Astronomy & Astrophysics manuscript no. WCSPaper-IV-v1.0
March 17, 2014
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Representations of Time Coordinates in FITS

Time and Relative Dimension in Space (V1.0)

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Received 1 April, 2014; accepted _____

ABSTRACT

Context. In a series of three previous papers, formulation and specifics of the represention of World Coordinate Transformations in FITS data have been presented. This fourth paper deals with encoding time.
Aims. Time on all scales and precisions known in astronomical datasets will 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 describe rigorously 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 an extension to the formalism in order to deal with general distortions of the coordinate grid.

This paper, the fourth in the series, formulates the representation of the time axis, or possibly 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 timing relative 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 that 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 first define the terms of reference of this standard (Section 2). 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 provides some general comments on implementing this standard. Section 6 on usage context refers back to the terms of reference, illustrated with six header examples and including a sub-section on time-related coordinate axes. The prescriptive part of this standard is contained in Sections 2, 3, 4, and Appendix A.

Generally helpful references may be found in Seidelmann (1992), Urban & Seidelmann (2012), and McCarthy & Seidelmann (2009). The report on the current (IAU 2009) system of astronomical constants is provided by Luzum et al. (2011) [1].

The interpretation of the terms *must*, *required*, *should*, and *may* follows common usage in standards documents:

⋆ Deceased

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

An implementation is compliant if it satisfies all the *must* or *required* level requirements for the protocols it implements. An implementation that satisfies all the *must* or *required* level and all the *should* level requirements for its protocols is said to be "unconditionally compliant"; one that satisfies all the *must* level requirements but not all the *should* level requirements for its protocols is said to be "conditionally compliant".

2. Terms of Reference

Time WCS information needs to be supported in five contexts:

- 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 distinguish the following components in the specification of time:

- Time coordinate frame, containing:
  - Time scale
  - Reference time (the zero point for relative times)
  - Time reference position
  - 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 and other folded or stacked light curves
- Power spectra, cross-, and auto-correlation spectra
- 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 absolute time axes, we provide accommodation for three types of time-related coordinates: Phase, Timelag, and Frequency; see Section 4.5.

[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; (OGIP/GSFC/NASA 2008).

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 *shall* 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.

In the following we first treat the ISO-8601 representation, then floating point values of elapsed time since a reference value. For time, more than any other coordinate, precision may be a concern and naive use of double precision floating point parameters for time values (especially Julian Dates) will be inadequate in some cases. However, a judicious combination of keywords and their values, as described in the remainder of this section, will allow almost any required precision to be achieved without having to resort to anything beyond double precision data types in handling keyword values. We urge creators of data products to apply special care, so that clients can rely on this being the case. If and when, in addition to the 32-bit (`E`) and 64-bit (`D`) floating point types, a 128-bit floating point data type becomes available and supported, we envision that such a type will also be used for time values, removing the need for any special provisions.

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`. In this paper we will use *datetime* as a pseudo data type to indicate its use. Following the current FITS standard (Pence et al., 2010) its values *must* be written as a character string in `A` format, but if and when an ISO-8601 data type is adopted, it *should* be used in table columns, 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 *must not* be omitted and timezone designators are not allowed.

This paper extends the definition to allow five-digit years with a (mandatory) sign, in accordance with ISO-8601. I.e., one *shall* 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:

- In counting years, ISO-8601 follows the convention established by Cassini (1740) of including year zero. Consequently, for negative year numbers there is an offset of one from BCE dates which do not recognize a year zero. Thus year 1 corresponds to 1 CE, year 0 to 1 BCE, year −1 to 2 BCE, and so on.
- 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 the present ISO-8601:2004(E) standard (ISO 2004) we specify that, for use in FITS files, dates prior to 1582 *must* 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.
- 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 4.1.1).
- 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. In general, if higher precision is required, it will be possible to achieve this by judicious use of keyword values, without having to resort to exotic datatypes, as described in the next subsection.

3.3. Higher Precision in Keyword Values

While the FITS standard (Pence, et al., 2010, Section 4.2.4). allows header values to be written to as many as 70 decimal digits, it must be recognised that practical implementations are currently based on double-precision floating point values which are capable of representing only approximately 15 decimal digits. While this has not been a limitation in the past, it may not be adequate for certain high-precision timing applications. In the absence of the widespread availability of quad-precision floating point, timing software often obtains the extra required precision by using a pair of double-precision values, typically containing the integer and fractional part, whose (implied) sum forms the high-precision value. In like vein we provide the `[M]JDREF[IF]` and `DATEREF` keywords (see Section 4.1.2) to define a global time reference epoch to which all times in the HDU are relative, and these should be used judiciously where high-precision timing is required. Implementations of this proposal should be aware that precision may be lost by adding relative times to the reference epoch, and maintain them as separate quantities until a final value is required (see Section 5.3).

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)

3.4. 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 (`TFORM`n = `'2D'`) where the first component of the doublet contains the integer portion of the time value and the second one the fractional part, such that their sum equals the true value and where both have the same sign. This will ensure that retention of precision can be effected in as simple a way as possible and avoiding any sign ambiguities. 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. 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 4.2), 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 4.2 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.

See Section 6.6 for the use of Besselian and Julian epochs in FITS files.

Caution: be aware of the offset of 1 in negative year numbers, compared with BCE dates (see Section 3.1).

4. Components of the Standard

This section describes the components of the standard. The keywords used to specify times are summarized in Table 5. Section 5.a of the table contains data items: time values that have, in principle, global validity in the HDU. Section 5.b presents keywords that define the time reference frame for all time values in the HDU and their context-dependent override keywords. 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"). The last section of the table (5.c) lists the keywords that allow overriding the global HDU keyword values for the time axis in images.

In the following *datetime-valued must* be interpreted as *string-valued* where the string conforms to ISO-8601 format as defined in Section 3.1 .

4.1. 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).

4.1.1. 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 4.1.3), 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):

$T(\mathrm{TCG}) = T(\mathrm{TT}) + L_{\mathrm{G}} \times 86400 \times (JD(\mathrm{TT}) - JD_0)$

$T(\mathrm{TDB}) = T(\mathrm{TCB}) - L_{\mathrm{B}} \times 86400 \times (JD(\mathrm{TCB}) - JD_0) + TDB_0$

where:

T is in seconds

$L_{\mathrm{G}} = 6.969290134 \times 10^{-10}$

$L_{\mathrm{B}} = 1.550519768 \times 10^{-8}$

$JD_0 = 2443144.5003725$

$TDB_0 = -6.55 \times 10^{-5}$ s

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 scales 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. In those cases the time reference value (see Section 4.1.2) *shall 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 synchronize closely 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.

Finally, it may be helpful, in order to put the different time scales into perspective, to emphasize that while UT1 is, in essence, an angle (of the earth's rotation – *i.e.,* a *clock*), the others are SI-second counters (*chronometers*); UTC, by employing leapseconds, serves as a bridge between the two types of time scales.

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 2012-07-01 UTC = TAI − 35 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*.

Keywords The global keyword that records the time scale is

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

In relevant context (*e.g.,* time axes in image arrays, table columns, or random groups) it *may* be overridden by a time scale recorded in `CTYPE`*ia*, its binary table equivalents, or `PTYPE`*i* (see Table 5).

The keywords `TIMESYS`, `CTYPE`*ia*, `TCTYP`*n*, and `TCTY`*na* *may* assume the values listed in Table 2. In addition, for backward compatibility, all except `TIMESYS` and `PTYPE`*i* *may* also assume the value `TIME` (case-insensitive), whereupon the time scale *shall* be that recorded in `TIMESYS` or, in its absence, its de-

fault value, UTC. See also Sections 6.2, 6.3, and 6.4. See Section 4.5 regarding their use for specific time-related axes.

As noted above, local time scales other than those listed in Table 2 *may* be used, but their use *should* be restricted to alternate coordinates in order that the primary coordinates will always refer to a properly recognized time scale; an example may be found in Section 6.3.

4.1.2. 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, *shall* be specified through one of three keywords:

MJDREF (floating-valued)
Reference time in MJD

JDREF (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 and fractional parts separately:

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

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

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

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

In the following, MJDREF and JDREF 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 *must* be assumed. If TREFPOS = 'CUSTOM' (Section 4.1.3) 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 10 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.

Table 3 Standard Time Reference Position Values[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

[1]Recognized values for TREFPOS, TRPOSn;
only the first three characters of the values are significant and solar system locations are as specified in the JPL Ephemerides

4.1.3. 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, either where the observation was made or the point in space for which light-time corrections have been applied. 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. Furthermore, in order to allow for alternative spellings, only the first three characters of all these values *shall* be considered significant. The value of the keyword *shall be* case-sensitive. 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

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; reference position coincides with the spatial origin of the space-time coordinates
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

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 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 with 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 *must* 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] *shall* apply to time coordinate axes in images as well. See Section 6.2.1 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 4.1.1) 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.

ITRS coordinates (X,Y,Z) may be derived from geodetic coordinates (L,B,H) through:

$$X = (N(B) + H)\cos(L)\cos(B)$$

$$Y = (N(B) + H)\sin(L)\cos(B)$$

$$Z = (N(B)(1 - e^2) + H)\sin(B)$$

where:

$$N(B) = \frac{a}{\sqrt{1 - e^2 \sin^2(B)}}$$

$$e^2 = 2f - f^2$$

a is the semi major axis, f the inverse of the inverse flattening.

Nanosecond precision in timing requires that OBSGEO-[BLH] be expressed in a geodetic reference frame defined after 1980 in order to be sufficiently accurate.

[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*.

4.1.4. 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 useful only 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}:

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

The reference direction is indicated 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 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 *shall* apply to time coordinate axes in images as well. See Section 6.2.1 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 10:

TRDIR20 = 'EventRA,EventDEC'

4.1.5. 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 TCB or TDB.

The ephemerides that are currently most often used 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 *shall* 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.

4.2. 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 3.5). The length of the tropical year ta in days is (based on Simon, et al. 1994):

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

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

The length of the Besselian year Ba in days is (based on Newcomb 1895 and 1898):

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

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). An alternative definition of the Besselian epoch in common use (*e.g.,* in SOFA 2010) is the one given by Lieske 1979:

$$B = 1900.0 + (JD - 2415020.31352)/365.242198781$$

which is based on a Besselian year of fixed length leading to:

$$1\ \mathrm{Ba} = 365.242198781\mathrm{d}$$

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.

See Section 6.6 for the use of Besselian and Julian epochs in FITS files.

Keywords The time unit is set by the keyword

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

In relevant context, this *may* be overridden (see Section 6 for details) by the `CUNIT`*ia* keywords and their binary table equivalents (see Table 5).

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

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

4.3.1. Time Offset (not applicable to images)

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 *shall* be added to `MJDREF`, `JDREF`, or `DATEREF`, and hence affects the values of `TSTART`, and `TSTOP`, as well as any time pixel values in a binary table.

However, this construct *may* only be used in tables and *must not* be used in images.

Keyword The time offset is set by:

`TIMEOFFS` (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`.

4.3.2. 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; see Section 6 for details) by the `CSYER`*ia* keywords and their binary table equivalents (see Table 5).

4.3.3. 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; see Section 6 for details) by the `CRDER`*ia* keywords and their binary table equivalents (see Table 5).

4.3.4. Time Resolution

The resolution of the time stamps (the width of the time sampling function) is represented by a simple double. In tables 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`.

4.3.5. Time Binning (not applicable to images)

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.

However, this construct *may* only be used in tables and *must not* be used in images.

Keyword The relative position of the time stamp in each time bin (`TIMEDEL` in the case of an event list) 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.

4.4. 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` (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` (floating-valued)
Start time of data in MJD according to `TIMESYS`

`MJD-AVG` (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` (floating-valued)
Stop time of data in MJD according to `TIMESYS`

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

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

The alternate-axis equivalent keywords `DOBS`*n*, `MJDOB`*n*, `DAVG`*n*, and `MJDA`*n*, as defined in the FITS Standard (Pence, et al., 2010, Table 22) are also allowed. Note that of the above only `TSTART` and `TSTOP` are relative to the time reference value.

It should be noted that, although they do not represent global time values within an HDU, the `CRVAL`*ia* and `CDELT`*ia* keywords, and their binary table equivalents (see Table 5), also represent (binary) time values. They should be handled with the same care regarding precision when combining them with the time reference value as any other time value (see also Section 5.3).

Finally, Julian and Besselian epochs (see Sections 3.5 and 4.2) *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` (floating-valued)
Julian epoch; implied time scale TDB

`BEPOCH` (floating-valued)
Besselian epoch; implied time scale ET

When these epochs are used as time stamps in a table column their interpretation will be clear from the context. When the keywords appear in the header without obvious context, they *must* be regarded as equivalents of `DATE-OBS` and `MJD-OBS`, i.e., with no fixed definition as to what part of the dataset they refer to.

4.5. Other 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 autocorrelation spectra. As a practical definition one may consider *frequency* as the Fourier transform equivalent of time and, particularly, the coordinate axis of power spectra, with the exception of spectra where the dependent variable is the electro-magnetic field. Specifically, the latter (excluded) case applies to electromagnetic waveforms of cosmic origin with fixed transformations to related variables such as wavelength, Doppler velocity, and redshift which do not apply to periodic phenomena in general. That specific case is covered by Greisen et al. (2006).

These coordinate axes *shall* be specified by giving `CTYPE`*i* and its binary table equivalents one of the values:

`PHASE`, `TIMELAG`, `FREQUENCY`

Note that the frequency coordinate of the electro-magnetic spectrum is indicated by the value `FREQ`.

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* as an alternate description. Phrased differently, a given vector of values for an observable can be paired with a coordinate 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* as an alternate description of the same axis. Its units *may* be `deg`, `rad`, or `turn`, the last of which is introduced here.

Time at the zero point of a *phase* axis *shall* be recorded in a new keyword

`CZPHS`*ia* (floating-valued)

with binary table forms `TCZPH`*n*, `TCZP`*na*, *i*`CZPH`*n*, and *i*`CZP`*na*.

Optionally, the period of a *phase* axis *may* be recorded in a new keyword

`CPERI`*ia* (floating-valued)

with binary table forms `TCPER`*n*, `TCPR`*na*, *i*`CPER`*n*, and *i*`CPR`*na*. One should be aware, however, that this can be used only 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).

Phase period and zero point *shall* be expressed in the globally valid time reference frame and unit as defined by the global keywords (or their defaults) in the header.

4.6. 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

[4] http://www.atnf.csiro.au/research/pulsar/psrfits/index.html

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. We suggest that these are are excellent candidates for definition through an appropriate formally registered FITS convention, rather than inclusion in this standard.

Because of their crucial role and common use, keywords are defined here to record exposure and elapsed time; in addition, a standard for good time intervals is defined in Section 4.7.

Keyword The only defined durations *shall* 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.

4.7. 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 *shall* contain two mandatory columns, `START` and `STOP`, and *may* contain 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. General Comments on Implementation

In the following we discuss some practical implementation issues, before turning, in the next section, to usage in specific contexts.

As a general comment, we should point out that the distortion conventions described by Calabretta et al. (2004) are also very much applicable to the time coordinate axis.

5.1. Getting Started

As a simple getting-started guide, we make the following recommendations (referring to Table 5):

- The presence of the Informational `DATE` keyword is STRONGLY RECOMMENDED in all HDUs.
- One or more of the Informational keywords `DATE-xxx` and/or `MJD-xxx` SHOULD be present in all HDUs.
- The Global keyword `TIMESYS` is STRONGLY RECOMMENDED.
- The Global keywords `MJDREF` or `JDREF` or `DATEREF` are RECOMMENDED.
- The remaining Informational and Global keywords SHOULD be present whenever applicable.
- All Context-Specific keywords SHALL be present as needed and required by the context of the data.

5.2. Global Keywords and Overrides

For reference to the keywords that are discussed here, see Table 5. The globally applicable keywords listed in section 5.b of the table serve as default values for the corresponding `C*` and `TC*` keywords in that same section, but only when axis and column specifications (including alternate coordinate definitions) use a time scale listed in Table 2 or when the corresponding `CTYPE` or `TTYPE` keywords are set to the value `TIME`. 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; see also Section 4.1.1.

5.3. Precision

In order to maintain the precision that is provided by the HDU, one needs to be careful while processing the information for high timing precision applications. Although it is safe to read floating point values in headers and binary data in double precision, arithmetic performed with those values may need to be executed with extended precision. For example, if the header contains:

```
MJDREFI = 1243
MJDREFF =    0.3746369623
CRVAL   =    0.0000000111111
CDELT   =    0.00000000251537257213
```

then the relative value of the first pixel is:

```
T       = CRVAL + 1*CDELT
        =    0.00000001362647257213
```

while the final answer, expressed in MJD and performed in quad precision, is:

```
TIME    = MJDREFI + MJDREFF + T
        = 1243.374636975926472572130000
```

The onus is on the application programmer to ensure that applications maintain their required precision.

5.4. Labeling

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". Authors should be explicit about the times that are posted and we strongly recommend that they adopt the following convention for axis labeling:

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

In order to facilitate the correct labeling we recommend 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 10.

6. Usage Contexts

In this section we discuss usage in the contexts to which this WCS time standard applies; these contexts refer back to Section 2.

6.1. Header Keywords

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

6.2. Time Axis in Images

Example 1 (Table 6) is a data cube in which the 3rd 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 multi-dimensional space-time-spectral hypercube) are also 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.

6.2.1. Restrictions on Alternate Descriptions

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.

6.2.2. `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`.

6.2.3. `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.

Sections 6.2.4 and 6.2.5 describe examples of the use of these keywords.

6.2.4. Example of an Image Constructed by a Moving Slit

As an example we present a header in Table 7 (Example 2) based on a simplified version of a SOHO Coronal Diagnostic Spectrometer observation from October 1998 (Harris, et al. 1992). An image of the Sun is focused onto the entrance slit of a stigmatic spectrograph, forming a spectral image on the intensified CCD detector with wavelength in one direction, and the latitudinal spatial dimension in the other direction. A spectrally resolved map of the Sun is formed by moving the slit from right to left during the observation; thus different parts (columns) of the data cube 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 the `PC4_2` matrix element.

An alternative approach for the example in Table 7 would be to define the time axis as `CTYPE2A`, tying it directly to the longitude pixel coordinate. However, it is possible to devise a scenario where this simple alternative approach is not sufficient. In the actual observation that Table 7 is based on, the slit was tilted relative to solar north, so that the resulting `PC`*i_j* matrix would have non-trivial values for axes 2 and 3. If the data were then rotated to be aligned to solar north, time would be dependent on both spatial axes, which would be reflected as non-zero values for both `PC4_2` and `PC4_3`.

This approach 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 `PC2_`*jA* matrix.

6.2.5. Less Tractable Space-Time Interactions

The following example does not have a fool-proof solution, but it may be instructive. It is derived from the APF telescope at Lick Observatory. This is a telescope on an azimuth-elevation mount where the guider has no rotator, so the Celestial WCS changes as the telescope tracks. The guide camera software can produce movies as 3-D FITS files.

There is no provision for a Celestial WCS which changes as a function of time (or position), so it is not possible for a FITS file to store a complete description of the WCS for every frame in a movie within the context of a single HDU.

However, it is possible to store a WCS for the beginning and end of a movie. That allows standard FITS WCS viewing programs to give some idea of the amount of field rotation that happens during a movie.

So the intent of the FITS header in Example 4 (Table 9) is to communicate that alternate WCS `S` is valid at the beginning of the exposure and alternate WCS `R` is valid at the end of the exposure.

Of course, an alternate approach would be to provide the WCS information for each frame in a binary table as a separate HDU. Each row in the table would represent a separate time step and the columns would contain the corresponding time-dependent WCS parameters using the Green Bank convention. This solution has the benefit of providing exact WCS information. However, it does require introducing a separate HDU, whereas the merit of the example in Table 9 is that it provides the extremes within the image HDU itself. In conclusion, these

two approaches may be considered complementary and are not mutually exclusive.

6.3. Time Columns in Tables

Example 5 (Table 10) 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 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 10 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.

6.3.1. Restrictions

The same restrictions imposed on the image time axis (see Section 6.2.1) 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.

6.4. 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 6.2 for the rules. If time is to be transmitted through a group parameter, it simply means that the `PTYPE`*i* 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.

6.5. The Time-related Coordinate Axes

Summarizing the definition of *phase*, *timelag*, and *frequency* in Section 4.5, we emphasize three key concepts:

- `FREQUENCY` may be used as the abscissa of any spectrum, except an electo-magnetic spectrum
- *Phase* can be used as an alternate description of the *time* coordinate; *timelag* and *frequency* cannot.
- The period of a *phase* axis may be provided through the keyword `CPERI`*ia* and its equivalents, but only if that period is a constant; when that is not the case, the period should either be absent or set to zero.

We provide an simple example of a binary table with one *time* and two *phase* columns in Example 6 (see Table 11). We readily admit that in this simple example the phase columns can also be projected onto the time column as linear alternate coordinate systems. The purpose of the example is to show the use of the *phase* coordinate, not an encouragement to make headers more complicated than necessary.

6.6. Use of Besselian and Julian Epochs

Use of Besselian and Julian epochs requires special care, as discussed in Sections 3.5 and 4.2. Their use is discouraged, but the fact remains that data exist with a time axis that is so labeled. We recommend the following convention for identifying these epochs (illustrated for binary table column 1, but easily translated to other use cases):

```
DATEREF = '0000-01-01T00:00:00'
TCUNI1  = 'Ba'    / for Besselian epochs
TCUNI1  = 'a'     / or 'yr'; for Julian epochs
TCNAM1  = 'B epoch' / or 'Besselian epoch'
TCNAM1  = 'J epoch' / or 'Julian epoch'
```

Acknowledgements. The authors want to express their deep gratitude and appreciation for the dedication and tireless efforts of their colleague and friend Peter Bunclark in moving the work on this paper forward. We received his last email on 8 December 2008, just two days before his untimely death. We miss Pete dearly, not only as a great co-author who kept us on the straight and narrow, but especially as a very good friend. It was a privilege to have collaborated with him. We are also very much indebted to IAU FITS Working Group chair Bill Pence, who provided valuable comments and kept exhorting us to finally finish this paper. AHR gratefully acknowledges the many helpful discussions he had with Jonathan McDowell.

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Table 5. Keywords for Specifying Time Coordinates

Keyword Description	Section	Global	Images		Table Pixel Columns		Table Vector Columns	
			Single	Multiple	Primary	Alternate	Primary	Alternate
5.a Informational Keywords								
Date of HDU creation[a]	4.4	DATE						
Date/time of observation	4.4	DATE-OBS			DOBS*n*		DOBS*n*	
		MJD-OBS			MJDOB*n*		MJDOB*n*	
		JEPOCH						
		BEPOCH						
Effective date/time of observation	4.4	DATE-AVG			DAVG*n*		DAVG*n*	
		MJD-AVG			MJDA*n*		MJDA*n*	
Start date/time of observation	4.4	DATE-BEG						
		MJD-BEG						
		TSTART						
End date/time of observation	4.4	DATE-END						
		MJD-END						
		TSTOP						
Net exposure time	4.6	XPOSURE						
Wall clock exposure time	4.6	TELAPSE						
5.b Global Time Reference Frame Keywords and their Optional Context-Specific Override Keywords								
Time scale[c]	4.1.1	TIMESYS	CTYPE*i*[d]	CTYPE*ia*[d]	TCTYP*n*[d]	TCTY*na*[d]	*i*CTYP*n*	*i*CTY*na*
Zero point in MJD	4.1.2	MJDREF[b]						
Zero point in JD	4.1.2	JDREF[b]						
Zero point in ISO-8601	4.1.2	DATEREF						
Reference position	4.1.3	TREFPOS			TRPOS*n*		TRPOS*n*	
Reference direction	4.1.4	TREFDIR			TRDIR*n*		TRDIR*n*	
Solar System ephemeris	4.1.5	PLEPHEM						
Time unit	4.2	TIMEUNIT	CUNIT*i*	CUNIT*ia*	TCUNI*n*	TCUN*na*	*i*CUNI*n*	*i*CUN*na*
Time offset	4.3.1	TIMEOFFS						
Absolute Error	4.3.2	TIMSYER	CSYER*i*	CSYER*ia*	TCSYE*n*	TCSY*na*	*i*CSYE*n*	*i*CSY*na*
Relative Error	4.3.3	TIMRDER	CRDER*i*	CRDER*ia*	TCRDE*n*	TCRD*na*	*i*CRDE*n*	*i*CRD*na*
Time resolution	4.3.4	TIMEDEL						
Time location in pixel	4.3.5	TIMEPIXR						
5.c Additional Context-Specific Keywords for the Time Reference Frame								
Time axis name	6.2		CNAME*i*	CNAME*ia*	TCNAM*n*	TCNA*na*	*i*CNAM*n*	*i*CNA*na*
Time axis reference pixel	6.2		CRPIX*i*	CRPIX*ia*	TCRPX*n*	TCRP*na*	*i*CRPX*n*	*i*CRP*na*
Time axis reference value	6.2		CRVAL*i*	CRVAL*ia*	TCRVL*n*	TCRV*na*	*i*CRVL*n*	*i*CRV*na*
Time scaling	6.2.3		CDELT*i*	CDELT*ia*	TCDLT*n*	TCDE*na*	*i*CDLT*n*	*i*CDE*na*
Period for temporal phase[e]	4.5		CPERI*i*	CPERI*ia*	TCPER*n*	TCPR*na*	*i*CPER*n*	*i*CPR*na*
Zero phase time[e]	4.5		CZPHS*i*	CZPHS*ia*	TCZPH*n*	TCZP*na*	*i*CZPH*n*	*i*CZP*na*
Transformation matrix	6.2.3		CD*i_j*	CD*i_ja*	TC*n_ka*		*ij*CD*na*	
Transformation matrix	6.2.3		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]Use PTYPE*i* in random groups

[d]These keywords may also assume the values PHASE, TIMELAG, or FREQUENCY to specify the corresponding time-related coordinate axes (see Section 4.5)

[e]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
XPOSURE =               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
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
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
CDELT3  =               13.3629 / Axis scale at reference 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
CDELT3A =               13.3629 / Axis scale at reference 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
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 coupled with Space, built up from individual exposures from a stigmatic slit spectrograph stepped across the solar disk

```
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   =              0.00000 /
PC2_2   =              1.00000 /
PC2_3   =              0.00000 /
PC2_4   =              0.00000 /
PC3_1   =              0.00000 /
PC3_2   =              0.00000 /
PC3_3   =              1.00000 /
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 coupled 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 an image cube where Space is coupled with Time through rotation, using different CD matrices for the beginning and end of the observation

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

COMMENT      ----------  Globally valid key words  ----------------
NAXIS   =                    3 / number of data axes
NAXIS1  =                  512 / length of data axis 1
NAXIS2  =                  512 / length of data axis 2
NAXIS3  =                    7 / length of data axis 3
DATEUINI= '2012-04-30T04:44:35.001905' / gettimeofday() basis for begin
DATE-BEG= '2012-04-30T04:44:32.801905' / estimated begin of initial frame
XPOSURE =                  14. / [s] total exposure duration
GEXPTIME=                   2. / [s] duration of one frame
DATEUFIN= '2012-04-30T04:44:47.944826' / gettimeofday() basis for end
DATE-END= '2012-04-30T04:44:47.744826' / estimated end of final frame
TIMESYS = 'UTC     '           / time scale
DATEREF = '2012-04-30T04:44:32.801905' / time reference
COMMENT      ---------- Celestial WCS at begin of movie ----------
WCSNAMES= 'sky     '           / APF sky coordinates
RADESYSS= 'FK5     '           / celestial coordinate reference system
EQUINOXS=                2000. / reference frame epoch
CTYPE1S = 'DEC--TAN'           / coordinate/projection type for WCS axis i=1
CTYPE2S = 'RA---TAN'           / coordinate/projection type for WCS axis i=2
CTYPE3S = 'UTC     '           / coordinate/projection type for WCS axis i=3
CUNIT1S = 'deg     '           / physical unit for WCS axis i=1
CUNIT2S = 'deg     '           / physical unit for WCS axis i=2
CUNIT3S = 's       '           / physical unit for WCS axis i=3
CRPIX1S =        273.459991455 / FITS axis j=1 pixel location of slit
CRPIX2S =        257.940002441 / FITS axis j=2 pixel location of slit
CRPIX3S =                  0.5 / FITS axis j=3 pixel for initial photons
CRVAL1S =     24.7497222222345 / WCS axis i=1 Dec
CRVAL2S =     163.903333333308 / WCS axis i=2 RA
CRVAL3S =                   0. / WCS axis i=3 UTC offset from DATEREF
CD1_1S  = 2.01333824032837E-05 / CTM i_j at begin, note difference from end
CD1_2S  = -2.16670022704079E-05 / CTM i_j at begin, note difference from end
CD1_3S  =                   0. / CTM i_j from pixel j to WCS i
CD2_1S  = 2.16670022704079E-05 / CTM i_j at begin, note difference from end
CD2_2S  = 2.01333824032837E-05 / CTM i_j at begin, note difference from end
CD2_3S  =                   0. / CTM i_j from pixel j to WCS i
CD3_1S  =                   0. / CTM i_j from pixel j to WCS i
CD3_2S  =                   0. / CTM i_j from pixel j to WCS i
CD3_3S  =            2.1632744 / CTM i_j UTC time step of movie frames
COMMENT      ---------- Celestial WCS at end of movie ------------
WCSNAMER= 'sky@end '           / APF sky coordinates at end
RADESYSR= 'FK5     '           / celestial coordinate reference system
EQUINOXR=                2000. / reference frame epoch
CTYPE1R = 'DEC--TAN'           / coordinate/projection type for WCS axis i=1
CTYPE2R = 'RA---TAN'           / coordinate/projection type for WCS axis i=2
CTYPE3R = 'UTC     '           / coordinate/projection type for WCS axis i=3
CUNIT1R = 'deg     '           / physical unit for WCS axis i=1
CUNIT2R = 'deg     '           / physical unit for WCS axis i=2
CUNIT3R = 's       '           / physical unit for WCS axis i=3
CRPIX1R =        273.459991455 / FITS axis j=1 pixel location of slit
CRPIX2R =        257.940002441 / FITS axis j=2 pixel location of slit
CRPIX3R =                  7.5 / FITS axis j=3 pixel for final photons
CRVAL1R =     24.7497222222345 / WCS axis i=1 Dec
CRVAL2R =     163.903333333308 / WCS axis i=2 RA
```

Table 9 (cont'd)

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789
CRVAL3R =            14.942921 / WCS axis i=3 UTC offset from DATEREF
CD1_1R  = 2.00306908641293E-05 / CTM i_j at end, note difference from begin
CD1_2R  = -2.17619736671195E-05 / CTM i_j at end, note difference from begin
CD1_3R  =                   0. / CTM i_j from pixel j to WCS i
CD2_1R  = 2.17619736671195E-05 / CTM i_j at end, note difference from begin
CD2_2R  = 2.00306908641293E-05 / CTM i_j at end, note difference from begin
CD2_3R  =                   0. / CTM i_j from pixel j to WCS i
CD3_1R  =                   0. / CTM i_j from pixel j to WCS i
CD3_2R  =                   0. / CTM i_j from pixel j to WCS i
CD3_3R  =            2.1632744 / CTM i_j UTC time step of movie frames
END
```

Table 10. Example 5: 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
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      '
TCNAM1  = '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
TCRDE1  =  1.0000000000000E-09 / Relative error
TCSYE1  =  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 10 (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  = 'd       '           / 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  = 'd       '           / 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
TCNAM20 = '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
TCRDE20 =  1.0000000000000E-09 / Relative error
TCSYE20 =  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 11. Example 6: 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
TIMEUNIT= 's       '           / Default time unit; applies to TCZPHi, TCPERi
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      '
TCNAM1  = '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  = 'turn    '
TCTYP2  = 'PHASE   '
TCNAM2  = '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  = 'turn    '
TCTYP3  = 'PHASE   '
TCNAM3  = '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 11 (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      0.05        50.0
  8    1156.4        0.7      0.10        40.0
  9    1486.8        0.9      0.20        20.0
 10    1652.0        0.0      0.25        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 4.1.1 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-

[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 (1895 and 1898) and Brown & Hedrick (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 aligned to a specific UTC(USNO) epoch, 19 s behind TAI, with the fractional part matching UTC(USNO) to within a microsecond.

GPS is a convenient source of accurate time. However, for precise timestamps it is necessary for applications 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 required to match only 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.

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.

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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 from any source is practical, but in order to provide precision timestamps one needs to know which realization was used.

UTC from a GPS receiver is also practical, but any tools that are to provide precision timestamps need 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" (Newcomb 1895 and 1898). 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).

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