for right ascensions as do observations leading to a dynamically based frame with its vernal equinox. As a matter of fact the former observations do not, strictly speaking, measure right ascensions at all. For this reason it is necessary to devise a procedure which can uniquely define an origin for this measured coordinate. In addition, it must be decided how such a coordinate is to be distinguished from right ascension. The problem is solvable and is just as much a matter of convention and protocol as of scientific principles. The important points are that a common origin, whose basis and construction are understood and agreed upon, must be defined and utilized by all, and that a similarly agreed upon nomenclature regarding coordinates must be adopted.

The vernal equinox is the origin of right ascension, and its definition involves both the rotational and orbital motion of the earth. As perceived by some, there are intrinsic difficulties with such involvements since problems with the definition of the orbital plane of the Earth immediately lead to related problems with the definition of the dynamical equinox. For example, assuming a continuosly moving equator versus using instantaneous orientations of the equator can lead to a difference as large as $0\overset{''}{.}1$ in the location of the equinox. Similarly, the definition of a "mean" orbital plane involves various assumptions. For these reasons a proposal has been made which is intended to remove the dependence of the origin on the orbital motion of the Earth. Reference is made to the *Non-Rotating Origin* (NRO) first proposed by Guinot and which has been described in various places, but perhaps most fully in the article, *A Non-Rotating Origin on the Instantaneous Equator: Definition, Properties and Use,* N. Capitaine, B. Guinot and J. Souchay, Celestial Mechanics **39** (1986), 283-307. Although proposed primarily for use in defining the sidereal rotation of the Earth and the definition of Universal Time, such an origin could be used for celestial positions. Of course a distinction between right ascension and the "corresponding" coordinate would be required. The name, *instantaneous ascension* has been suggested. The NRO requires a celestial reference frame based upon extragalactic objects with respect to which the motion of the Earth's pole is specified. This is, of course, exactly what the IERS provides. Reaction to the concept of the NRO has been mixed, but a thorough evaluation of the concept as it applies to celestial positions and motions is definitely called for.

Terrestrial Reference Frames

Various terrestrial reference frames exist around the world. Some are local systems while others may be used for global applications. In general it is the latter which are of most interest to the IAU. The name, Conventional Terrestrial Reference System, is used to delineate that system which is defined by the most precise geodetic techniques. Currently the BIH Terrestrial System (BTS), adopted for use in the determination of Earth orientation parameters by the IERS, makes use of these techniques to provide the most suitable terrestrial reference system. This system is described most recently in the *Bureau International de l'Heure Annual Report for 1987,* Observatoire de Paris. For general information consult, *Realization of the BIH Terrestrial System,* Boucher, C. and M. Feissel, Proc. Internat. Symp. on Space Techniques for Geodynamics, 1984, Sopron, Hungary.

Briefly, the BTS consists of a reference frame defined by the station coordinates of the observatories contributing observations of Earth orientation to the IERS plus a model describing the motions of the tectonic plates on which the observatories are located. Transformation parameters relating the terrestrial systems used in the determination of Earth orientation data are also given. The epoch of the coordinates is 1984.0 The plate motion model, AMO-2, of Minster and Jordan is used, (*Present-Day Plate Motions,* J. Geophys. Res., **83**, 1978, pp. 5331- 5354).

The reference frame of the BTS is Earth-centered, with the pole designated as the BIH pole and longitude origin as the BIH Origin of Longitudes. See, *Comments on the terrestrial pole of reference, the origin of longitudes, and on the definition of UT1,* Guinot, B., Proc. IAU Coll. No. 56, 1981, D. Reidel Pub. Co. The pole is offset from the Conventional International Origin of the International Latitude Service (no longer in existence).

In practice, the system is accessed through the use of the Earth orientation parameters which are published routinely by the IERS. By employing these data in transforming from the Conventional Celestial System, the user obtains coordinates or directions in the BTS. Uncertainties in the reference frame of the BTS are: a few centimeters in the origin, 0.002 parts per million in scale, and up to $0\overset{''}{.}004$ in orientation.

The WG has no explicit recommendations to make regarding terrestrial reference frames, but it should be noted that the IAU must maintain an on-going liaison with the geodetic community regarding terrestrial systems, most especially regarding matters of Earth orientation and the reference frame to which the orientation is referred. Of course such a liaison occurs naturally in the work of Commission 19 and also with Commission 31, the WG merely reaffirms the necessity of supporting close collaboration together with the timely exchange of information.

Time

The current names, definitions and underlying resolutions which, when taken together, represent the official position of the IAU regarding time, have been found to be unsatisfactory by many. This dissatisfaction has arisen for both practical and theoretical reasons, and therefore the consideration of possible changes in the present posture was made a part of the charter of the WG.

The specific complaints involve the facts that:

1) There are perceived differences between the viewpoints of the IAU and those of the time keeping and physics communities.

2) There are questions regarding the units of Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB), and regarding the definitions of these times and their relationship to International Atomic Time (TAI).

3) There are many reservations about the use of the word "Dynamical" in the naming of TDT and TDB.

4) There are outstanding disagreements regarding the characterization of TAI as a proper and/or coordinate time.

5) There is a need to clarify the relationship between the IAU and the International Radio Consultative Committee (CCIR) and the Comité Internationale des Poids et Mesures (CIPM).

After the discussions held during IAU Symposium 128 in Coolfont, B. Guinot and P.K. Seidelmann indicated an interest in pursuing these questions. The Chairman of the WG encouraged this effort, and the result was the publication of an article, *Time Scales: their history, definition and interpretation,* [Astron. Astrophys. 194, (1988), 304-308]. As the title indicates, the events leading up to the adoption of TDT and TDB are described and the reasons for the subsequent ambiguities and disagreements are explained. This historical section may be considered a part of the report of the WG, and therefore the WG wishes to express its appreciation for the work undertaken by Guinot and Seidelmann. Following the historical background, their article culminates with a recommendation regarding the time reference for the ephemerides together with the grounds upon which the proposal is based. Since the publication of the article, Guinot and Seidelmann in conjunction with D. Allan, S. Aoki, M. Fujimoto and T. Fukushima, have communicated a revised recommendation. The revised recommendation, which is a replacement for Section 6.2 as printed in the article, but which is not at present a recommendation of the WG, follows.

"It is recommended that:

(a) the time reference, or the independent variable, of the apparent geocentric ephemerides be Terrestrial Time, TT,

(b) TT be the proper time for the geocenter,

(c) the time unit of TT, the terrestrial day, being chosen so that the reading of TT agrees with that of a proper time on the rotating geoid whose time unit is 86400 SI seconds,

(d) at the instant of 1977 January $01^{d}00^{h}00^{m}00^{s}$ TAI, TT be synchronized with TAI plus 0.0003725 day exactly.

(e) the time reference for ephemerides referred to the barycenter of the solar system be Barycentric Time, TB,

(f) the time unit of Barycentric Time, the barycentric day, be chosen so that there are only periodic variations between the readings of TT and TB.

Notes

1. The recommendation refers to the definition of the SI second adopted by the 13th CGPM, 1967 (atomic second).

2. In practice, realizations of the ideal TT are needed. Such realized time scales are designated by TT(xxx), where xxx is an identifier.

3. A realization of TT is that it be synchronized, according to the conventions of the CCIR and the CCDS, with TAI plus 0.0003725 day. The synchronization can be improved by analysis of atomic time data at future times.

4. The designation of a time as being "proper" or "coordinate" time is a cause of much confusion. Perhaps the following statement by Fukushima helps clarify the problem. "Usually in the general relativistic theories, a coordinate time is defined as the proper time of a standard clock which rests at the space origin of a chosen coordinate system. For example, the coordinate time of a geocentric coordinate system is defined as the proper time of a clock which rests at the geocenter while the gravitational effect of the Earth itself is ignored in computing the proper time." Thus, TT should be the proper time of an ideal clock moving with the geocenter while suffering the gravitational effects due to the solar system bodies except for the Earth. Similarly, the proper time for the barycenter of the solar system in the universe means the proper time of an ideal clock comoving with the barycenter of the solar system while suffering the gravitational effects due to the universe except for the solar system. TB is used as a time coordinate in a frame referred to the barycenter of the solar system.

5. Differences in gravitational potentials and velocities may introduce secular terms in the conversion formula between two time scales if the same definition of the unit of time is used for each of them. Therefore, in order to satisfy the requirement that TT and TB differ only by periodic terms, their units must be different; the difference amounts to 1.5×10^{-8}. In a like manner, the unit of TT differs from the unit of TAI by 0.7×10^{-9}. This might be understood if one considers an ideal atomic clock on the geoid keeping TAI. If that ideal clock could be slowly moved to the geocenter, the change in the gravitational potential and the velocity, due to the Earth's rotation, would cause a change in the rate of the clock. Thus, the clock would not keep TT without a rate adjustment. Similarly, if the clock were moved to the barycenter of the solar system, there would be a change in the rate of the clock and clock would not be keeping TB unless it were adjusted in rate.

6. The statement that there are only periodic variations between TB and TT may be considered equivalent to stating that there is no secular

term in the relationship between TB and TT. The number of terms and the length of the periods included in the relationship depends on the accuracy and the time period of concern. Further clarification of the relationship between TB and TT may be desired in the future.

7. Prior to the existence of atomic time, the accuracy achieved by time scales was not as good, so that the practical time scale was not sufficiently precise to distinguish between TB and TT. Thus, prior to 1955 the realization of either TT or TB can be assumed to be Ephemeris Time (ET); but another theoretical relationship might be required in the future."

The recommendation quoted above represents the viewpoint of a number of people, some of whom have contributed directly or indirectly to the discussions which led to the formulation as given. However, it would be incorrect to imply that the recommendation is acceptable to all, or indeed at present, even to a majority. Nevertheless, the recommendation can and should serve admirably as a starting point for thoughtful discussion and indeed possibly for final adoption. In addition, it can help to define and refine any contrasting positions held by others. Most importantly, it can be a catalyst in the process of informing the great majority of IAU members, many of whom are very unfamiliar with the issues and scientific ramifications involved even though their work may be affected in one way or another.

It is impracticable to attempt to list here all of the different points of view or explicit objections to the present or other proposed definitions. However, the following points should be noted.

1. Although no one has come forward to the WG and expressed a desire to retain the word "dynamical" in perpetuity for either TDT or TBT, some have stated that, for the present, the names should remain unchanged. There is little doubt that a majority favors the eventual elimination of this word.

2. In conjunction with No.1, immediately above, it is held that the names Terrestrial Time and Barycentric Time should be reserved until clearly defined and understood transformations of both time and space are agreed upon.

3. The objection has been raised that the IAU appears to have at least three classes of clocks which, if colocated and comoving, would run at different rates and have different associated meter rods.

4. In conjunction with No.3, immediately above, it is held that anyone familiar with relativistic concepts would not understand why there should exist several standard clocks which do not run at the same rate when colocated and comoving. This apparent contradiction arises from the implied rate adjustments which would be made to hypothetical, physical TT and TB clocks.

5. There appears to be general (although not universal) agreement that

TAI may be either a proper or a coordinate time. Indeed, depending upon the application, TAI is considered to be one or the other by various users and their distinct characterizations are entirely appropriate.

6. The position has been taken that ephemerides should be published using TAI or UTC as the time argument, the choice depending upon the period which a particular ephemeris covers. The use of TB as a coordinate time by the celestial mechanician, for example, is a part of the calculation of the ephemerides, but the user need not be forced to deal with concepts such as TT and TB.

7. In conjunction with No. 6, immediately above, it is held that there exist conceptual problems with TB. If TB is a coordinate time in the solar system, it has then been interpreted as being the proper time of a clock at the barycenter with all solar system mass removed, (see Note 4 in the quoted, revised recommendation above). However, removing this mass also removes the cause of the periodic differences between TT and TB. But, if the mass is not removed, then serious difficulties occur when the barycenter moves into the Sun or moves while inside the Sun. Considerations such as these are used as examples of the conceptual difficulties.

8. The position has been taken that there must exist periodic differences between TT and TAI due to the changes in the potentials at the geocenter and on the rotating geoid due to solar system bodies other than the Earth. The change in this potential is not identical for clocks at the geocenter and on the rotating geoid.

The above comments while not exhaustive, do show that valid issues remain to be settled and that alternative viewpoints exist which deserve a comprehensive examination. Although a final disposition of this matter at the XX General Assembly would be highly desirable, the interests of the IAU are more likely to be served in the long term by a thorough airing of contrasting viewpoints, even if such a course of action requires an additional effort with a concomitant delay.

General Considerations

Passing on to a matter related to the responsibilities of the WG, the following is presented for general consideration.

If one examines the history of reference frames within the IAU, it becomes evident that there has existed a symbiotic relationship among the various commissions which have contributed to reference frame work. For example, the FK5 represents a combination of: observations and compilation by Commissions 8 and 24, of ephemerides and the underlying celestial mechanics by Commissions 4 and 7, of polar motion and time determinations by Commissions 19 and 31, and of binary star orbits from Commission 26. Although each of these contributors have unique attitudes and interests regarding reference frames, the combination did work well in the past. However, it is not clear

https://doi.org/10.1017/S1539299600008170 Published online by Cambridge University Press

that such a distributed, cooperative effort would function satisfactorily if the basis for reference frames were to be changed as recommended. Hence the question now arises; How should the matter of responsibility for reference frames be addressed in the future? The WG has not been charged with answering this question and can make no official recommendations regarding the matter. However, since many, varied, *ad hoc* suggestions have been made to the WG, thus indicating a great deal of general interest in the matter, it appears appropriate for the WG to offer general comments upon the situation for consideration by the members of the IAU and by the Executive Committee if it chooses to do so.

There are various options: 1) do nothing, 2) assign the WG the responsibility for the next reference frame, 3) name an existing commission to bear the responsibility for reference frames, 4) institute a new commission for reference frames, 5) restructure the existing commissions.

If the potential for difficulties is acknowledged to exist, then the first option is not a realistic choice. Furthermore, a very good case can be made for the necessity of having a dedicated forum and meeting place for those interested in and working on reference frames in general. Such a meeting place would help meld individual, specialized approaches to reference frames into a cohesive, more unified conception, reminiscent of the symbiosis described earlier. If one considers the many tasks which will have to be undertaken to unify and develop the various approaches to reference frames, then such a common meeting ground does indeed become a necessity. Given this assessment, it then becomes necessary to take action along the lines of one, or possibly of a combination, of the options listed above.

These comments are offered in order to stimulate discussion and thought based upon the perception that something should be done. However, with the realization that careful consideration is required, hasty actions at this GA are not envisioned nor encouraged.