PART 1. ORAL PAPERS

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REPORT OF THE SUB-GROUP ON TIME

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1. Introduction

The report of the Sub-Group on Time (SGT) of the IAU Working Group on Reference Systems (WGRS) is divided as follows.

Sections 2 to 4 recall the scope of the work of the SGT and briefly describe its activity.

Section 5 summarizes the discussions on several topics which form the background of the draft recommendations and notes of Section 6.

2. Scope of the work

This has been defined in a letter of 1 June 1989 by the chairman of the WGRS, Dr J.A. Hughes, : "Define time- scales and time-like arguments and their interrelationships within the framework of General Relativity. Provision must be made for projecting these time scales into the past. The consequences of adopting any time-scale, when viewed in the context of a relativistic space-time continuum, must be carefully considered. The need for theoretically acceptable transformations meeting the accuracy requirements for all the diverse applications must be considered. The practical difficulty of defining and determining appropriate units of time as well as the precise transfer of time must also be addressed with reference to protocols already established."

3. Historical background

The atomic definition of the unit of time, in 1967, and the availability of atomic time scales since 1955, with accuracy requiring a relativistic treatment, generated new problems in dynamical astronomy. These problems were considered by a Working Group on Units and Time-Scales, created in 1970, chaired by G.A. Wilkins. The activity of this SG led to IAU Recommendation 5 (1976) on "Time-scales for dynamical theories and ephemerides", defining the time-scales which were designated in 1979 as the Terrestrial Dynamical Time (TDT) and the Barycentric Dynamical Time (TDB).

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The 1976/79 recommendations raised much controversy (Guinot and Seidelmann, 1988) for reasons which are essentially:
-the lack of a correct definition in a relativistic framework encompassing space and time,
-the ambiguity between the ideal form of atomic time and the time-like argument of dynamical theories.

4. Development of the work of the SGT

The list of members of the SGT is given in Annex I. The necessity of receiving a wider range of opinions and advices, especially from experts in relativity, appeared in the course of the discussions. Annex I also gives the list of persons who were consulted. In the following, all these persons are usually designated by the initials given in Annex I.

The development of the activity of the SG on Coordinate Frames and Origins (SGFO) made clear the need of a strong interaction between the SGFO and the SGT. This led to frequent contacts with J. Kovalevsky, leader of the SGFO, and to common draft recommendations, as will be seen later. The work was performed almost entirely by correspondence, but I had the privilege of fruitful meetings with J. Kovalevsky and T. Damour.

The documents I received from my correspondents have been circulated. In the following abbreviated presentation, it is not possible to refer fully to the opinions which have been expressed : I rather concentrate on controversial topics. In the subtle problems which were encountered, opinions may diverge, even if based on correct scientific reasoning. In such cases, I followed the majority, at least when it is well marked.

5. Background of draft recommendations and notes

5.1. SPACE-TIME (DRAFT RECOMMENDATIONS G1 AND G2)

The necessity of a global treatment of space-time coordinates was unanimously recognized: "We must resolve the complete question of space and time transformations" (I quote L). In such a treatment there appears "the necessity of defining and using on an equal footing several systems of space-time coordinates, especially the systems centered at the barycenter of the solar system and of the Earth" (D). Brumberg and Kopejkin (1990) give a comprehensive study of "a set of reference systems mutually superimposing and covering altogether the whole of space-time" and advocate the use of non-rotating systems with the harmonic condition on the metric tensor; their work offers a complete and self-consistent set of coordinate transformations for the four space-time coordinates.

However, the choice of the coordinate conditions is still a domain of theoretical researches (Damour et al., 1990) and no particular solution can be recommended officially, at present.

It is in the nature of our work on recommended references and constants that the IAU recommendations often cannot meet the requirements of the most advanced studies : the freedom of innovating is essential. We were guided, J. Kovalevsky and myself, by the necessity of offering a sound basis which is a good and accepted approximation of the most advanced theories and which can be improved without bringing drastic changes when it it is desirable and possible.

These considerations led to the draft of the Conceptual Recommendation G1, common to the SGFO and SGT, initially written by D, then slightly modified by K and Gu.

I would like to stress that G1 was made quite general and covers the cases where, for example, selenocentric or planetocentric coordinate systems are convenient. In the case of the system centered at the barycenter of the solar system ("barycentric system"), the effect of external bodies is presently negligible, but this is nevertheless covered by the general wording of the recommendation.

The Constraint Recommendation G2 fixes the state of rotation of the space coordinate grids by a constraint on barycentric coordinates, while the time coordinates are defined by a geocentric constraint. This was imposed by the physical measurement methods and did not meet any objection. Several correspondents observed that the state of rotation of the geocentric grid is left undetermined: this aspect of the barycentric/geocentric transformation cannot be solved unambiguously at the level of the metric in G1.

Both G1 and G2 exclude scaling factors of the units of time and length in the coordinate transformations, using the metric coefficients of G1. This important issue is discussed in 5.2.

5.2 THE PROBLEM OF SCALING THE UNITS

We can reasonably assume that the physical units of the International System of Units (SI) are given by ideal standards on their world line, because it ensures the universality of physical measurements and constants in local experiments, devoid of any conversion factors. It is well known that this point of view leads to secular divergence between the coordinate times in various coordinate systems and also between coordinate times and proper time, if we assume that far from the space origin of the coordinate systems, the metrics tends to be Minkowskian, as in G1.

In Recommendation 5 (1976), secular divergence between the ideal form of TAI (TDT + const.), the geocentric and barycentric coordinate times were cancelled by retaining only the periodic terms in the transformations. This is equivalent to the introduction of "scaling factors" in the unit of time, and, therefore in the unit of length, assuming a constant value of the velocity of light. As far as I remember, this decision was taken without controversy. However, difficulties appeared later.
(a) A practical problem is that the distinction between secular and periodic terms is not clear when long periods are considered. The distinction is even not possible in case of numerical integration, the separation then depending upon the averaging time.

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(b) A more fundamental problem is the consequence of scaling factors on other units, constants and values of physical quantities (Fukushima et al., 1986).

It turned out, in our present discussions, that the dissatisfaction with the introduction of scaling factors was latent and crystallized in the form of a majority in favor of making them equal to unity.

Since it is an important change with respect to the 1976 Recommendation, with consequences for other sub-groups, especially on astronomical constants, I will discuss it further, for the benefit of those who did not participate in the work of the SGT, by summarizing the most characteristic opinions I received.

I first quote D. "This choice of normalization [scaling factors equal to 1] ensures the smooth merging of these relativistic frames with all the standard approximate description of the relativistic gravitational field... This normalization has the great advantage that it leads to simple formulas for extracting the physical 'gravitational mass' GM, expressed in SI units, from measured properties of the motions... If one uses a different normalization of e.g. time scales, this leads not only to an appreciable complication of the theoretical relativistic description, but, moreover, this can lead to real physical mistakes, as it implies that the various GM's that one can read off from the metric coefficients, or equations of the motion, for various systems differ from the physically well defined SI-measured GM by some 'redshift factors'... In conclusion, I think that the spirit of universality that motivated the definition of the International System of Units, has, to-day, the consequence that one should abandon the IAU recommendations of linking in a 'regional' way the graduation units of both Earth-based and Solar-system-based time scales to the SI second, and should prefer a more 'universal' (and theoretically preferred) way of linking them by requiring the graduation units to tend asymptotically in space, in each reference system when one neglects external influences, to the physical units : meter and second."

Murray writes : "You are right in quoting my opinion that we should avoid conventions which are adopted for pratical reasons, but which obscure principles. My reaction to the statement in Question (h) [The SGT recommends that the convention requiring that in the relation TDB-TDT only periodic terms are kept be abandoned] is, therefore, approval in principle; this should be accompanied by a corresponding statement that the unit of TDT differs from the SI second by the geopotential factor. However, I realized that to change now might cause difficulties for some people; therefore, before a decision is made, a careful survey of the likely consequences for the existing software used by observers and theoreticians should be carried out."

Fukushima has first expressed some fears that the user be confused by secular differences among time-scales. Then he expressed his agreement in keeping secular parts in the relations. "This is because this option makes the new system of astronomical constants simpler". He agrees with the "opinion that unnecessary conventions should be avoided, as long as the ordinary users will not be confused".

At this stage, I would like to recall that the secular divergence between TAI and a barycentric coordinate time, without rescaling the units, is $1{,}55\times10^{-8}$T, and amounts to 49s in a century. It is of the same order as the difference between TAI and UTC (if the UTC system is maintained under the present form). These differences are sufficiently small to avoid any risk of confusion in the day number in a reasonable future. Anyway, draft recommendation T2 states that the apparent geocentric ephemerides shoud use a time scale without rate offset with respect to TAI and UTC : this should avoid confusion for the 'ordinary user'.

Other persons have expressed their agreement with the proposal of setting to 1 the scaling factors : B (and Kopejkin), Gr, K, Se, and myself, for similar reasons as above. In contrast, A and X disagree.

Xu writes that he "rather disapprove, it is inconvenient to treat old observations".

Aoki recalls that the Kepler's third law holds in the isotropic form of the Schwartzschild coordinates when the mean motion n of an orbiting test particle is expressed with the proper time along the world line of the particle (for details refer to Murray, 1983, Chap. I).But using the coordinate time at the barycenter, we have

$$n = (1 - L)\, k \quad \mathrm{rad}/D_B, \qquad (1)$$

where k is the Gaussian gravitational constant, D_B is a day of 86400 coordinate seconds of the barycentric frame and L is given by

$$L = 3GM \,/\, 2c^2A \approx 1{,}48\times10^{-8}, \qquad (2)$$

A, being the astronomical unit, all quantities being expressed in SI units.

We can make L = 0 in (1) by rescaling the unit of time, as it was done by the IAU Recommendation 5 (1976) on time scales. But the consequence is that L appears in the units of time and length, and in most of the quantities expressed with these units (in particular the GM's).

I would like to point out that accepting to rescale the units of time and length is not limited to the geocentric and barycentric frames, but could be extended to other frames centered on planets, barycenter of multiple stars, etc. This would be extremely confusing.

The draft recommendations of Sub-Groups of the WGRS are a first step toward a correct and coherent treatment of the reference systems in relativistic theories. I am aware that much remains to be done, but, at least, we must start on a sound basis. We have to accept all the consequences of relativistic theories. I am personally opposed to unnecessary conventions adopted on purely practical grounds. In the present case, I even fail to see the practical advantages of the scaling factors.

These considerations led to define :
(a) a Terrestrial Time TT (draft T2), which is an ideal form of TAI (with possible constant time offset, see discussion below),
(b) a Geocentyric Coordinate Time TCG, with a constant frequency offset with respect to TT, due to the fact that the unit of TT and TAI is the second of SI as obtained on the geoid (draft T1),
(c) a Barycentric Coordinate Time TCB, keeping all the terms of the TCB - TCG conversion, including a mean frequency offset (draft T1).

All my correspondents estimated that the relativistic definition of TAI, given in a CCDS declaration in 1980, is sufficient for the time being (see Huang et al.,1989).

5.3. Origins of TT, TCG, TCB

In a previous draft recommendation TB, I suggested that TT have the same reading as TAI on 1977 January 1. With such an origin, it would have been possible, in many cases, to use TAI (available) instead of TT as time argument of ephemerides. This proposal has been unanimously rejected. The enclosed draft recommendations retain the historical time offset of 32,184s, so that TT is equivalent to TDT of the 1976/79 recommendations. Possible realizations of TT are, using the notation of note (h) of draft T2:

until July 1955 TT(TEi) = TEi,
since July 1955 TT(TAI) = TAI + 32,184s.

5.4. The TCB - TCG relationship

The TCB - TCG relationship is a full 4-dimensional transformation of coordinates. Most of my correspondents expressed the wish that a conventional development of the 'geocentric' part be given, but no clear preference has been expressed between the use of numerical integration and analytical formulas. Therefore two possibilities are offered in note (c) of T1.

5.5. Time-like argument of theories

An important problem is raised by Se: "Presumably we can have a theoretical version of TCB and TCG, which is the time-like argument for a planetary theory or numerical integration, before being fit to observations. Would that be designated as TCB(Theo)?". According to T1 and T2, TT, TCG and TCB are definitely ideal forms of atomic time. I reproduce here my answer to Se.

"Let us take the example of TCB. My proposal is that TCB be the ideal form of TAI, transformed in the barycentric frame, in an ideal way. Thus TCB is an ideal form of quantum time. The chain of transformations is :

TAI realized atomic time,
TT ideal form of TAI,
TCB resulting from tranformation topocentric to barycentric of TT.

These two steps involve uncertainties :

TAI - TT , physical defects of time standards,

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TT - TCB , approximation of the theory and of the
required numerical constants.

For these reasons, in note (e) of recommendation T1, I suggest designating a realization of TCB by TCB(xxx), where xxx states the source of the realized time scale and the theory.

Now, the time-like argument of theories, *t*, is something different which might not be easily reconciled with TCB, especially if there is some fundamental divergence between dynamical time and quantum time. But in the latter case, there should be a relation between *t* and TCB.

As I see this problem, the ideal TCB should be approximated from two sides :
-by the best possible realization from terrestrial clocks (to which observations are ultimately referred),
-by the most adequate relationship with the time-like argument of theories. This time argument could be called TCB(theor), as you propose, but I would prefer some freedom for its designation; the letter *t* seems convenient."

5.6. DESIGNATION OF TIME-SCALES

As said previously, TT is equivalent to TDT of 1976/79. I nevertheless suggest abandoning the letter "D" which is confusing because it suggests that TDT is obtained from a dynamical theory, as was Ephemeris Time. For TCG and TCB, I propose notations which seem to be more explicit.

5.7. COORDINATED UNIVERSAL TIME

Fukushima and Zhu stress the inconvenience of the leap seconds of UTC. The definition of UTC is primarily a matter to be considered by CCIR, IMO (International Maritime Organization), ICAO (International Civil Aviation Organization). Our only possible action could be, I believe, to ask for a reevaluation of the usefulness of the UTC system. I leave this question open for discussion.

6. Draft recommendations and notes

6.1. RECOMMENDATIONS G1 AND G2 COMMON TO SGFO AND SGT

Conceptual recommendation G1

.... considering

that it is necessary to define in the framework of the General Relativity Theory several systems of space-time coordinates,

recommends that

the four space-time coordinates ($x^0 \equiv ct, x^1, x^2, x^3$) be selected in such a way that in each coordinate system centered at the barycenter of an ensemble of masses exerting the main action, the interval ds^2 be expressed at the minimum degree of approximation by

$$ds^2 = -\left(1 - \frac{2U}{c^2}\right)(dx^0)^2 + \left(1 + \frac{2U}{c^2}\right)\left[(dx^1)^2 + (dx^2)^2 + (dx^3)^2\right]$$

where c is the velocity of light and U the sum of the gravitational potentials of the above mentioned ensemble of masses and of a potential generated by the external bodies, the latter vanishing at the barycenter.

Constraint recommendation G2

.... considering

(a) the necessity to define a barycentric coordinate system centered on the barycenter of the solar system and a geocentric coordinate system, centered on the barycenter of the Earth,

(b) the desirability that the coordinate systems be linked to the best physically realized references in space and time,

(c) that the use of the International System of Units (SI) should be extended to outer space, without introduction of scaling factors depending on the coordinate system under consideration,

recommends that

1. the state of rotation of the space coordinate grid centered at the solar system barycenter be such that the coordinates of a set of distant extragalactic objects present no global rotation,

2. the time coordinates be derived from the geocentric coordinate time realized by atomic clocks operating in conformity with the definition of the second,

3. the physical basic units of the space-time be the second of SI for the proper time and that it be connected to the meter of SI for proper length by the value of the velocity of light c = 299 792 458 m s^{-1}.

6.2. Notes on recommendations G1 and G2

Although G1 and G2 are common recommendations of SGFO and SGT, no attempt has been made to unify the notes. The following notes are drafted for the SGT.

(a) It does not seem possible, at the present stage of our knowledge, to agree on a particular form of the metric beyond approximation given in Recommendation G1. Recommendation G1 allows the possibility of using all forms of metric accepting this approximation.

(b) Recommendations G1 and G2 exclude the use of scaling factors for the units of length and time in the transformations of coordinates. These points are considered more specifically in recommendations T1 and T2.

(c) Recommendation G2 fixes the state of rotation of the grid of barycentric coordinates by a kinematical constraint. It is recognized that G2, 1 cannot be rigorously fulfilled, either for fundamental reasons such as a possible incompatibility of reference systems dynamically and kinematically defined, or for practical reasons such as the uncertainties of the realization of the kinematical reference frame. Constraint G2, 1 must be realized in so far as possible.

(d) Recommendation G2 does not fix the state of rotation of the geocentric grid because it cannot be done unambiguously at the considered level of approximation. [These matters are considered by the SGFO].

(e) While the state of rotation of the coordinate grids is fixed by a constraint on barycentric coordinates, the time coordinates are defined by a geocentric constraint. These hybrid constraints are imposed by the need to realize the reference frames, in space and time, without degrading data obtained from measurements and from standards.

6.3. Recommendations and notes of the SGT

Recommendation T1

The ....

considering

- the desirability of standardization of the units and origins of coordinate times used in astronomy,

- the importance of coordinate systems having their origins at the center of mass of the Earth and at the center of mass of the solar system,

recommends that

1. the unitary interval of coordinate times of all coordinate systems centered at the barycenter of material systems tend asymptotically to the proper SI second, far from the spatial origins of these coordinate systems,

2. the reading of these coordinate times be 1977 January 1, 0 h 0 m 32,184 s on 1977 January 1, 0 h 0 m 0 s TAI (MJD = 43 144.0..., TAI), at the geocenter,

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3. coordinate times in non-rotating reference systems having their spatial origins respectively at the geocenter and at the solar system barycenter, and established in conformity with the above recommendations, be designated as Geocentric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB).

Notes on Recommendation T1

(a) Recommendation T1 recognizes that the space-time cannot be covered with a single reference system, because a good choice of coordinate system may significantly facilitate the treatment of the problem at hand and elucidate the meaning of the relevant physical events. In "recommends 1", it must be understood that, far from the space origin, the potential of the material system to which the coordinate system pertains becomes negligible, while the potential of external bodies manifests itself only by tidal terms which vanish at the space origin. In the domain common for two coordinate systems "recommends 1" implies that the tensor transformation law, applied to the metric tensor, is valid without re-scaling the unit of time. Therefore, the various coordinate times under consideration exhibit secular variations. Recommendation 5 (1976) of IAU Commissions 4, 8 and 31, completed by Recommendation 5 (1979) of IAU Commissions 4, 19 and 31, stated that the Terrestrial Dynamical Time (TDT) and the Barycentric Dynamical Time (TDB) should differ only by periodic variations. This requirement has now been cancelled.

(b) According to Recommendations G1 and G2, the absence of re-scaling of the unit of time, implies the absence of re-scaling of the unit of length, in conformity with its definition by the 17th Conférence Générale des Poids et Mesures (1983). The astronomical constants are thus expressed in SI units, without conversion factors depending on the coordinate systems to which they belong.

(c) The relation TCB-TCG involves a full 4-dimensional transformation. For observers on the surface of the Earth, the terms depending on their terrestrial coordinates are diurnal, with a maximum amplitude of 2,1 μs. The numerical expression of TCB - TCG can be evaluated from the positions and velocities of the solar system bodies obtained by numerical integration, using the formula by Moyer [Moyer, T.D., 1981, Celest. Mechanics, 23, 33-68]. Another possibility is to use the analytical formula by Hirayama et al. [Proc. IUGG Symposia, Vancouver, 1987], with the secular part in conformity with the IAU System of Astronomical Constants. The secular term is approximately, in seconds

$$[\mathrm{TCB} - \mathrm{TCG}]_{\mathrm{secular}} = 1{,}4808 \times 10^{-8} \times (\mathrm{MJD} - 43144{,}0) \times 86400$$

the MJD being reckoned in TAI.

(d) The origin of the coordinate times has been arbitrarily set so that they all coincide with the Terrestrial Time TT of Recommendation T2, at the geocenter, on 1977 January 1, 0 h 0 m 0 s TAI. See note (c) of Recommendation T2.

(e) When realizations of TCB and TCG are needed, it is suggested that these realizations be designated by expressions such as TCB(xxx), where xxx states the source of the realized time scale (TAI, for example) and the theory used for the transformation into considered time.

Recommendation T2

The ....

considering

- that the time scales used for dating events observed from the surface of the Earth and for terrestrial metrology should have a unitary interval close to the SI second, as realized by terrestrial time standards,

- the definition of the International Atomic Time, TAI, approved by the 14th General Conference of Weights and Measures (1971) and completed by a declaration of the 9th session of the Comité Consultatif pour la Définition de la Seconde (1980),

recommends that

1. the time reference for apparent geocentric ephemerides be the Terrestrial Time TT,

2. TT be a coordinate time in a non-rotating geocentric coordinate system, its unitary interval being chosen so that it agrees with the SI second on the geoid,

3. at instant 1977 January 1, 0 h TAI exactly, TT have the reading 1977 January 1, 0 h 0 m 32,184 s.

Notes on Recommendation T2

(a) The basis of the measurement of time on the Earth is International Atomic Time, TAI, which is made available by the dissemination of corrections to be added to the readings of national time scales and clocks. The time scale TAI has been defined by the 59th session of the Comité International des Poids et Mesures (1970) and approved by the 14th Conférence Générale des Poids et Mesures (1971) as a realized time scale. As the errors in the realization of TAI are not always negligible, it has been found necessary to define an ideal form of TAI now designated "Terrestrial Time", TT.

(b) In order to define TT without ambiguity, it would be necessary to define the coordinate system precisely, by the metric form, to which it belongs. However, ambiguities can be tolerated if they generate frequency errors much smaller than the uncertainties of the frequency of the best standards. It is at present (1990) sufficient to consider that the reference system does not rotate, in a broad sense (i.e. with respect to the average direction of distant bodies such as quasars), and to use the metric of the first post-Newtonian approximation of the General Relativity theory.

(c) For ensuring an approximate continuity of the time argument of ephemerides, previously the Ephemeris Time, a time offset between TT and TAI is introduced, so that TT - TAI = 32,184 s on 1977 January 1, 0 h TAI. This date corresponds to the implementation of a steering process of the TAI frequency, so that the TAI unitary scale interval remain in close agreement with the best realizations of the SI second on the geoid. TT can be considered as equivalent to TDT as defined by the IAU Recommendations 5 (1976) and 5 (1979) of Commissions 4, 19 and 31.

(d) The divergence between TAI and TT is a consequence of physical defects of atomic time standards. In the interval 1977-1990 in addition to the constant offset of 32,184 s, the deviation remained probably within the approximate limits of ± 10 µs. It is expected to increase more slowly in the future, as a consequence of the progress of atomic time standards. In many cases, especially for the publication of ephemerides, this deviation is negligible. In such cases, it can be stated that the argument of the ephemerides is TAI + 32,184 s.

(e) The Terrestrial Time differs from TCG of Recommendation T1 uniquely by a scaling factor:

$$TCG - TT = 6{,}969 \times 10^{-10} \times (MJD - 43144{,}0) \times 86400 \text{ in seconds}$$

These two time scales are distinguished by different names to avoid scaling errors.

(f) The time interval unit of TT is the SI second on the geoid(coordinate second). The usual multiples such as the TT day of 86400 TT seconds, the TT julian century of 36525 TT days can be used, providing that the reference to TT be clearly indicated. The corresponding time interval units of TAI are in agreement with the TT units within the uncertainties of the primary atomic time standards (for example, within $\pm 2 \times 10^{-14}$ in 1990, on yearly average).

(g) The markers of the TT scale can follow any date system based on the TT second, for example the usual calendar date or the Modified Julian Date, providing that the reference to TT be clearly indicated.

(h) It is suggested that realizations of TT be designated by TT(xxx) where xxx is an identifyer. In most cases, a convenient approximation is

$$TT(TAI) = TAI + 32{,}184 \text{ s.}$$

But in some applications it may be advantageous to use other realizations; for example, the BIPM has issued time scales such as TT(BIPM90).

7. Acknowledgement

I consider this report as a collective work. We must thank all those who participated in the preparatory discussions, who are mentioned in the text and appear in Annex I

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Annex I

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Sub-Group on Time

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