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Representations of Time Coordinates in FITS

Time and Relative Dimension in Space (V0.93)

Arnold H. Rots,[1] Peter S. Bunclark,[2,⋆] Mark R. Calabretta,[3] Steven L. Allen,[4] Richard N. Manchester,[3] and William T. Thompson[5]

[1] Harvard-Smithsonian Center for Astrophysics/Smithsonian Astrophysical Observatory, 60 Garden Street MS 67, Cambridge, MA 02138, USA

[2] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

[3] CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia

[4] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA

[5] Adnet Systems, Inc., NASA Goddard Space Flight Center, Code 671, Greenbelt, MD 20771, USA

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ABSTRACT

Context. In a series of four previous papers, formulation and specifics of the represention of World Coordinate Transformations in FITS data have been presented. This fifth paper deals with encoding time.
Aims. Time on all scales and precision known in astronomical datasets shall be described by extending the established FITS standard.
Methods. Employing the well–established World Coordinate System framework, and maintaining compatibility with the FITS conventions that are currently in use to specify time, the standard is extended to rigorously describe the time coordinate.
Results. World coordinate functions are defined for temporal axes sampled linearly and as specified by a lookup table.

Key words. time – methods: data analysis – techniques: miscellaneous – astronomical databases: miscellaneous – reference systems

1. Introduction

Time as a dimension in astronomical data presents challenges in its representation in FITS files as great as those met by the previous papers in this series. The first, Paper I (Greisen & Calabretta 2002), lays the groundwork by developing general constructs and related FITS header keywords and the rules for their usage in recording coordinate information. Paper II (Calabretta & Greisen 2002) addresses the specific problem of describing celestial coordinates in a two-dimensional projection of the sky. In Paper III, Greisen et al. (2006) apply these methods to spectral coordinates. A draft paper (Calabretta et al. 2004) proposes and extension to the formalism in order to deal with general distortions of the coordinate grid.

This paper, the next in the series, formulates the representation of the time axis, or possible multiple time axes, into the FITS World Coordinate System (WCS) previously described. We show how much of the basic structure is employed, while developing extensions to cope with the differences between time and other dimensions; notable amongst these differences is the huge dynamic range covering the highest resolution relative timing to the age of the Universe.

The precision with which any time stamp conforms to any conventional time scale is highly dependent on the characteristics of the acquiring system. The definitions of many conventional time scales vary over their history along with the precision which can be attributed to any time stamp. The meaning of any time stamp may be ambiguous if a time scale is used for dates prior to its definition by a recognized authority, or for dates after that definition is abandoned. However, common sense should prevail and it would be overly pedantic to require a precision in the description of the time coordinate that far exceeds the accuracy of the temporal information in the data.

In the following sections we will first define the terms of reference of this standard. Section 3 deals with time values and representations of time. Section 4 forms the core of this standard, providing an explanation of the components that are involved and defining the keywords to be used for specifying those components. Section 5 on usage context refers back to the terms of reference, illustrated with five header examples and including a sub-section on time-related coordinate axes. We conclude with some remarks on precision.

Generally helpful references may be found in Seidelmann (1992) and McCarthy & Seidelmann (2009). The report on the current (IAU 2009) system of astronomical constants is provided by Luzum et al. (2011) [1].

2. Terms of Reference

Time WCS information needs to be supported in five contexts:

⋆ Deceased

[1] Current Best Estimates are maintained at http://maia.usno.navy.mil/NSFA/NSFA_cbe.html

- Recording time stamps in header keywords
- Time coordinate axes in images
- Time columns in tables
- Time coordinate axes in table vector columns
- Time in random groups

We shall distinguish the following components in the specification of time:

- Time Coordinate Frame, containing:
  - Time Scale
  - Time Reference Position
  - Reference Time (the zero point for relative times)
  - Time Reference Direction (if applicable)
  - Solar System ephemeris used (if applicable)
- Time Unit
- Corrections, errors, etc.:
  - Time offsets
  - Absolute error
  - Relative error
  - Time resolution
- Durations

The following use cases illustrate the scope of the requirements for time axes.

- Photon arrival times ("event lists")
- Time-sampled data streams (referred to as "light curves" in some of our communities)
- Pulsar pulse profiles (folded or stacked light curves)
- Image cubes: typically a series of two-dimensional images acquired at regular time spacing, and stacked so the third axis is time. Usually precision isn't demanding, but the time axis must be integrated into a three-dimensional WCS.
- Simulation data

"Mixed" axes, where spatial or spectral coordinates change as a function of time (e.g., during an observation) represent a special challenge.

Where possible, we have adopted the same keywords as in the OGIP convention[2], which has become a *de facto* standard for representing timing information within high-energy astrophysics data files, particularly from NASA as well as many ESA missions.

In addition to "proper" time axes, we provide accommodation for three types of time-related coordinates: Phase, Timelag, and Frequency; see Section 5.5.

Contrary to the convention followed in previous FITS standards papers, Appendix A is to be considered part of this standard. The more subtle issues associated with the definition of time scales are, of necessity, germaine to the details of the standard, but it seemed unwieldy to include them in the main text of this paper.

3. Time Values and Representations of Time

The three most common ways to specify time are: ISO-8601, Julian Date (JD; see Herschel 1851), or Modified Julian Date (MJD = JD − 2,400,000.5; see IAU 1997). Julian Dates are counted from Julian proleptic calendar date 1 January 4713 BCE at noon, or Gregorian proleptic calendar date 24 November 4714 BCE, also at noon. For an explanation of the calendars, see the note in Section 3.1.

Even though we may tend to think of certain representations of time as absolute (ISO-8601, Julian dates), time values in this paper will all be considered relative: elapsed time since a particular reference point in time. It may help to view the "absolute" values as merely relative to a globally accepted zero point. Besselian and Julian epochs are the only exceptions to being considered relative.

In the following we will first treat the ISO-8601 representation, then floating point values of elapsed time since a reference value. Concerning the latter, usage cases show that values of time elapsed since a particular reference time cannot always be represented satisfactorily by existing FITS data types. In addition to the 32-bit (`E`) and 64-bit (`D`) floating point types it is desirable to have a 128-bit floating point data type. We conclude the section with a specification of epochs.

3.1. ISO-8601 Datetime Strings

FITS uses a subset of ISO-8601 (which in itself does not imply a particular time scale) for several time-related keywords (Bunclark & Rots 1997), such as `DATE-xxx` and `MJD-xxx`. In this paper we will use *datetime* as a pseudo data type. Using the current FITS standard (Pence et al, 2010) its values can be written as a character string in `A` format, but it would be desirable to have it included as a data type in its own right into the FITS standard as type `’T’`. It is premature to prescribe a full format specifier, but we expect it to be similar to the way the `A` format is handled. If and when an ISO-8601 data type is adopted we will assume that it will be used, rather than the string type.

The full specification for the format of the *datetime* string till now has been:

`CCYY-MM-DD[Thh:mm:ss[.s...]]`

All of the time part may be omitted (just leaving the date) or the decimal seconds may be omitted. Leading zeroes may not be omitted and timezone designators are not allowed.

This paper extends the definition to allow five-digit years with a (mandatory) sign. I.e., one may either use the *unsigned* four-digit year format or the *signed* five-digit year format:

`[±C]CCYY-MM-DD[Thh:mm:ss[.s...]]`

Note the following:

- The earliest date that may be represented in the four-digit year format is 0000-01-01T00:00:00 (in the year 1 BCE); the latest date is 9999-12-31T23:59:59. This representation of time is tied to the Gregorian calendar (Pope Gregorius 1582). In conformance with with the present ISO-8601:2004(E) standard (ISO 2004) we specify that, for use in FITS files, dates prior to 1582 are to be interpreted according to the proleptic application of the rules of Gregorius (1582). For dates not covered by the range we recommend the use of Modified Julian Date (MJD) or Julian Date (JD) numbers or the use of the signed five-digit year format.
- In the five-digit year format the earliest and latest dates are −99999-01-01T00:00:00 (i.e., −100000 BCE) and +99999-12-31T23:59:59.
- Recalling the definition of JD provided at the top of Section 3, we can express its origin as −04713-11-24T12:00:00.
- In time scale UTC the integer part of the seconds field runs from 00 to 60; in all other time scales the range is 00 to 59.

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[2] This convention was developed by the Office of Guest Investigator Programs within the HEASARC (High Energy Astrophysics Science Archive Research Center) at the NASA Goddard Space Flight Center.

- This data type is not allowed in image axis descriptions since `CRVAL` is required to be a floating point value.
- ISO-8601 *datetime* does not imply the use of any particular time scale (see Section 4.2.1).
- As specified by Bunclark & Rots (1997), time zones are explicitly not supported in FITS and, consequently, appending the letter ’Z’ to a FITS ISO-8601 string is not allowed. The rationale for this rule is that its role in the ISO standard is that of a time zone indicator, not a time scale indicator. As the concept of a time zone is not supported in FITS, the use of time zone indicator is inappropriate.

3.2. Single or Double Precision Floating Point Relative Time

These are existing data types that do not need any particular provisions and can be used when their precision suffices. The following sections deal with situations where double precision floating point does not provide enough precision. A common application, for example, is a double precision Time column in a binary table where the values are relative to a reference value that is chosen such that the precision of the data type is adequate for the required accuracy.

3.3. Higher Precision in Keyword Values

In headers, the value may be written to as many significant figures as required. Such free-format floating point is already recognized in the FITS standard (Pence, et al., 2010). We emphasize that it always is, and always has been, the implementer’s responsibility to check on the required accuracy of keyword values, rather than to assume that “a double is good enough” (see Section 4.2.4 of the standard), although FITS readers and general applications may need to be checked whether they handle this correctly. Nevertheless, the conclusion is that there are no problems with keyword values or the time axis in images.

Note that this technique can also be used in ASCII tables with the use of the `F`, `E`, and `D` formats.

3.4. Higher Precision in Binary Tables: Doublet Vectors

In binary tables one may use pairs of doubles. The time column in such a table shall contain a vector of two doubles where the first component of the doublet contains the integer portion of the time value and the second one the fractional part. We readily admit that a combination of an integer and a floating point number would be preferable, but the use of two doubles allows us to keep the time stamps in a single table column.

3.5. Higher Precision in Binary and ASCII Tables: Quad Floating Point

For ASCII tables there may not be any need for a high-precision data type (see Section 3.3).

In binary tables, we expect that at some point a new data type will be defined, *long double* or *quad*. With the `L` and `Q` type codes spoken for, we propose that the value of `TFORM`*n* shall be *r*`S`*a* (suggesting sixteen bytes – or super-double); see Section 7.3.1 of the FITS Standard (Pence, et al., 2010) for the interpretation of this string. If and when this data type is adopted we shall assume that it will be used for time stamps and eventually supersede the use of doublet vectors (see Section 3.4).

Table 1 Some Besselian and Julian Epochs

Epoch	ISO-8601 date	Julian Date
B1900	1899-12-31T19:31:26.4(ET)	2415020.3135(ET)
B1950	1949-12-31T22:09:50.4(ET)	2433282.4235(ET)
J1900	1899-12-31T12:00:00(ET)	2415020.0(ET)
J2000	2000-01-01T12:00:00(TDB)	2451545.00(TDB)
J2001	2000-12-31T18:00:00(TDB)	2451910.25(TDB)
J2002	2002-01-01T00:00:00(TDB)	2452275.50(TDB)
J2003	2003-01-01T06:00:00(TDB)	2452640.75(TDB)
J2004	2004-01-01T12:00:00(TDB)	2453006.00(TDB)

3.6. Julian and Besselian Epochs

In a variety of contexts *epochs* are provided with astronomical data. Until 1976 these were commonly based on the Besselian year (see Section 4.3), with standard epochs B1900.0 and B1950.0. After 1976 the transition was made to Julian epochs based on the Julian year of 365.25 days, with the standard epoch J2000.0. They are tied to time scales ET and TDB, respectively. Table 1 provides conversion values for some Besselian and Julian epochs. See also Seidelmann (1992, Table 15.3). Note that the Besselian epochs are scaled by the variable length of the Besselian year (see Section 4.3 and its cautionary note, which also applies to this context). The Julian epochs are easier to calculate, as long as one keeps track of leap days.

Caution: be aware that the year 1 corresponds to 1 CE, year 0 to 1 BCE, year −1 to 2 BCE, and so on. For negative year numbers there is an offset of one, since the (B)CE counting of years does not recognize a year 0. In counting years, ISO-8601 follows the convention established by Cassini (1740).

4. Components of the Standard

This section describes the components of the standard. The keywords used to specify times are summarized in Table 5. The first section of the table contains data items: time values that have, in principle, global validity in the HDU. The second section presents metadata keywords that define the time reference frame for all time values in the HDU. If the HDU contains a table, all keywords in the first two sections may be replaced by columns, with specific values for each row (“Green Bank convention”). A subset of the metadata keywords may also be overridden in individual table columns, as summarized in the third section, while the fourth section lists the keywords that allow overriding the global HDU keyword values for the time axis in images.

In the following *high-precision floating-valued* should be interpreted as *floating-valued* with the caveat that routine double floating precision may not provide sufficient accuracy; see Section 3. *Datetime-valued* should be interpreted as *string-valued* where the string conforms to ISO-8601 format as defined in Section 3.1 .

4.1. Keywords that Represent Global Time Values

Keywords The following time values may only be found in the header, independent of any time axes in the data. Except for `DATE`, they provide the top-level temporal bounds of the data in the HDU. As noted before, they may also be implemented as table columns.

`DATE` (datetime-valued)
Creation date of the HDU in UTC

`DATE-OBS` (datetime-valued)
Time of data in ISO-8601 according to `TIMESYS`

`MJD-OBS` (high-precision floating-valued)
Time of data in MJD according to `TIMESYS`

`DATE-OBS` is already defined in Section 4.4.2.2 of the FITS Standard. It is not specifically defined as the start time of the observation and has also been used to indicate some form of mean observing date and time. In order to specify a start date and time unambiguously one should use:

`DATE-BEG` (datetime-valued)
Start time of data in ISO-8601 according to `TIMESYS`

`DATE-AVG` (datetime-valued)
Average time of data in ISO-8601 according to `TIMESYS`; note: this paper does not prescribe how average times should be calculated

`DATE-END` (datetime-valued)
Stop time of data in ISO-8601 according to `TIMESYS`

`MJD-BEG` (high-precision floating-valued)
Start time of data in MJD according to `TIMESYS`

`MJD-AVG` (high-precision floating-valued)
Average time of data in MJD according to `TIMESYS`; note: this paper does not prescribe how average times should be calculated

`MJD-END` (high-precision floating-valued)
Stop time of data in MJD according to `TIMESYS`

`TSTART` (high-precision floating-valued)
Start time of data in `TIMEUNIT` relative to `MJDREF`, `JDREF`, or `DATEREF` according to `TIMESYS`

`TSTOP` (high-precision floating-valued)
Stop time of data in `TIMEUNIT` relative to `MJDREF`, `JDREF`, or `DATEREF` according to `TIMESYS`

The following time values are part of an axis definition (see Section 5 for details):

`CRVAL`*i* (high-precision floating-valued)
Reference pixel time value

`CRVAL`*ia* (high-precision floating-valued)
Reference pixel time value

`TCRVL`*n* (high-precision floating-valued)
Reference pixel time value

`TCRV`*na* (high-precision floating-valued)
Reference pixel time value

Finally, Julian and Besselian epochs (see Sections 3.6 and 4.3) may be expressed by these two keywords – to be used with great caution, as their definitions are more complicated and hence their use more prone to confusion:

`JEPOCH` (high-precision floating-valued)
Julian epoch

`BEPOCH` (high-precision floating-valued)
Besselian epoch

4.2. Time Coordinate Frame

This section defines the various components that constitute the time coordinate frame. For a full review of the IAU resolutions concerning space-time coordinate transformations, see Soffel et al. (2003).

4.2.1. Time Scale

The time scale defines the temporal reference frame (in the terminology of the IVOA Space-Time Coordinate metadata standard; see Rots 2008). See also the USNO (2008) page on time scales, Wallace (2011), and SOFA (2010).

Table 2 lists recognized values. For a detailed discussion of the time scales we refer to Appendix A; that information will be of particular relevance for high-precision timing. In cases where this is significant, one may append a specific realization, in parentheses, to the values in the table; e.g., `TT(TAI)`, `TT(BIPM08)`, `UTC(NIST)`. Note that linearity is not preserved across all time scales. Specifically, if the reference position remains unchanged (see Section 4.2.2), the first ten, with the exception of `UT1`, are linear transformations of each other (excepting leap seconds), as are `TDB` and `TCB`. The relations between coordinate time scales and their dynamical equivalents have been defined as (see Luzum et al. 2011, Wallace 2011, SOFA 2010):

$$T(\mathrm{TCG}) = T(\mathrm{TT}) + L_\mathrm{G} \times (JD(\mathrm{TT}) - JD_0)$$

$$T(\mathrm{TDB}) = T(\mathrm{TCB}) - L_\mathrm{B} \times (JD(\mathrm{TCB}) - JD_0) + TDB_0$$

where:

T is in seconds
$L_\mathrm{G} = 6.969290134 \times 10^{-10}$
$L_\mathrm{B} = 1.550519768 \times 10^{-8}$
$JD_0 = 2443144.5003725$
$TDB_0 = -6.55 \times 10^{-5}$

Linearity is virtually guaranteed since images and individual table columns do not allow more than one reference position to be associated with them and since there is no overlap between reference positions that are meaningful for the first nine time scale on the one hand, and for the barycentric ones on the other. All use of the time scale GMT in FITS files shall be taken to have its zero point at midnight, conformant with UT, including dates prior to 1925; see Sadler (1978).

Any other time scales that are not listed in Table 2 are intrinsically unreliable and/or ill-defined. These should be tied to one of the existing scales with appropriate specification of the uncertainties; the same is true for free-running clocks. However, a local time scale, such as MET (Mission Elapsed Time) or OET (Observation Elapsed Time), may be defined for practical reasons. The Time Reference Value (see Section 4.2.3) should not be applied to the values and we strongly recommend that such timescales be provided as alternate time scales, with a defined conversion to a recognized time scale.

Most current computer operating systems adhere to the POSIX standard for time, and use Network Time Protocol (NTP) to closely synchronize to UTC. This reasonable approximation to UTC is then commonly used to derive timestamps for FITS data. However, authors of FITS writers and subsequent users of FITS timing information should be aware of the accuracy limitations of POSIX and NTP, especially around the time of a leap second.

Keywords The following keywords may assume the values for the time scale that are listed in Table 2. In addition, for backward compatibility, all except `TIMESYS` may also assume the value `TIME` (case-insensitive). The foundational keyword for the time scale is:

`TIMESYS` (string-valued)
Time Scale; default `UTC`

Table 2 Recognized Time Scale Values[1,2]

`TAI`	(International Atomic Time): atomic time standard maintained on the rotating geoid
`TT`	(Terrestrial Time; IAU standard): defined on the rotating geoid, usually derived as TAI + 32.184 s
`TDT`	(Terrestrial Dynamical Time): synonym for TT (deprecated)
`ET`	(Ephemeris Time): continuous with TT; should not be used for data taken after 1984-01-01
`IAT`	synonym for TAI (deprecated)
`UT1`	(Universal Time): Earth rotation time
`UTC`	(Universal Time, Coordinated; default): runs synchronously with TAI, except for the occasional insertion of leap seconds intended to keep UTC within 0.9 s of UT1; as of 2009-01-01 UTC = TAI − 34 s
`GMT`	(Greenwich Mean Time): continuous with UTC; its use is deprecated for dates after 1972-01-01
`GPS`	(Global Positioning System): runs (approximately) synchronously with TAI; GPS ≈ TAI − 19 s
`TCG`	(Geocentric Coordinate Time): TT reduced to the geocenter, corrected for the relativistic effects of the Earth's rotation and gravitational potential; TCG runs faster than TT at a constant rate
`TCB`	(Barycentric Coordinate Time): derived from TCG by a 4-dimensional transformation, taking into account the relativistic effects of the gravitational potential at the barycenter (relative to that on the rotating geoid), thus ensuring consistency with fundamental physical constants
`TDB`	(Barycentric Dynamical Time): runs slower than TCB at a constant rate so as to remain approximately in step with TT; runs therefore quasi-synchronously with TT, except for the relativistic effects introduced by variations in the Earth's velocity relative to the barycenter; when referring to celestial observations, a pathlength correction to the barycenter may be needed which requires the Time Reference Direction used in calculating the pathlength correction
`LOCAL`	for simulation data and for free-running clocks.

[1] Specific realizations may be appended to these values, in parentheses; see text. For a more detailed discussion of time scales, see Appendix A

[2] Recognized values for `TIMESYS`, `CTYPE`*ia*, `TCTYP`*n*, `TCTY`*na*.

In relevant context (*e.g.,* time axes in image arrays or table columns) it may be overridden by (see Sections 5.2 and 5.3 for details):

`CTYPE`*i* (string-valued)

`CTYPE`*ia* (string-valued)

`TCTYP`*n* (string-valued)

`TCTY`*na* (string-valued)

The default value is `UTC`. Note that the time scale for time axes is encoded in the `CTYPE` family of keywords; if these are absent or have the value `TIME`, it defaults to the value of `TIMESYS`; if that is absent, too, the time scale is `UTC`. See also the notes relating to these keywords in Sections 5 and 5.3, and their use for time-related axes in Section 5.5.

Table 3 Standard Time Reference Position Values Contained in the JPL Ephemerides[1]

`TOPOCENTER`	Topocenter: the location from where the observation was made (default)
`GEOCENTER`	Geocenter
`BARYCENTER`	Barycenter of the Solar System
`RELOCATABLE`	Relocatable: to be used for simulation data only
`CUSTOM`	A position specified by coordinates that is not the observatory location
Less common allowed standard values are:	
`HELIOCENTER`	Heliocenter
`GALACTIC`	Galactic center
`EMBARYCENTER`	Earth-Moon barycenter
`MERCURY`	Center of Mercury
`VENUS`	Center of Venus
`MARS`	Center of Mars
`JUPITER`	Barycenter of the Jupiter system
`SATURN`	Barycenter of the Saturn system
`URANUS`	Barycenter of the Uranus system
`NEPTUNE`	Barycenter of the Neptune system
`PLUTO`	Barycenter of the Pluto system

[1] Recognized values for `TREFPOS`, `TRPOS`*n*; may be truncated to 8 characters

4.2.2. Time Reference Position

An observation is an event in space-time. The reference position, specified by the keyword `TREFPOS` specifies the spatial location at which the time is valid; i.e., where the time was measured or to which the observations were reduced. This may be a standard location (such as `GEOCENTER` or `TOPOCENTER`) or a point in space defined by specific coordinates. In the latter case one should be aware that a (3-D) spatial coordinate frame needs to be defined that is likely to be different from the frame(s) that the data are associated with. Note that `TOPOCENTER` is only moderately informative if no observatory location is provided or indicated.

The commonly allowed standard values are shown in Table 3. Note that for the gaseous planets we use the barycenters of their planetary systems, including satellites, for obvious reasons. Our preference is to spell the location names out in full, but in order to be consistent with the practice of Paper III (2006) and the FITS Standard (Pence, et al., 2010) the values are allowed to be truncated to eight characters. We envisage that at some time in the future we may need a provision to add minor planets to this list.

Some caution is in order, here. Time scales and reference positions cannot be combined arbitrarily if one wants a clock that runs linearly at `TREFPOS`. Table 4 provides a summary of compatible combinations. `BARYCENTER` should only be used in conjunction with time scales `TDB` and `TCB` and should be the only reference position used with these time scales. With proper care `GEOCENTER`, `TOPOCENTER`, and `EMBARYCENTER` are appropriate for the first ten time scales in Table 2. However, one needs to be aware that relativistic effects introduce a (generally linear) scaling in certain combinations; highly eccentric spacecraft orbits are the exception. Problems will arise when using a reference position on another solar system body (including `HELIOCENTER`). At this point we recommend synchronizing the local clock with one of the time scales defined on the Earth's surface, `TT`, `TAI`, `GPS`, or `UTC` (in the last case: beware of leap seconds). This is common practice for spacecraft clocks. Locally, such a clock

Table 4 Compatibility of Time Scales and Reference Positions[1]

Reference Position	TT, TDT TAI, IAT GPS UTC, GMT	TCG	TDB	TCB	LOCAL
TOPOCENTER	t	ls			
GEOCENTER	ls	c			
BARYCENTER			ls	c	
RELOCATABLE					c
Other[2]	re	re			

[1] Legend (combination is not recommended if no entry):
c: correct match
t: correct match on Earth's surface, otherwise usually linear scaling
ls: linear relativistic scaling
re: non-linear relativistic scaling
[2] All other locations in the solar system

will not appear to run at a constant rate, because of variations in the gravitational potential and in motions with respect to Earth, but the effects can be calculated and are probably small compared to errors introduced by the alternative: establishing a local time standard.

In order to provide a complete description, TOPOCENTER requires the observatory's coordinates to be specified. We offer three options: the ITRS Cartesian coordinates (X, Y, Z) introduced in Paper III; a geodetic latitude/longitude/height triplet; or a reference to an orbit ephemeris file.

A non-standard location indicated by CUSTOM will be specified in a manner similar to the specification of the observatory location (indicated by TOPOCENTER). One should be careful with the use of the CUSTOM value and not confuse it with TOPOCENTER, as use of the latter imparts additional information on the provenance of the data.

Keywords The time reference position is specified by the keyword

TREFPOS (string-valued)
Time reference position; default TOPOCENTER

TREFPOS[3] will apply to time coordinate axes in images as well. See Section 5.2.1 for an explanation.

In binary tables different columns may represent completely different Time Coordinate Frames. However, each column can have only one time reference position, thus guaranteeing linearity (see Section 4.2.1) and the following keyword may override TREFPOS:

TRPOS*n* (string-valued)

If the value of any of these keywords is TOPOCENTER, the observatory position needs to be specified. If the value is CUSTOM, the "custom" position needs to be specified. In either case we allow three mechanisms for this.

The ITRS Cartesian coordinates (with respect to the geocenter) as defined in Paper III:

OBSGEO-X (floating-valued)
ITRS Cartesian X in m

OBSGEO-Y (floating-valued)
ITRS Cartesian Y in m

OBSGEO-Z (floating-valued)
ITRS Cartesian Z in m

Similarly defined geodetic coordinates have to be recognized, although the ITRS Cartesian coordinates are strongly preferred:

OBSGEO-B (floating-valued)
Latitude in deg, North positive

OBSGEO-L (floating-valued)
Longitude in deg, East positive

OBSGEO-H (floating-valued)
Altitude in m

An orbit ephemeris file:

OBSORBIT (string-valued)
URI, URL, or name of orbit ephemeris file

Beware that only one set of coordinates is allowed in a given HDU. Cartesian ITRS coordinates are the preferred coordinate system; however, when using these in an environment requiring nanosecond accuracy, one should take care to distinguish between meters consistent with TCG or with TT. If one uses geodetic coordinates, the geodetic altitude OBSGEO-H is measured with respect to IAU 1976 ellipsoid which is defined as having a semi-major axis of 6378140 m and an inverse flattening of 298.2577. Nanosecond precision in timing requires that OBSGEO-[*BLH*] be expressed in a geodetic reference frame defined after 1980 in order to be sufficiently accurate.

4.2.3. Time Reference Value

We allow the time reference point to be defined in the three common systems: ISO-8601, JD, or MJD. These reference values are only to be applied to time values associated with one of the recognized time scales listed in Table 2.

Keywords The reference point in time, to which all times in the HDU are relative, may be specified through one of three keywords:

MJDREF (high-precision floating-valued)
Reference time in MJD

JDREF (high-precision floating-valued)
Reference time in JD

DATEREF (datetime-valued)
Reference time in ISO-8601

MJDREF and JDREF may, for clarity and/ or precision reasons, be split into two keywords holding the integer an fractional parts separately:

MJDREFI (integer-valued-valued)
Integer part of reference time in MJD

MJDREFF (integerfloating-valued-valued)
Fractional part of reference time in MJD

---

[3] The OGIP convention uses the keyword TIMEREF and only allows values 'LOCAL' (i.e., Topocenter), 'GEOCENTRIC', 'HELIOCENTRIC', 'SOLARSYSTEM' (i.e., Barycenter); the convention contains also the somewhat peculiar keyword TASSIGN. We will not adopt these keywords in order to avoid confusion on allowed values and meaning. Instead, we adopt the keywords TREFPOS and TRPOS*n*.

`JDREFI` (integer-valued-valued)
Integer part of reference time in JD

`JDREFF` (integerfloating-valued-valued)
Fractional part of reference time in JD

In the following `MJDREF` and `JDREF` shall refer to their literal meaning or the combination of their integer and fractional parts.

If, for whatever reason, a header contains more than one of these keywords, `JDREF` shall have precedence over `DATEREF` and `MJDREF` shall have precedence over both the others. If none of the three keywords is present, there is no problem as long as all times in the HDU are expressed in ISO-8601; otherwise `MJDREF` = 0.0 shall be assumed. If `TREFPOS` = '`CUSTOM`' it is legitimate for none of the reference time keywords to be present, as one may assume that we are dealing with simulation data.

Note: The *value* of the reference time has global validity for all time values, but it does not have a particular time scale associated with it.
Therefore, assuming the use of TT(TAI), if `MJDREF` = 50814.0 and `TIMEUNIT`= `'s'`:
a time instant $T = 86400.0$ associated with TT will fall on
1998-01-02T00:00:00.0(TT) or
1998-01-01T23:59:27.816(TAI),
but a time instant $T = 86400.0$ associated with TAI will fall on
1998-01-02T00:00:32.184(TT) or
1998-01-02T00:00:00.0(TAI).
Table 9 provides examples of this; one may compare the reference pixel values of TT, TCG, and UTC for column 1, and of TDB and TCB for column 20.

4.2.4. Time Reference Direction

If any pathlength corrections have been applied to the time stamps (i.e., if the reference position is not `TOPOCENTER` for observational data), the reference direction that is used in calculating the pathlength delay should be provided in order to maintain a proper analysis trail of the data. However, this is only useful if there is also information available on the location from where the observation was made (the observatory location). The direction will usually be provided in a spatial coordinate frame that is already being used for the spatial metadata, although that is not necessarily the case. It is, for instance, quite conceivable that multiple spatial frames are already involved: spherical ICRS coordinates for celestial positions, and Cartesian FK5 for spacecraft ephemeris. We also acknowledge that the time reference direction does not by itself provide sufficient information to perform a fully correct transformation; however, within the context of a specific analysis environment it should suffice.

The uncertainty in the reference direction affects the errors in the time stamps. A typical example is provided by barycentric corrections where the time error t_{err} is related to the position error pos_{err}:

$t_{err}(\mathrm{ms}) \leq 2.4 pos_{err}(\mathrm{arcsec})$

We shall indicate the reference direction through a reference to specific keywords. These keywords may hold the reference direction explicitly or indicate columns holding the coordinates. In event lists where the individual photons are tagged with a spatial position, those coordinates may have been used for the reference direction and the reference will point to the columns containing these coordinate values. The *de facto* OGIP convention, on the other hand, uses the keywords `RA_NOM` and `DEC_NOM` indicating a globally applied direction for the entire HDU.

Keywords The time reference direction is specified by the keyword

`TREFDIR` (string-valued)
Pointer to time reference direction

`TREFDIR` will apply to time coordinate axes in images as well. See Section 5.2.1 for an explanation.

In binary tables different columns may represent completely different Time Coordinate Frames. However, also in that situation the condition holds that each column can have only one Time Reference Direction. Hence, the following keyword may override `TREFDIR`:

`TRDIR`*n* (string-valued)

The value of the keyword shall consist of the name of the keyword or column containing the longitudinal coordinate, followed by a comma, followed by the name of the keyword or column containing the latitudinal coordinate. For the above quoted OGIP convention this would result in:
`TREFDIR= 'RA_NOM,DEC_NOM'`
For the example in Table 9:
`TRDIR20 = 'EventRA,EventDEC'`

4.2.5. Solar System Ephemeris

If applicable, the Solar System ephemeris used for calculating pathlength delays should be identified. This is particularly pertinent when the time scale is `TDB`.

The ephemerides that are currently in use are JPL's (JPL 2007a and 2007b):

- `DE200` (Standish 1990; considered obsolete, but still in use)
- `DE405` (Standish 1998; default)
- `DE421` (Folkner et al. 2008)

Future ephemerides will be accepted and recognized as they are released.

Keyword The Solar System ephemeris used for the data (if required) is indicated by the value of the keyword

`PLEPHEM` (string-valued)
Solar System ephemeris; default `DE405`

Historically, the name `PLEPHEM` referred to Planetary and Lunar Ephemeris; we continue the use of that keyword name.

4.3. Time Unit

The specification of the time unit allows the values defined in Paper I (2002) and the FITS Standard (Pence, et al., 2010), with the addition of the century. We recommend the following:

- `s`: second (default)
- `d`: day (= 86,400 s)
- `a`: (Julian) year (= 365.25 d)
- `cy`: (Julian) century (= 100 a)

The following values are also acceptable:

- `min`: minute (= 60 s)
- `h`: hour (= 3600 s)
- `yr`: (Julian) year (= `a` = 365.25 d)
- `ta`: tropical year
- `Ba`: Besselian year

The use of `ta` and `Ba` is not encouraged, but there are data and applications that require the use of tropical years or Besselian epochs (see Section 3.6). The length of the tropical year `ta` in days is (based on Simon, et al. 1994):

$$\begin{aligned} 1\ \mathrm{ta} = {} & 365.24219040211236 - 0.00000615251349\,T \\ & -6.0921\times10^{-10}\,T^2 + 2.6525\times10^{-10}\,T^3\ \mathrm{d} \end{aligned}$$

where T is in Julian centuries since J2000, using time scale TDB.

The length of the Besselian year `Ba` in days is:

$$1\ \mathrm{Ba} = 365.2421987817 - 0.00000785423\,T\ \mathrm{d}$$

where T is in Julian centuries since J1900, using time scale ET – although for these purposes the difference with TDB is negligible.

A cautionary note is in order here. The subject of tropical and Besselian years presents a particular quandary for the specification of standards. The expressions presented here specify how to calculate them for use in data files while creating these. However, that is pretty much a non-statement since such practice is strongly discouraged. Our purpose in providing the expressions is to guide the user in how to interpret existing data that are based on these units. But there is no guarantee that the authors of the data applied these particular definitions and there is ample evidence that many did not (see, e. g., Meeus & Savoie 1992). Therefore, all we can state here is that these are the most accurate available expressions for the units, but at the same time we strongly advise any user of existing data that contain them to pay special attention and attempt to ascertain what the data's authors really used.

Keywords The time unit is set by the keyword

`TIMEUNIT` (string-valued)
Time unit; default `s`

In relevant context, this may be overridden by (see Section 5 for details):

`CUNIT`*i* (string-valued)

`CUNIT`*ia* (string-valued)

`TCUNI`*n* (string-valued)

`TCUN`*na* (string-valued)

4.4. Assorted Items Affecting Time Data: Corrections, Errors, etc.

All quantities enumerated below will be expressed in the prevailing time units (`TIMEUNIT` or its local overrides), the default being `s`.

4.4.1. Time Offset

It is sometimes convenient to be able to apply a uniform clock correction in bulk by just putting that number in a single keyword. A second use for a time offset is to set a zero offset to a relative time series, allowing zero-relative times, or just higher precision, in the time stamps. Its default value is zero.

Its value is to be added to `MJDREF`, `JDREF`, or `DATEREF`, and hence affects the values of `TSTART`, `TSTOP`, and the time axis reference values (`CRVAL`*i*, c.s.), as well as any time pixel values in a binary table.

Keyword The time offset is set by:

`TIMEOFFS` (high-precision floating-valued)
Time offset; default 0.0

and has global validity for all times in the HDU. It has the same meaning as the keyword `TIMEZERO` in the OGIP convention – which we did not adopt out of concern for the potentially ambiguous meaning of the name. The net effect of this keyword is that the value of `TIMEOFFS` is to be added to the time stamp values in the file. Formally, this is effected by adding that value to `MJDREF`, `JDREF`, and/or `DATEREF`.

4.4.2. Absolute Error

The absolute time error is the equivalent of the systematic error defined in previous papers.

Keywords The absolute time error is set by:

`TIMSYER` (floating-valued)
Absolute time error

but may be overridden, in appropriate context (*e.g.,* time axes in image arrays or table columns), by (see Section 5 for details):

`CSYER` (floating-valued)

`CSYER`*ia* (floating-valued)

`TCSYE`*n* (floating-valued)

`TCSY`*na* (floating-valued)

4.4.3. Relative Error

The relative time error specifies accuracy of the time stamps relative to each other. This error will usually be much smaller than the absolute time error. This error is equivalent to the random error defined in previous papers.

Keywords The relative time error (the random error between time stamps) is set by:

`TIMRDER` (floating-valued)
Relative time error

but may be overridden, in appropriate context (*e.g.,* time axes in image arrays or table columns), by (see Section 5 for details):

`CRDER` (floating-valued)

`CRDER`*ia* (floating-valued)

`TCRDE`*n* (floating-valued)

`TCRD`*na* (floating-valued)

4.4.4. Time Resolution

The resolution of the time stamps is represented by a simple double. This may, for instance, be the size of the bins for time series data or the bit precision of the time stamp values.

Keyword The time resolution is global in the HDU, and set by the keyword

`TIMEDEL` (floating-valued)
Time resolution

in the units of `TIMEUNIT`.

4.4.5. Time Binning

When data are binned in time bins (or, as a special case, events are tagged with a time stamp of finite precision) it is important to know to which position in the bin (or pixel) that time stamp refers. This is an important issue: the FITS standard assumes that coordinate values correspond to the center of all pixels; yet, clock readings are effectively truncations, not rounded values, and therefore correspond to the lower bound of the pixel.

Keyword The relative position of the time stamp in each time bin (`TIMEDEL` in the case of an event list) or pixel (`CDELT` in the case of an image axis) is set universally in the HDU by the keyword:

`TIMEPIXR` (floating-valued)
Pixel position of the time stamp; from 0.0 to 1.0, default 0.5.

In conformance with the FITS pixel definition, the default is 0.5, although the value 0.0 may be more common in certain contexts. Note, for instance, that this is required when truncated clock readings are recorded, as is the case for almost all event lists. It seems unwise to allow this keyword to be specified separately for multiple time frames, rather than requiring its value to apply to all.

4.5. Durations

Durations shall not be expressed in ISO-8601 format, but only as actual durations (i.e., numerical values) in the units of the specified time unit.

There is an extensive collection of header keywords that indicate time durations, such as exposure times, but there are many pitfalls and subtleties that make this seemingly simple concept treacherous. One may encounter similar-sounding keywords for concepts like: awarded exposure time; scheduled exposure time; on-target time; duration of the exposure, including dead time and lost time; exposure time charged against the awarded exposure time; exposure time corrected for lost (bad) data; and exposure time corrected for dead time. Related to these are various keywords providing dead time correction factors, dead time correction flags, and duty cycle information, `TELAPSE`, as well as Good-Time-Interval (GTI) tables. We suggest that these are are excellent candidates for definition through an appropriate formally approved FITS convention, rather than inclusion in this standard.

We shall only define `XPOSURE` and `TELAPSE` in the present standard.

Keyword The only defined durations are indicated by the keywords:

`XPOSURE` (floating-valued)

in the units of `TIMEUNIT`. It shall be the effective exposure time for the data, corrected for dead time and lost time. If the HDU contains multiple time slices, it shall be the total accumulated exposure time over all slices. More obvious candidates for the keyword name (like `EXPOSURE`) had to be avoided since they have been used with conflicting definitions in various subcommunities.

`TELAPSE` (floating-valued)

also in the units of `TIMEUNIT` provides the amount of time elapsed between the start (`TSTART`, `MJD-BEG`, etc.) and the end (`TSTOP`, `DATE-END`, etc.) of the observation or data stream.

4.6. Good Time Interval (GTI) Tables

Good-Time-Interval (GTI) tables are indispensable for data with "holes" in them, especially photon event files, as they allow one to discriminate between "no data received" *versus* "no data taken". GTI tables contain two mandatory columns, `START` and `STOP`, and one optional column, `WEIGHT`. The first two define the interval, the third, with a value from 0 to 1, the quality of the interval; *i.e.*, a weight of 0 indicates a *Bad*-Time-Interval. `WEIGHT` has a default value of 1. Any time interval not covered in the table shall be considered to have a weight of zero.

5. Usage Contexts

Before getting to specific usage context, we need to make a few general comments.

First, we should point out that the distortion conventions described in Paper IV (2004) are also very much applicable to the time coordinate axis. The keywords that are discussed in the following in detail are summarized in Table 5.

Second, the globally applicable keywords like `TIMESYS`, `MJDREF` et al., `TIMEUNIT`, etc., provide default values for the corresponding `C*` and `TC*` keywords im images and tables with `CTYPE` or `TTYPE` set to `TIME`. Furthermore, with the exception of `TIMESYS` itself, they provide defaults for all axis and column specifications (including alternate coordinate definitions) that use a time scale listed in Table 2. Any alternate coordinate specified in a non-recognized time scale assumes the value of the axis pixels or the column cells, optionally modified by applicable scaling and/or reference value keywords.

Finally, we have observed that there is a confusing variation in the labeling of time axes in figures and presentations. In particular, the usage of terms like "TJD", "HJD", and "BJD" is highly ambiguous. Julian and Modified Julian Date counts do not imply any particular time scale or any particular reference position. The "B" in "BJD" raises the question whether it refers to the reference position `BARYCENTER` or the time scale `TDB`. And an expression like "BJD−2400000" leaves the reader in doubt whether the value is to be taken literally or whether the author really meant "BJD−2400000.5". We strongly recommend that authors be explicit about the times that are posted and adopt the following convention for axis labeling:

`JD|MJD(<timescale>;<reference position>`

In order to facilitate the correct labeling we suggest that these strings be provided in the `CNAME*` and `TCNA*` keywords if possible; for instance:

`TCNAM1 = 'MJD(TDB;Barycenter)'`

Also, see the examples of `TCNA1E` and `TCNA1F` in Table 9.

5.1. Header Keywords

The rules governing these keywords are elaborated on in Section 4 and summarized in Table 5.

5.2. Time Axis in Images

Example 1 (Table 6) is a data cube in which the 3^{rd} axis is time. It is in fact a sequence of 2-D images stacked together.

The rules governing keywords defining the time axis in an image (which could be a one-dimensional time series or a multidimensional space-time-spectral hypercube) are also largely being dealt with in Section 4 and summarized in Table 5, but there are some aspects that require further elaboration as presented in the following sub-sections.

5.2.1. Restrictions

An image will have at most one time axis as identified by having the `CTYPE`*i* value of `TIME` or one of the values listed in Table 2. Consequently, as long as the axis is identified through `CTYPE`*i*, there is no need to have axis number identification on the global time-related keywords. In addition, we expressly prohibit the specification of multiple time reference positions on this axis for alternate time coordinate frames, since this would give rise to complicated model-dependent non-linear relations between these frames. Hence, time scales `TDB` and `TCB` (or `ET`, to its precision) may be specified in the same image, but cannot be combined with any of the first nine time scales in Table 2; those first nine can be expressed as linear transformations of each other, too, provided the reference position remains unchanged. Time scale `LOCAL` is by itself, intended for simulations, and should not be mixed with any of the others.

5.2.2. `CDELT`*ia*, `CD`*i_ja* and `PC`*i_ja*

If the image does not use a matrix for scaling, rotation and shear (Paper I, 2002), `CDELT`*ia* provides the numeric value for the time interval.

If the `PC` form of scaling, rotation and shear (Paper I, 2002) is used, `CDELT`*ia* provides the numeric value for the time interval, and `PC`*i_j*, where $i = j$ = the index of the time axis (in the typical case of an image cube with axis 3 being time, $i = j = 3$) would take the exact value 1, the default (Paper I, 2002).

When the `CD`*i_j* form of mapping is used, `CD`*i_j* provides the numeric value for the time interval.

If one of the axes is time and the matrix form is used, then the treatment of the `PC`*i_ja* (or `CD`*i_ja*) matrices involves at least a Minkowsky metric and Lorentz transformations (as contrasted with Euclidean and Galilean). See Soffel et al. (2003) for a full review of the IAU resolutions concerning space-time coordinate transformations.

As an example we present a header in Table 7 (Example 2) that describes a SOHO Coronal Diagnostic Spectrometer observation from October 1998 (Harris, et al. 1992): a linear slit moves across the field from right to left during the observation, so different parts (columns) of the image are observed at different times. The example header defines the relations between the different coordinate systems by specifying a degenerate Time axis that is related to the first spatial pixel axis through a `PC`*i_j* matrix; the non-diagonal spatial elements are not zero since the detector was not aligned to solar north.

An alternative approach would be to define the Time axis as `CTYPE`2A tieing it directly to the almost-longitude pixel coordinate.

If we align the image to solar north, the header changes to what is shown in Example 3 (Table 8). One could still use the alternative description of Time as an alternate axis on longitude, but in that case it would need its own `PC`2_*jA* matrix.

5.2.3. `CRVAL`*ia*

The WCS standard requires this keyword to be numeric and cannot be expressed in ISO-8601 format. Therefore, `CRVAL`*ia* is required to contain the elapsed time in units of `TIMEUNIT` or `CUNIT`*ia*, even if the zero point of time is specified by `DATEREF`.

5.3. Time Columns in Tables

Example 4 (Table 9) is part of the header of an event list (a binary table in pixel list mode) with two time columns. Column 1 carries time in TT, with alternate time coordinate frames in UTC, TCG, Mission Elapsed Time, Observation Elapsed Time, MJD, and JD. Column 20 contains the time stamps in TDB with alternate frames in TCB and Julian epoch; columns 21 and 22 provide the events' positions.

The rules governing keywords defining the time in table columns (pixel as well as vector columns) are largely being dealt with in Section 4 and summarized in Table 5, but, again, there are some aspects that require further elaboration.

All times (other than ISO-8601), expressed in a recognized time scale (see Table 2), are relative (to `MJDREF`, `JDREF` or `DATEREF`). That means that they are elapsed times and that users have to take care of leap seconds when using UTC; the unit '`d`' is defined as 86400 elapsed seconds. But beware of the following: the reference time values are to be taken in the time scale specified for the coordinate one is dealing with. That is why the `TCRV1A` in the Table 9 needs to account for the difference between `MJDREF`(TT) and `MJDREF`(UTC).

Times that are expressed in any other time scale (e.g., Mission Elapsed Time, a common scale) take the values in the table cells at face value, though they may be modified by applicable keywords such as `TCRP*`, `TCRV*`, and `TCD*`.

In the context of tables the most important point to keep in mind is that `TCTYP`*n* and/or `TCTY`*na* contain the time scale. However, it should also be pointed out that a binary table column with `TTYPE`*n* = `'TIME'` and either lacking any `TC*`*n* keywords or with `TC*`*n* = `'TIME'` will be controlled by the global keywords listed in Table 5. This is a common convention in existing files that will still be compliant with the present standard.

The keywords `JEPOCH` and `BEPOCH`, of course, may also be turned into table columns. However, one should be mindful that they are implicitly tied to specific time scales and represent absolute times. Consequently, they have no association with any of the global keywords.

5.3.1. Restrictions

The same restrictions imposed on the image time axis (see Section 5.2.1) also apply to individual table columns. However, since one can have more than one column with time information in the same table, it is possible to mix different time reference positions and time scales that are not linearly related to each other – provided that one does not mix these in the same column.

5.4. Time in Random Groups

There are two ways in which time can enter into random group data (see Greisen & Harten 1981): as one of the subarray axes or through a group parameter. In the former case the situation is identical to that in images and we refer to Section 5.2 for the rules. If time is to be transmitted through a group parameter, it simply means that the

`PTYPE`*i* (string-valued)

keyword needs to be set to one of the time scale codes from Table 2, just like the `CTYPE`*i*. All the global time reference frame keywords (see Table 5) apply, just as they would if `CTYPE`*i* were set to the same time scale value, except that there is no possibility of override since the `PUNIT`*i*, `PSYER`*i*, and `PRDER`*i* keywords are not defined in the standard.

5.5. Time-related Coordinate Axes

There are a few coordinate axes that are related to time and that are accommodated in this standard: (temporal) Phase, Timelag, and Frequency. Phase results from folding a time series on a given period. Timelag is the coordinate of cross- and auto-correlation spectra. As a practical definition one may consider Frequency as the Fourier transform equivalent of time and, particularly, the coordinate axis of power spectra (as distinct from the spectroscopic frequency axis described in Greisen et al., 2006). A more formal definition of Frequency allows its use as the coordinate axis of any dependent variable with the exception of the electro-magnetic field; that specific case is covered by Greisen et al. (2006).

These coordinate axes may be specified by giving the keywords:
`CTYPE`*i*, `CTYPE`*ia*, `TCTYP`*n*, or `TCTY`*na*
one of the values:
`PHASE`, `TIMELAG`, `FREQUENCY`
Timelag's units are the regular time units and Frequency's basic unit is `Hz`. Neither of these two coordinates is a linear or scaled transformation of Time and therefore cannot appear in parallel with Time. Phrased differently, a given vector of values for an observable can be paired with a vector of Time, or Timelag, or Frequency, but not with more than one of these; the three coordinates are orthogonal.

Phase, on the other hand, can appear in parallel with Time. Its units may be `deg`, `rad`, or it may be unitless, in which case Phase shall be expressed in `turns`. The zero-phase point of a Phase axis may be specified through one of the keywords:
`CZPHS`*i*, `CZPHS`*ia*, `TCZPH`*n*, `TCZP`*na*
setting the time at which Phase=0 occurred.
The period may be set by:
`CPERI`*i*, `CPERI`*ia*, `TCPER`*n*, `TCPR`*na*
but this can only be used if the period is a constant. When that is not the case, the period should either be absent or set to zero, and one should follow a convention like PSRFITS[4] (see also Hotan et al., 2004, and Hobbs et al., 2006).

We provide an simple example of a binary table with one time and two phase columns in Example 5 (see Table 10).

6. Concluding Remarks on Precision

The following comments summarise some salient points that may otherwise go unnoticed.

Times have special requirements when it comes to precision and, hence, data types. We anticipate at some time in the future that one or two new data types may be added to the FITS standard that will address this requirement. In the meantime, we recommend that relative elapsed times may be expressed as `2D`, but require that the first element of the `2D` doublet vector contain the integer part, the second the fractional part of time. This is, in a way, an unfortunate bandaid, but not unprecedented, since the device is used in various ephemeris and timing packages.

There is no precision problem with time-related keywords, as they may contain as many digits as necessary. However, users should take special care in reading these values and not simply assume that "a double is good enough".

Times are relative (to `MJDREF`, `JDREF` or `DATEREF`), except when they are expressed as an ISO-8601 *datetime* string.

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Table 5. Keywords for Specifying Time Coordinates

Keyword Description	Section	Header Only	Images		Table Pixel Columns		Table Vector Columns	
			Single	Multiple	Primary	Alternate	Primary	Alternate
Informational Keywords (data)								
Date of HDU creation[a]	4.1	`DATE`						
Date/time of observation	4.1	`DATE-OBS`						
		`MJD-OBS`						
Effective date/time of observation	4.1	`DATE-AVG`						
		`MJD-AVG`						
Start date/time of observation	4.1	`DATE-BEG`						
		`MJD-BEG`						
		`TSTART`						
End date/time of observation	4.1	`DATE-END`						
		`MJD-END`						
		`TSTOP`						
Net exposure time	4.5	`XPOSURE`						
Wall clock exposure time	4.5	`TELAPSE`						
Global Time Reference Frame Keywords (metadata)								
Time scale	4.2.1	`TIMESYS`						
Zero point in MJD	4.2.3	`MJDREF`[b]						
Zero point in JD	4.2.3	`JDREF`[b]						
Zero point in ISO-8601	4.2.3	`DATEREF`						
Reference position	4.2.2	`TREFPOS`						
Reference direction	4.2.4	`TREFDIR`						
Solar System ephemeris	4.2.5	`PLEPHEM`						
Time unit	4.3	`TIMEUNIT`						
Time resolution	4.4.4	`TIMEDEL`						
Time offset	4.4.1	`TIMEOFFS`						
Time location in pixel	4.4.5	`TIMEPIXR`						
Absolute Error	4.4.2	`TIMSYER`						
Relative Error	4.4.3	`TIMRDER`						
Optional Context-Specific Override Keywords for Metadata								
Time scale[c]	4.2.1	`TIMESYS`	`CTYPE`*i*	`CTYPE`*ia*	`TCTYP`*n*	`TCTY`*na*	*i*`CTYP`*n*	*i*`CTY`*na*
Reference position	4.2.2	`TREFPOS`			`TRPOS`*n*		`TRPOS`*n*	
Reference direction	4.2.4	`TREFDIR`			`TRDIR`*n*		`TRDIR`*n*	
Time unit	4.3	`TIMEUNIT`	`CUNIT`*i*	`CUNIT`*ia*	`TCUNI`*n*	`TCUN`*na*	*i*`CUNI`*n*	*i*`CUN`*na*
Absolute Error	4.4.2	`TIMSYER`	`CSYER`*i*	`CSYER`*ia*	`TCSYE`*n*	`TCSY`*na*	*i*`CSYE`*n*	*i*`CSY`*na*
Relative Error	4.4.3	`TIMRDER`	`CRDER`*i*	`CRDER`*ia*	`TCRDE`*n*	`TCRD`*na*	*i*`CRDE`*n*	*i*`CRD`*na*
Context-Specific Keywords for Metadata								
Time axis name	5.2		`CNAME`*i*	`CNAME`*ia*	`TCNAM`*n*	`TCNA`*na*	*i*`CNAM`*n*	*i*`CNA`*na*
Time axis reference pixel	5.2		`CRPIX`*i*	`CRPIX`*ia*	`TCRPX`*n*	`TCRP`*na*	*i*`CRPX`*n*	*i*`CRP`*na*
Time axis reference value	5.2		`CRVAL`*i*	`CRVAL`*ia*	`TCRVL`*n*	`TCRV`*na*	*i*`CRVL`*n*	*i*`CRV`*na*
Time scaling	5.2.2		`CDELT`*i*	`CDELT`*ia*	`TCDLT`*n*	`TCDE`*na*	*i*`CDLT`*n*	*i*`CDE`*na*
Period for temporal phase[d]	5.5		`CPERI`*i*	`CPERI`*ia*	`TCPER`*n*	`TCPR`*na*	*i*`CPER`*n*	*i*`CPR`*na*
Zero phase time[d]	5.5		`CZPHS`*i*	`CZPHS`*ia*	`TCZPH`*n*	`TC0`_*P*na	*i*`CZPH`*n*	*i*`CZP`*na*
Transformation matrix	5.2.2		`CD`*i_j*	`CD`*i_ja*	`TC`*n_ka*		*ij*`CD`*na*	
Transformation matrix	5.2.2		`PC`*i_j*	`PC`*i_ja*	`TP`*n_ka*		*ij*`PC`*na*	

[a] In UTC if the file is constructed on the Earth's surface

[b] These keywords maybe split into an integer (`MJDREFI` or `JDREFI`) and fractional (`MJDREFF` or `JDREFF`) part

[c] The values `PHASE`, `TIMELAG`, and `FREQUENCY` may be used to introduce these specific time-related coordinate axes (see Section 5.5)

[d] Optional; only for use with coordinate type `PHASE`

Table 6. Example 1: Cube with two spatial & one time axis

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

SIMPLE  =                    T / Fits standard
BITPIX  =                  -32 / Bits per pixel
NAXIS   =                    3 / Number of axes
NAXIS1  =                 2048 / Axis length
NAXIS2  =                 2048 / Axis length
NAXIS3  =                   11 / Axis length
DATE    = '2008-10-28T14:39:06' / Date FITS file was generated
OBJECT  = '2008 TC3'           / Name of the object observed
EXPTIME =               1.0011 / Integration time
MJD-OBS =       54746.02749237 / Obs start
DATE-OBS= '2008-10-07T00:39:35.3342'    / Observing date
TELESCOP= 'VISTA   '           / ESO Telescope Name
INSTRUME= 'VIRCAM  '           / Instrument used.
TIMESYS = 'UTC     '           / From Observatory Time System
TREFPOS = 'TOPOCENT'           / Topocentric
MJDREF  =              54746.0 / Time reference point in MJD
RADESYS = 'ICRS    '           / Not equinoctal
CTYPE2  = 'RA---ZPN'           / Zenithal Polynomial Projection
CRVAL2  =     2.01824372640628 / RA at ref pixel
CUNIT2  = 'deg     '           / Angles are degrees always
CRPIX2  =               2956.6 / Pixel coordinate at ref point
CTYPE1  = 'DEC--ZPN'           / Zenithal Polynomial Projection
CRVAL1  =     14.8289418840003 / Dec at ref pixel
CUNIT1  = 'deg     '           / Angles are degrees always
CRPIX1  =               -448.2 / Pixel coordinate at ref point
CTYPE3  = 'UTC     '           / linear time (UTC)
CRVAL3  =             2375.341 / Relative time of first frame
CUNIT3  = 's       '           / Time unit
CRPIX3  =                  1.0 / Pixel coordinate at ref point
CTYPE3A = 'TT      '           / alternative linear time (TT)
CRVAL3A =             2440.525 / Relative time of first frame
CUNIT3A = 's       '           / Time unit
CRPIX3A =                  1.0 / Pixel coordinate at ref point
OBSGEO-B=             -24.6157 / [deg] Tel geodetic latitute (=North)+
OBSGEO-L=             -70.3976 / [deg] Tel geodetic longitude (=East)+
OBSGEO-H=            2530.0000 / [m]   Tel height above reference ellipsoid
CRDER3  =               0.0819 / random error in timings from fit
CSYER3  =               0.0100 / absolute time error
PC1_1   =     0.999999971570892 / WCS transform matrix element
PC1_2   =     0.000238449608932 / WCS transform matrix element
PC2_1   =    -0.000621542859395 / WCS transform matrix element
PC2_2   =     0.999999806842218 / WCS transform matrix element
CDELT1  =  -9.48575432499806E-5 / Axis scale at reference point
CDELT2  =   9.48683176211164E-5 / Axis scale at reference point
CDELT3  =               13.3629 / Axis scale at reference point
PV1_1   =                   1. / ZPN linear term
PV1_3   =                  42. / ZPN cubic term
END
```

Table 7. Example 2: Header extract of an image where Time is entangled with Space

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

SIMPLE  =                    T /Written by IDL:  Fri Sep 25 14:01:44 2009
BITPIX  =                  -32 /Real*4 (floating point)
NAXIS   =                    4 /
NAXIS1  =                   20 / Wavelength
NAXIS2  =                  120 / Detector X
NAXIS3  =                  143 / Detector Y
NAXIS4  =                    1 / Time (degenerate)
DATE    = ’2009-09-25’         /
BUNIT   = ’erg/cm^2/s/sr/Angstrom’ /
DATE-OBS= ’1998-10-25T16:59:41.823’ /
DATEREF = ’1998-10-25T16:59:41.823’ /
TIMESYS = ’UTC     ’           / We will use UTC
CTYPE1  = ’WAVE    ’           /
CUNIT1  = ’Angstrom’           /
CRPIX1  =              10.5000 /
CRVAL1  =              629.682 /
CDELT1  =           0.11755400 /
CTYPE2  = ’HPLN-TAN’           /
CUNIT2  = ’arcsec  ’           /
CRPIX2  =              60.5000 /
CRVAL2  =              897.370 /
CDELT2  =            2.0320000 /
CTYPE3  = ’HPLT-TAN’           /
CUNIT3  = ’arcsec  ’           /
CRPIX3  =              72.0000 /
CRVAL3  =             -508.697 /
CDELT3  =            1.6800000 /
CTYPE4  = ’TIME    ’           / Might also have been ’UTC’
CUNIT4  = ’s       ’           /
CRPIX4  =              1.00000 /
CRVAL4  =              3147.84 /
CDELT4  =            6344.8602 /
PC1_1   =              1.00000 /
PC1_2   =              0.00000 /
PC1_3   =              0.00000 /
PC1_4   =              0.00000 /
PC2_1   =          -0.00128426 /
PC2_2   =             0.987269 /
PC2_3   =             0.131508 /
PC2_4   =              0.00000 /
PC3_1   =          -0.00964133 /
PC3_2   =            -0.192389 /
PC3_3   =             0.987269 /
PC3_4   =              0.00000 /
PC4_1   =              0.00000 /
PC4_2   =          -0.00832947 /
PC4_3   =              0.00000 /
PC4_4   =              1.00000 /
END
```

Table 8. Example 3: Header extract of an image where Time is entangled with Space needing a PC matrix

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

SIMPLE  =                    T /Written by IDL:  Fri Sep 25 14:01:44 2009
BITPIX  =                  -32 /Real*4 (floating point)
NAXIS   =                    4 /
NAXIS1  =                   20 / Wavelength
NAXIS2  =                  120 / Longitude
NAXIS3  =                  143 / Latitude
NAXIS4  =                    1 / Time (degenerate)
DATE    = '2009-09-25'         /
BUNIT   = 'erg/cm^2/s/sr/Angstrom' /
DATE-OBS= '1998-10-25T16:59:41.823' /
DATEREF = '1998-10-25T16:59:41.823' /
TIMESYS = 'UTC     '           / We will use UTC
CTYPE1  = 'WAVE    '           /
CUNIT1  = 'Angstrom'           /
CRPIX1  =              10.5000 /
CRVAL1  =              629.682 /
CDELT1  =           0.11755400 /
CTYPE2  = 'HPLN-TAN'           /
CUNIT2  = 'arcsec  '           /
CRPIX2  =              60.5000 /
CRVAL2  =              897.370 /
CDELT2  =            2.0320000 /
CTYPE3  = 'HPLT-TAN'           /
CUNIT3  = 'arcsec  '           /
CRPIX3  =              72.0000 /
CRVAL3  =             -508.697 /
CDELT3  =            1.6800000 /
CTYPE4  = 'TIME    '           / Might also have been 'UTC'
CUNIT4  = 's       '           /
CRPIX4  =              1.00000 /
CRVAL4  =              3147.84 /
CDELT4  =            6344.8602 /
PC1_1   =              1.00000 /
PC1_2   =              0.00000 /
PC1_3   =              0.00000 /
PC1_4   =              0.00000 /
PC2_1   =          -0.00128426 /
PC2_2   =             1.000000 /
PC2_3   =          3.50908E-05 /
PC2_4   =              0.00000 /
PC3_1   =          -0.00964133 /
PC3_2   =         -5.13000E-05 /
PC3_3   =             1.000000 /
PC3_4   =              0.00000 /
PC4_1   =              0.00000 /
PC4_2   =          -0.00822348 /
PC4_3   =           0.00109510 /
PC4_4   =              1.00000 /
END
```

Table 9. Example 4: Header extract of a binary table (event list) with two time columns

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

COMMENT      ----------  Globally valid key words  ----------------
TIMESYS = 'TT      '           / Time system   REPEATED FOR CLARITY    ###
MJDREF  =  50814.000000000000  / MJD zero point for (native) TT        ###
MJD-BEG =  53516.157939301     / MJD start time in  (native) TT        ###
MJD-END =  53516.357939301     / MJD stop  time in  (native) TT        ###
MJD-OBS =  53516.257939301     / MJD for observation in (native) TT    ###
MJD-AVG =  53516.257939301     / MJD at mid-observation in (native) TT ###
TSTART  =  233466445.95561     / Start time in MET                     ###
TSTOP   =  233468097.95561     / Stop time in MET                      ###
TELAPSE =  1652.0              / Wall clock exposure time              ###
XPOSURE =  1648.0              / Net exposure time                     ###
TIMEPIXR=  0.5000000000000     / default                               ###
TIMEDEL =  3.2410400000000     / timedel Lev1 (in seconds)             ###
TREFPOS = 'TOPOCENT'           / Time is measured at the telescope
PLEPHEM = 'DE405   '           / SS ephemeris that is used
TIMRDER =  1.0000000000000E-09 / Relative error
TIMSYER =  5.0000000000000E-05 / Absolute error
OBSORBIT= 'orbitf315230701N001_eph1.fits' / Orbit ephemeris file
RADESYS = 'ICRS    '           / Spatial reference system

COMMENT      ----------  First Time Column  -----------------------
TTYPE1  = 'Time    '           / S/C TT corresponding to mid-exposure  ###
TFORM1  = '2D      '           / format of field                       ###
TUNIT1  = 's       '                                                   ###
TCTYP1  = 'TT      '
TCNA1   = 'Terrestrial Time'   / This is TT
TCUNI1  = 's       '
TCRPX1  = 0.0                  / MJDREF is the true zero point for TIME-TT ...
TCRVL1  = 0.0                  / ...and relative time is zero there
TCDLT1  = 1.0                  / 1 s is 1 s
TCRD1   =  1.0000000000000E-09 / Relative error
TCSY1   =  5.0000000000000E-05 / Absolute error

TCTY1A  = 'UTC     '           / UTC  ELAPSED seconds since MJDREF
TCNA1A  = 'Coordinated Universal Time' / This is UTC
TCUN1A  = 's       '
TCRP1A  = 0.0
TCRV1A  = 63.184
TCDE1A  = 1.0

TCTY1B  = 'TCG     '           / TCG
TCNA1B  = 'Geocentric Coordinate Time' / This is TCG
TCUN1B  = 's       '           / still in seconds
TCRP1B  = 0.0                  / MJDREF is the reference point
TCRV1B  = 0.46184647           / But TCG is already ahead of TT at MJDREF
TCDE1B  = 1.0000000006969290   / And it keeps running faster

TCTY1C  = 'MET     '           / Mission Elapsed Time
TCNA1C  = 'Mission Elapsed Time' / This is MET

TCTY1D  = 'OET     '           / Observation Elapsed Time
TCNA1D  = 'Observation Elapsed Time' / This is OET
TCRV1D  = 0.0                  / Reference pixel: 0 is at: ...
TCRP1D  =  233466445.95561     / ... start time in MET
```

Table 9 (cont'd)

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

TCTY1E  = 'MJD     '           / For listing MJD
TCNA1E  = 'MJD(TT;Topocenter)' / This allows a properly labeled MJD axis
TCUN1E  = 's       '           / Now in days
TCRP1E  = 0.0                  / MET 0 is the reference point
TCRV1E  = 50814.0              / Not surprising, that is MJDREF
TCDE1E  = 1.157407407407e-05   / = 1/86400

TCTY1F  = 'JD     '            / For listing JD
TCNA1F  = 'JD(TT;Topocenter)'  / This allows a properly labeled JD axis
TCUN1F  = 's       '           / Now in days
TCRP1F  = 0.0                  / MET 0 is the reference point
TCRV1F  = 2450814.5            / Not surprising, that is JDREF
TCDE1F  = 1.157407407407e-05   / = 1/86400

COMMENT      ----------  Second Time Column  ----------------------
TTYPE20 = 'Barytime'           / S/C TDB corresponding to mid-exposure
TFORM20 = '2D      '           / format of field
TUNIT20 = 's       '
TCTYP20 = 'TDB     '
TRPOS20 = 'BARYCENT'           / Time is measured at the Barycenter
TRDIR20 = 'EventRA,EventDEC'   / Reference direction is found in cols 21 and 22
TCNA20  = 'Barycentric Dynamical Time' / This is TDB
TCUNI20 = 's       '
TCRPX20 = 0.0                  / MJDREF is the true zero point for Barytime ...
TCRVL20 = 0.0                  / ...and relative time is zero there
TCDLT20 = 1.0                  / 1 s is 1 s
TCRD20  =  1.0000000000000E-09 / Relative error
TCSY20  =  5.0000000000000E-05 / Absolute error

TCTY20C = 'TCB     '           / TCB
TCNA20C = 'Barycentric Coordinate Time' / This is TCB
TCUN20C = 's       '           / still in seconds
TCRP20C = 0.0                  / MJDREF is the reference point
TCRV20C = 10.27517360          / But TCB is already ahead of TDB at MJDREF
TCDE20C = 1.00000001550520     / And it keeps running faster

TCTY20G = 'JEPOCH  '           / JEPOCH
TCNA20G = 'Julian Epoch'       / This is a proper Julian epoch
TCUN20G = 'a       '           / now in Julian years
TCRP20G = 63115200             / 2000-01-01T12:00:00 in MET seconds
TCRV20G = 2000.0               / J2000.0
TCDE20G = 3.16880878141E-08    / Convert seconds to Julian years

COMMENT      ----------  RA and Dec of each photon event  ---------
TTYPE21 = 'EventRA '           / RA of photon event
TFORM21 = 'D       '           / format of field
TUNIT21 = 'deg     '
TTYPE22 = 'EventDEC'           / Dec of photon event
TFORM22 = 'D       '           / format of field
TUNIT22 = 'deg     '

END
```

Table 10. Example 5: Header extract of a binary table with two phase columns

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

COMMENT      ----------  Globally valid key words  ----------------
TIMESYS = ’TT      ’           / Time system   REPEATED FOR CLARITY    ###
MJDREFI =  53516               / MJD zero point for TT (integer part)  ###
MJDREFF =      0.157939301     / MJD zero point for TT (fractional part) ###
MJD-BEG =  53516.157939301     / MJD start time in  (native) TT        ###
MJD-END =  53516.357939301     / MJD stop  time in  (native) TT        ###
MJD-OBS =  53516.257939301     / MJD for observation in (native) TT    ###
MJD-AVG =  53516.257939301     / MJD at mid-observation in (native) TT ###
TSTART  =  0.0                 / Start time in MET                     ###
TSTOP   =  1652.0              / Stop time in MET                      ###
TELAPSE =  1652.0              / Wall clock exposure time              ###
TREFPOS = ’TOPOCENT’           / Time is measured at the telescope
PLEPHEM = ’DE405   ’           / SS ephemeris that is used
TIMRDER =  1.0000000000000E-09 / Relative error
TIMSYER =  5.0000000000000E-05 / Absolute error
OBSORBIT= ’orbitf315230701N001_eph1.fits’ / Orbit ephemeris file

COMMENT      ---------- Time Column  ------------------------------
TTYPE1  = ’Time    ’           / S/C TT                                ###
TFORM1  = ’D       ’           / format of field                       ###
TUNIT1  = ’s       ’                                                   ###
TCTYP1  = ’TT      ’
TCNA1   = ’Terrestrial Time’   / This is TT
TCUNI1  = ’s       ’
TCRPX1  = 0.0                 / MJDREF is the true zero point for TIME-TT ...
TCRVL1  = 0.0                 / ...and relative time is zero there
TCDLT1  = 1.0                 / 1 s is 1 s

COMMENT      ----------  First Phase Column  ----------------------
TTYPE2  = ’Phase_1 ’           / Phase of feature 1
TFORM2  = ’D       ’           / format of field
TUNIT2  = ’s       ’
TCTYP2  = ’PHASE   ’
TCNA2   = ’Phase of Feature 1’ / Just a name
TCZPH2  = 0.0                 / Phase=0 occurs at MJDREF[IF]
TCPER2  = 1652.0              / The period for this phase column

COMMENT      ----------  Second Phase Column  ---------------------
TTYPE3  = ’Phase_2 ’           / Phase of feature 2
TFORM3  = ’D       ’           / format of field
TUNIT3  = ’s       ’
TCTYP3  = ’PHASE   ’
TCNA3   = ’Phase of Feature 2’ / Just a name
TCZPH3  = 826.0               / Phase=0 occurs at this offset from MJDREF[IF]
TCPER3  = 3304.0              / The period for this phase column

COMMENT      ----------  Observable  ------------------------------
TTYPE4  = ’Observable’         / Some random quantity
TFORM4  = ’D       ’           / format of field
END
```

Table 10 (cont'd)

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789
=======================  Data =====================================

Row     Time       Phase_1   Phase_2   Observable
-------------------------------------------------
  1       0.0        0.0      0.75        10.0
  2     165.2        0.1      0.80        20.0
  3     330.4        0.2      0.85        40.0
  4     495.6        0.3      0.90        80.0
  5     660.8        0.4      0.95        70.0
  6     826.0        0.5      0.00        60.0
  7     991.2        0.6      1.05        50.0
  8    1156.4        0.7      1.10        40.0
  9    1321.6        0.8      1.15        30.0
 10    1486.8        0.9      1.20        20.0
 11    1652.0        1.0      1.25        10.0

End of data
```

Appendix A: Time Scales

If one is dealing with high-precision timing, there are more subtle issues associated with the various time scales that should be considered. This Appendix provides the necessary information that supplements Section 4.2.1 and Table 2. It also provides some background information on how some of the time scales are realized and how they relate to each other.

A.1. TT and TDT

TT is defined by Resolution B1.9 of the 24th General Assembly of the IAU in 2000 at Manchester (IAU, 2000[5]). This is a redefinition of TT as originally defined by Recommendation IV of Resolution A4 of the XXIst General Assembly of the IAU in 1991 at Buenos Aires (IAU, 1991[6]). By that resolution TT was recognized as a better-defined replacement for TDT.

The initial definition of TT was explained by Seidelmann & Fukushima (1992). For explanation of the redefinition see Petit in IERS Technical Note 29[7].

Due to the rotation of the Earth (and motion of other bodies), a point on the surface changes its depth in the gravitational potential of the solar system. As noted in Soffel et al. 2003, the proper time experienced by chronometers on the surface of Earth differs from TT with a diurnal variation at the picosecond level.

Because TDT never had a satisfactory definition its meaning is ambiguous at microsecond precision. For most uses other than historical tabulation it is more practical to express such time stamps as TT.

A.2. TCG and TCB

TCG and TCB are defined by Recommendation III of Resolution A4 of the XXIst General Assembly of the IAU in 1991 at Buenos Aires (IAU, 1991[8]). Note 4 suggests that precise use of these time scales requires specification of both the realized time scale (i.e., TAI) and the theory used to transform from the realized time scale to the coordinate time scale. All of the references given above for TT are also relevant for TCG and TCB.

Given that TT and TCG differ only by a constant rate, a precise value of TCG is specified by documenting the realization of TT. Thus we suggest that TCG(TAI) be shorthand for TCG computed from TT = TAI + 32.184 s or, alternatively, TCG(TT(TAI)). Likewise, we suggest that TCG(BIPMnn) be shorthand for TCG(TT(BIPMnn)).

Specifying a precise value for TCB requires documenting a precise value of TT and additionally a time ephemeris. A current example of a time ephemeris is TE405 given by Irwin & Fukushima (1999).

It is not immediately clear to us how best to express this in a concise value for the FITS keyword, for there is no guarantee of a controlled vocabulary for the time ephemerides: nothing prevents other authors from producing another time ephemeris based on DE405. However we may proceed on the assumption that the differences between any two time ephemerides will be incon-

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[5] http://www.iau.org/static/resolutions/IAU2000_French.pdf

[6] http://www.iau.org/static/resolutions/IAU1991_French.pdf

[7] http://www.iers.org/nn_11216/SharedDocs/Publikationen/EN/IERS/Publications/tn/TechnNote29/tn29__019,templateId=raw,property=publicationFile.pdf/tn29_019.pdf

[8] http://www.iau.org/static/resolutions/IAU1991_French.pdf

sequentially small. Consequently, we suggest that TCB(BIPMnn,TE405) be shorthand for TCB computed from TT(BIPMnn) and TE405.

A.3. TDB

TDB is defined by Resolution B3 of the XXVIth General Assembly of the IAU in 2006 at Prague (IAU, 2006[9]). This definition is required for microsecond precision.

A.4. ET

ET was defined by Clemence (1948), named by Resolution 6 of the 1950 Conference on the Fundamental Constants of Astronomy held at CNRS in Paris, and adopted by a recommendation from IAU Commission 4 during the VIIIth General Assembly in 1952 at Rome. The definition of ET is based on the works of Newcomb Tables of the Sun, Astr. Papers Amer. Ephemeris 6, 1895 and Brown Tables of the Motion of the Moon, 1919 At the IAU General Assemblies in 1961 and 1967 Commission 4 designated three improvements on ET named ET0, ET1, and ET2.

Because ET is nonrelativistic its meaning is ambiguous at millisecond precision. For most uses other than historical tabulation it is more practical to express such time stamps as TT or TDB. For the purposes of historical tabulation we might want to recommend the use of ’ET(ET0)’, ’ET(ET1)’, and ’ET(ET2)’.

A.5. TAI

TAI is defined by BIPM[10].

Thus TAI is intended to be the best possible realization of TT, which means its aim is to be a geocentric coordinate time scale. Because of deficiencies in the realization, TAI is only approximately equal to TT − 32.184 s

TAI is a special case of the atomic time scales because the only valid realization is the one in Circular T which is published in arrears by the BIPM. As such a FITS keyword value of ’TAI’ should only be used for timestamps which have been reduced using a chain of chronometers traceable through Circular T. TAI should not be used casually. For example, there are GPS devices which provide time stamps that claim to be TAI.

TAI should be avoided prior to 1972 because:

- TAI had not been authorized until the 14th CGPM in late 1971[11]
- TAI had not been available for any contemporary time stamping mechanisms prior to 1972-01-01

TAI should be used with caution prior to 1977 because of the 10^{-12} change in rate, and for precision work TAI should always be corrected using TT(BIPMnn).

A.6. GPS time

GPS time is currently defined by the Interface Specification document “IS-GPS-200F, Revision F”[12]. Note that GPS time is defined in terms of UTC(USNO). That is to emphasize that GPS time is *not* defined in terms of TAI. GPS time is only required to match UTC to within a microsecond.

GPS time is convenient, but precision timestamps want to know whether the receiver has implemented the corrections to the satellite clocks and ionosphere given by the contents of Subframe 1 as documented in section 20.3.3.3 of IS-GPS-200.

GPS system time should not be used before its date of inception (1980-01-06).

A.7. UTC

UTC is defined by ITU-R TF.460, and according to that specification the broadcasters are only required to match to within a millisecond. Because of the international recommendations and treaty obligations regarding its use, most national metrology agencies have adopted UTC and disseminate it as part of their statutory obligation.

UTC should be used with caution prior to 1974 because the meaning of the name was unknown outside the metrology community.

UTC should be used with extreme caution prior to 1972-01-01 because different contemporary sources of timestamps were providing different time scales.

UTC with its current definition was not available prior to 1972. Aside from historical tabulations, most terrestrial time stamps prior to 1972 should be expressed as UT and we recommend specifically that GMT be interpreted as UT for such dates.

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[9] http://www.iau.org/static/resolutions/IAU2006_Resol3.pdf

[10] http://www.bipm.org/en/committees/cc/cctf/ccds-1970.html (Note the 1980 amendment and the change implicit by the IAU 1991 Resolution A4)

[11] http://www.bipm.org/en/CGPM/db/14/1/
http://www.bipm.org/en/CGPM/db/14/2/

[12] http://www.gps.gov/technical/icwg/#is-gps-200

UTC should not be used prior to 1960-01-01 because coordination of broadcast time did not begin until then, and prior to 1961 only time sources in the US and UK were providing it.

UTC from any source is practical, but precision timestamps want to know which realization was used.

UTC from a GPS receiver is also practical, but precision timestamps want to know whether the receiver has implemented the corrections given by the contents of Subframes 4 and 5 as documented in section 20.3.3.5 of IS-GPS-200.

A.8. GMT

Greenwich Mean Time (GMT) is an ill-defined timescale that nevertheless continues to persist in popular parlance as well as scientific papers. Its use is to be discouraged, but if encountered it should be interpreted as UTC, with the caveat that it is rather loosely defined as such and any assertions as to the precision of the time stamps should be regarded with caution.

A.9. UT

The underlying concept for UT originated at the International Meridian Conference held in Washington in 1884 which defined the Universal Day as a mean solar day to be reckoned from Greenwich midnight. UT was initially defined by Newcomb's fictitious mean sun Tables of the Sun, Astr. Papers Amer. Ephemeris 6, 1895 The name Universal Time was established as the subdivision of the Universal Day by Commission 4 of the IAU at the IIIth General Assembly in 1928 at Leiden (IAU, 1928[13]).

Most terrestrial time stamps prior to 1972 should be expressed as UT. For events with time stamps established by radio transmissions we note that it is possible to use Bulletin Horaire of the BIH to obtain sub-second precision on one of the time scales here. In exceptional cases of events with time stamps established by chronometers at observatories with meridian instruments, calibration is possible to sub-second precision as far back as 1830 (Jordi, et al., 1994).

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[13] http://www.iau.org/static/resolutions/IAU1928_French.pdf