Astronomy & Astrophysics manuscript no. WCSPaperV0.73
September 28, 2009

Representations of Time Coordinates in FITS

Time and Relative Dimension in Space (V0.73)

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Received December 25, 2008; accepted January 1, 2009

ABSTRACT

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

Key words. methods: data analysis – techniques: image processing

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. Paper IV (Calabretta et al. 2005) extends the formalism to deal with general distortions of the coordinate grid.

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

In the following sections we will first define the terms of reference of this standard. The next section provides an explanation of the components that are involved and defines the keywords to be used for specifying those components. A section on usage context that includes two header examples refers back to the terms of reference. Finally, we present some concluding remarks.

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 shall distinguish the following components in the specification of time:

- Time Coordinate Frame, containing:
  - Time Scale
  - Time Reference Position
  - Reference Time (the zero point for relative times)
  - Time Reference Direction (if applicable)
  - Planetary and 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”)

⋆ Deceased

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

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

3. Components of the Standard

This section describes the components of the standard. However, we will first define a set of global keywords, their scope, and data type. They will be defined more precisely in subsequent sections. This set applies to all subsections of the current section. In the following *high precision floating-valued* should be interpreted as *floating-valued* with the caveat that routine double floating precision may not provide sufficient accuracy; see Section 3.1 *Datetime-valued* should be interpreted as *string-valued* where the string conforms to ISO-8601 format as defined in Section 3.1.1 .

Keywords The following keywords have global validity in a Header-Data Unit (HDU; i.e., the header as well as all the data):

`TIMEDEL` (floating-valued)
Time resolution (see Section 3.5.4)

`TIMEPIXR` (floating-valued)
Pixel position of the time stamp; between 0.0 and 1.0, default 0.5.(see Section 3.5.5)

`PLEPHEM` (string-valued)
Solar System ephemeris; default `DE405` (see Section 3.3.5)

`TIMEOFFS` (high precision floating-valued)
Time offset; default 0.0 (see Section 3.5.1)

In addition, one of these three (see Section 3.3.3):

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

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

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

The following global keywords have conditional validity in an HDU. they are valid in the header, but may be overridden for the data):

`TIMESYS` (string-valued)
Time scale; default `UTC` (see Section 3.3.1)

`TREFPOS` (string-valued)
Time reference position; default `TOPOCENT` (see Section 3.3.2)

`TREFDIR` (string-valued)
Pointer to time reference direction (see Section 3.3.4)

`TIMEUNIT` (string-valued)
Time unit; default `s` (see Section 3.4)

`TIMSYER` (floating-valued)
Absolute time error (see Section 3.5.2)

`TIMRDER` (floating-valued)
Relative time error (see Section 3.5.3)

3.1. Time Values and Representations of Time

Even though we may tend to think of certain representations of time as absolute (ISO-8601, Julian days), time values in this paper will all be considered relative: elapsed time since a particular reference point in time; it may help to view the “absolute” values as merely relative to a globally accepted zero point. In the following we will first treat the ISO-8601 representation, then floating point values of elapsed time since a reference value. Concerning the latter, usage cases show that values of time elapsed since a particular reference time cannot always be represented satisfactorily by existing FITS data types. In addition to the 32-bit (`E`) and 64-bit (`D`) floating point types it is desirable to have a 128-bit floating point data type (provisionally designated as data type `S`, see below).

3.1.1. ISO-8601 *Datetime* Strings

FITS uses a subset of ISO-8601 (which in itself does not imply a particular time scale) for several time-related keywords (Bunclark & Rots 1997), such as `DATE-xxx` and `MJD-xxx`. In this paper we will use *datetime* as a pseudo data type. At the present time its values can be written as a character string in `A` format, but it would be desirable to have it included as a data type in its own right into the FITS standard as type `’T’`. If and when that happens we will assume that new data type will be used, rather than the string type.

The full specification for the format of the *datetime* string is:

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

All of the time part may be omitted (just leaving the date) or the decimal seconds may be omitted. Leading zeroes may not be omitted and timezone designators are not allowed. It is premature to prescribe a full format specifier, but we expect it to be similar to the way the `A` format is handled.

Note the following:

- The earliest date that may be represented in this 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) which means that its use for times before 1582 is not defined by the ISO standard itself. However, for use in FITS files we specify that such dates are to be interpreted according to the proleptic application of the rules of Gregorius (1582). For dates not covered by the range we recommend the use of Modified Julian Day (MJD) or Julian Day (JD) numbers.
- 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 3.3.1).

3.1.2. Single or Double Precision Floating Point Relative Time

These are existing data types that do not need any particular provisions and can be used when their precision suffices.

The following sections deal with situations where double precision floating point does not provide enough precision.

3.1.3. Higher Precision in Header Keywords

In headers, the value may be written to as many significant figures as required. Such free-format floating point is already recognized in the FITS standard (IAU FITS Working Group, 2008). We emphasize that it always is, and always has been, the implementer's responsibility to check on the required accuracy of keyword values, rather than to assume that "a double is good enough" (see Section 4.2.4 of the standard), although FITS readers and general applications may need to be checked whether they handle this correctly. Nevertheless, this takes care of keyword values as well as the time axis in images.

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

3.1.4. Higher Precision in Binary Tables: Doublet Vectors

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

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

For ASCII tables there may not be any need for a high-precision data type (see Section 3.1.3).

In binary tables, we expect that at some point a new data type will be defined, *long double* or *quad*. With the `L` and `Q` type codes spoken for, we propose that the value of `TFORM`*n* shall be *r*`S`*a* (suggesting sixteen bytes – or super-double); see Section 7.3.1 of the FITS Standard (2008) for the interpretation of this string. If and when this data type is adopted we shall assume that it will be used for time stamps.

3.2. Keywords that Represent Time Values

Keywords The following time values are found in the header, independent of any time axes in the data:

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

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

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

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

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

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

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

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

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

The following time values are part of an axis definition (see Section 4 for details):

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

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

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

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

Notes This paper does not prescribe how average times (for the keywords `*-AVG`) need to be calculated.
`MJD-OBS` is specifically defined as the start time of the observation; `DATE-OBS` is not. Consequently, one may use (as many have done) the keyword

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

3.3. 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).

3.3.1. 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.

Table 1 lists allowed values. 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 location remains unchanged (see Section 3.3.2), the first eight are linear transformations of each other (excepting leap seconds), and so are `TDB` and `TCB`. 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 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.

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

Table 1 Recognized Time Scale Values[1,2]

TT	(Terrestrial Time; IAU standard): defined on the rotating geoid
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
TAI	(International Atomic Time): TT − 32.184 s
IAT	synonym for TAI (deprecated)
UTC	(Universal Time, Coordinated; default): runs synchronously with TAI, except for the occasional insertion of leap seconds; as of 2009-01-01 UTC = TAI − 34 s
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.
GMT	(Greenwich Mean Time): continuous with UTC; should not be used after 1972-01-01.
TDB	(Barycentric Dynamical Time): runs 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.
TCB	(Barycentric Coordinate Time): TDB corrected for the relativistic effects of the gravitational potential at the barycenter (relative to that on the rotating geoid), thus ensuring consistency with fundamental physical constants; TCB runs faster than TDB at a constant rate.
LOCAL	for simulation data and for free-running clocks.

[1] Specific realizations may be appended to these values, in parentheses; see text.
[2] Recognized values for `TIMESYS`, `CTYPE`*ia*, `TCTYP`*n*, `TCTY`*na*.

Keywords The following keywords may assume the values for the Time Scale that are listed in Table 1. The foundational keyword for the Time Scale is:

`TIMESYS` (string-valued)

In relevant context it may be overridden by (see Sections 4.2 and 4.3 for details):

`CTYPE`*i* (string-valued)

`CTYPE`*ia* (string-valued)

`TCTYP`*n* (string-valued)

`TCTY`*na* (string-valued)

The default value is `UTC`. Note that the Time Scale for time axes is encoded in the `CTYPE` family of keywords; if these are absent, it defaults to the value of `TIMESYS`; if that is absent, too, the Time Scale is `UTC`.

3.3.2. Time Reference Position

The reference position specifies the spatial location where the time was measured. This may be a standard location (such as `GEOCENTE` or `TOPOCENT`) 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 `TOPOCENT` is only moderately informative if no observatory location is provided or indicated.

Table 2 Standard Time Reference Position Values Contained in the JPL Ephemerides[1]

TOPOCENTER	To the
GEOCENTER	Ge
BARYCENTER	Ba
RELOCATABLE	Re tio
CUSTOM	A tha
Less common allowed standard values are:	
HELIOCENTER	He
GALACTIC	Ga
EMBARYCENTER	Ea
MERCURY	Ce
VENUS	Ce
MARS	Ce
JUPITER	Ce
SATURN	Ce
URANUS	Ce
NEPTUNE	Ce
PLUTO	Ce

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

The common allowed standard values are shown in Table 2. 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 (IAU FWG 2008) these values are allowed to be truncated to eight characters.

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

A non-standard location indicated by `CUSTOM` will be specified in a manner similar to the specification of the observatory location (indicated by `TOPOCENT`). One should be careful with the use of the `CUSTOM` value and not confuse it with `TOPOCENT`, 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)

`TREFPOS` will apply to time coordinate axes in images as well. See Section 4.2.1 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 Position. Hence, the following keyword may override `TREFPOS`:

`TRPOS`*n* (string-valued)

If the value of any of these keywords is `TOPOCENT`, 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 ICRS Cartesian coordinates (with respect to the geocenter) as defined in Paper III:

`OBSGEO-X` (floating-valued)
ICRS Cartesian X in m

`OBSGEO-Y` (floating-valued)
ICRS Cartesian Y in m

`OBSGEO-Z` (floating-valued)
ICRS Cartesian Z in m

The geodetic coordinates:

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

Note The OGIP convention[1] 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* (see above).

3.3.3. Time Reference Value

We allow the time reference point to be defined in three different systems: ISO-8601, Julian Day (JD; see Herschel 1851), or Modified Julian Day (MJD = JD − 2,400,000.5; see IAU 1997).

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

`DATEREF` (datetime-valued)

`JDREF` (high precision floating-valued)

`MJDREF` (high precision floating-valued)

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

Note: The *value* of the reference time has universal validity for all time values, but it does not have a particular Time Scale associated with it. Therefore if `MJDREF = 50814.0`, and assuming `TIMEUNIT= 's'`, a time instant $T = 86400.0$ associated with TT will fall on 1998-01-02T00:00:00.0(TT) or 1998-01-01T23:59:27.186(TAI), but a time instant $T = 86400.0$ associated with TAI will fall on 1998-01-02T00:00:32.814(TT) or 1998-01-02T00:00:00.0(TAI).

3.3.4. Time Reference Direction

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

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

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

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

Keywords The Time Reference Position is specified by the keyword

`TREFDIR` (string-valued)

`TREFDIR` will apply to time coordinate axes in images as well. See Section 4.2.1 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`:

---

[1] These were originally developed by the Office of Guest Investigator Programs at Goddard's Lab for High Energy Astrophysics. The better known part of that same organization is HEASARC. Those conventions have been pretty much universally adopted for HEA missions, particularly NASA, but also many ESA missions.

`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 5:
`TRDIR20 = 'TTYPE21,TTYPE22'`

3.3.5. Planetary and Solar System Ephemeris

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

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

- `DE200` (Standish 1990; considered obsolete, but still in use)
- `DE405` (Standish 1998; default)

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

`PLEPHEM` (string-valued)

3.4. Time Unit

The specification of the time unit allows the values defined in Paper I (2002) and the FITS Standard (IAU FWG 2008), with the addition of the century. We would 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)

Keywords The time unit is set by the keyword

`TIMEUNIT` (floating; default: 's'-valued)

In relevant context, this may be overridden by (see Section 4 for details):

`CUNIT`*i* (floating-valued)

`CUNIT`*ia* (floating-valued)

`TCUNI`*n* (floating-valued)

`TCUN`*na* (floating-valued)

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

All quantities enumerated below will be expressed in the prevailing time units, the default being `s`.

3.5.1. Time Offset

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

Keyword The time offset is set by:

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

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 value of `TIMEOFFS` is to be added to the time stamp values in the file.

3.5.2. 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)

but may be overridden, in appropriate context, by (see Section 4 for details):

`CSYER` (floating-valued)

`CSYER`*ia* (floating-valued)

`TCSYE`*n* (floating-valued)

`TCSY`*na* (floating-valued)

3.5.3. 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)

but may be overridden, in appropriate context, by (see Section 4 for details):

`CRDER` (floating-valued)

`CRDER`*ia* (floating-valued)

`TCRDE`*n* (floating-valued)

`TCRD`*na* (floating-valued)

3.5.4. Time Resolution

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

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

`TIMEDEL` (floating-valued)

in the units of `TIMEUNIT`.

3.5.5. Time Binning

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

The OGIP conventions specify the time position of the time value in the pixels through the keyword `TIMEPIXR`. Its value ranges from 0.0 to 1.0. 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.

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

`TIMEPIXR` (floating-valued)

`TIMEPIXR` may vary between 0.0 and 1.0; the default value is 0.5.

3.6. 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 and lost time; exposure time charged against the awarded exposure time; exposure time corrected for lost (bad) data; and exposure time corrected for dead time. Related to these are various keywords providing dead time correction factors, dead time correction flags, and duty cycle information, `TELAPSE`, as well as Good-Time-Interval (GTI) tables, which we may or may not want to cover.

At this time we shall only define `XPOSURE` in the present standard and, possibly, recommend a standard format for GTI tables. That format recommends tables with three columns: start, stop, and weight. The third column contains a value between 0 and 1 (i.e., a weight of 0 indicates a *Bad*-Time-Interval), is optional, and has a default value of 1. Any time interval not covered in the table shall be considered to have a weight of zero.

Keyword At this time (TBD) the only defined duration is indicated by the keyword:

`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, is 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.

4. Usage Contexts

As a general comment, we should point out that the distortion conventions described in Paper IV (2005) are also very much applicable to the time coordinate axis. The keywords discussed in detail, following, are summarized in Table 3.

4.1. Header Keywords

The rules governing these keywords are elaborated on in Section 3 and summarized in Table 3. The remaining issues are the specification of `TREFDIR` and, potentially, Good Time Interval tables and the specification of additional durations other than `XPOSURE`.

4.2. Time Axis in Images

Example 1 (Table 4) is a data cube in which the 3^{rd} axis is time. It is in fact a sequence of 2-D images stacked together.

The rules governing keywords defining the time axis in an image (which could be a one-dimensional time series or a multidimensional space-time-spectral hypercube) are also largely being dealt with in Section 3 and summarized in Table 3, but there are some aspects that require further elaboration.

4.2.1. Restrictions

An image will have at most one time axis. Consequently, as long as the axis is identified through `CTYPE`*i*, there is no need to have axis number identification on the other 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` may be specified in the same image, but cannot be combined with any of the first nine time scales in Table 1; those first nine can be expressed as linear transformations of each other, too, provided the reference position remains unchanged.

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

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

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

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

If one of the axes is time and the matrix form is used, then the treatment of the `PC`*i_ja* (or `CD`*i_ja*) matrices involves at least a Minkowsky metric and Lorentz transformations (as contrasted with Euclidean and Galilean). This calls in the need to ensure that the references include the IAU resolutions on coordinates and metrics from the past two decades.

At this point I have inserted a SOHO/CDS header as suggested by Bill Thompson.

As an example we present a header in Table 5 (Example 2) that describes a SOHO Coronal Diagnostic Spectrometer observation from October 1998: a linear slit moves across the field from right to left during the observation, so different parts (columns) of the image are observed at different times. The example header defines the relations between the different coordinate systems by specifying a degenerate Time axis that is related to the first spatial pixel axis through a `PC`*i*_*j* matrix; the non-diagonal spatial elements are not zero since the detector was not aligned to solar north.

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

If we align the image to solar north, the header changes to what is shown in Example 3 (Table 6). One could still use the alternative description of Time as an alternate axis on longitude, but in that case it would need its own `PC`2_*jA* matrix.

4.2.3. `CRVAL`*ia*

One should be aware that, even if the zero point of time is specified by `DATEREF`, `CRVAL`*ia* is required to contain the elapsed time in units of `TIMEUNIT` or `CUNIT`*ia*; the WCS standard this keyword (`CRVAL`*ia*) to be numeric.

4.3. Time Columns in Tables

Example 4 (Table 7) 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 and TCG. Column 20 contains the time stamps in TDB with an alternate frame in TCB, columns 21 and 22 the events' positions.

The rules governing keywords defining the time in table columns (pixel as well as vector columns) are also largely being dealt with in Section 3 and summarized in Table 3, but, again, there are some aspects that require further elaboration.

Also 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 lacking any `TC*`*n* keywords will be controlled by the global keywords listed in Table 3. This is a common convention in existing files that will still be compliant with the present standard.

4.3.1. Restrictions

The same restrictions imposed on the image time axis (see Section 4.2.1) 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.

4.4. 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 4.2 for the rules. If time is to be transmitted through a group parameter, it simply means that the

`PTYPE`*i* (string-valued)

keyword needs to be set to one of the Time Scale codes from Table 1, just like the `CTYPE`*i*. All the global time reference frame keywords (see Table 3) apply, just as they would if `CTYPE`*i* were set to the same time scale value, except that there is no possibility of override since the `PUNIT`*i*, `PSYER`*i*, and `PRDER`*i* keywords are not defined in the standard.

5. Concluding Remarks

The following comments summarise some salient points that may otherwise go unnoticed, as they are buried in scattered places. These are currently just notes and will need to be turned into proper prose if thet are deemed to be important enough to be included

In images there will be 0 or 1 time axis, so having unnumbered global keywords apply to it is not problem as long as the time axis is identified.

All times scales in an image and all times scales on a single column in a table need to refer to the same `TREFPOS` or `TRPOS`*n*.

Linear alternative time scales may easily be specified for images and table columns; non-linear ones are not out of the question, but do not make much sense, as they are required to refer to the same `TREFPOS` or `TRPOS`*n*.

Time scale `LOCAL` is by itself; `TDB` and `TCB` are linearly related; and all the other time scales are linearly related to each other (except for leap seconds; see below).

All times 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 5 needs to account for the difference between `MJDREF`(TT) and `MJDREF`(UTC).

Times are relative, except when they are expressed as an ISO-8601 *datetime* string or, if and when available, data type `T`.

Times have special requirements when it comes to precision and, hence, data types. We anticipate at some time in the future that two new data types may be added to the FITS standard:

- `T`: ISO-8601 (as defined in the Y2k agreement; see Bunclark & Rots 1997)
- `S`: 128 bit quad floating point (IEEE 754-2008)

Times may then be expressed using data types `I`, `J`, `F`, `D`, `S`, or `T`, as appropriate.

As an alternative to the new datatype `S`, we recommend that relative elapsed times may also be expressed as `2D`, but require that the first element of the `2D` doublet vector contain the integer part, the second the fractional part of time. This is, in a way, an unfortunate bandaid, but not unprecedented, since the device is used in various ephemeris and timing packages.

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

In terms of backward compatibility: note that a binary table column with `TTYPE`*n* = '`TIME`' and lacking any `TC*n` keywords will be controlled by the global keywords listed in Table 3. Therefore, these files will not be invalidated.

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.

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Table 3. Time Scale Keywords

Keyword Description	Header Only	Images		Table Pixel Columns		Table Vector Columns	
		Single	Multiple	Primary	Alternate	Primary	Alternate
Informational Keywords							
Date of HDU creation[a]	DATE						
Date/time of whole observation	DATE-OBS						
Effective date/Time of observation	DATE-AVG						
	MJD-AVG						
Start date/time of observation	MJD-OBS						
	TSTART						
End date/time of observation	DATE-END						
	MJD-END						
	TSTOP						
Global Time Reference Frame Keywords							
Time scale	TIMESYS						
Zero point in MJD	MJDREF						
Zero point in JD	JDREF						
Zero point in ISO-8601	DATEREF						
Reference position	TREFPOS						
Reference direction	TREFDIR						
Solar System ephemeris	PLEPHEM						
Time unit	TIMEUNIT						
Time resolution	TIMEDEL						
Time offset	TIMEOFFS						
Time position in pixel	TIMEPIXR						
Absolute Error	TIMSYER						
Relative Error	TIMRDER						
Optional Context-Specific Override Keywords							
Time scale	TIMESYS	CTYPE*i*	CTYPE*ia*	TCTYP*n*	TCTY*na*	*i*CTYP*n*	*i*CTY*na*
Reference position	TREFPOS			TRPOS*n*		TRPOS*n*	
Reference direction	TREFDIR			TRDIR*n*		TRDIR*n*	
Time unit	TIMEUNIT	CUNIT*i*	CUNIT*ia*	TCUNI*n*	TCUN*na*	*i*CUNI*n*	*i*CUN*na*
Absolute Error	TIMSYER	CSYER*i*	CSYER*ia*	TCSYE*n*	TCSY*na*	*i*CSYE*n*	*i*CSY*na*
Relative Error	TIMRDER	CRDER*i*	CRDER*ia*	TCRDE*n*	TCRD*na*	*i*CRDE*n*	*i*CRD*na*
Context-Specific Keywords							
Time axis name		CNAME*i*	CNAME*ia*	TCNAM*n*	TCNA*na*	*i*CNAM*n*	*i*CNA*na*
Time axis reference pixel		CRPIX*i*	CRPIX*ia*	TCRPX*n*	TCRP*na*	*i*CRPX*n*	*i*CRP*na*
Time axis reference value		CRVAL*i*	CRVAL*ia*	TCRVL*n*	TCRV*na*	*i*CRVL*n*	*i*CRV*na*
Time scaling		CDELT*i*	CDELT*ia*	TCDLT*n*	TCDE*na*	*i*DLT*n*	*i*CDE*na*
Transformation matrix		CD*i_j*	CD*i_ja*	TC*n_ka*		*ij*CD*na*	
Transformation matrix		PC*i_j*	PC*i_ja*	TP*n_ka*		*ij*PC*na*	

[a] In UTC at Earth's surface

Table 4. Cube with two spatial & one time axis

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

SIMPLE  =                    T / Fits standard
BITPIX  =                  -32 / Bits per pixel
NAXIS   =                    3 / Number of axes
NAXIS1  =                 2048 / Axis length
NAXIS2  =                 2048 / Axis length
NAXIS3  =                   11 / Axis length
DATE    = '2008-10-28T14:39:06' / Date FITS file was generated
OBJECT  = '2008 TC3'           / Name of the object observed
EXPTIME =               1.0011 / Integration time
MJD-OBS =       54746.02749237 / Obs start
DATE-OBS= '2008-10-07T00:39:35.3342'    / Observing date
TELESCOP= 'VISTA   '           / ESO Telescope Name
INSTRUME= 'VIRCAM  '           / Instrument used.
TIMESYS = 'UTC     '           / From Observatory Time System
TREFPOS = 'TOPOCENT'           / Topocentric
MJDREF  =              54746.0 / Time reference point in MJD
RADESYS = 'ICRS    '           / Not equinoctal
CTYPE2  = 'RA---ZPN'           / Zenithal Polynomial Projection
CRVAL2  =     2.01824372640628 / RA at ref pixel
CUNIT2  = 'deg     '           / Angles are degrees always
CRPIX2  =               2956.6 / Pixel coordinate at ref point
CTYPE1  = 'DEC--ZPN'           / Zenithal Polynomial Projection
CRVAL1  =     14.8289418840003 / Dec at ref pixel
CUNIT1  = 'deg     '           / Angles are degrees always
CRPIX1  =               -448.2 / Pixel coordinate at ref point
CTYPE3  = 'UTC     '           / linear time (UTC)
CRVAL3  =             2375.341 / Relative time of first frame
CUNIT3  = 's       '           / Time unit
CRPIX3  =                  1.0 / Pixel coordinate at ref point
CTYPE3A = 'TT      '           / alternative linear time (TT)
CRVAL3A =             2410.525 / Relative time of first frame
CUNIT3A = 's       '           / Time unit
CRPIX3A =                  1.0 / Pixel coordinate at ref point
OBSGEO-B=             -24.6157 / [deg] Tel geodetic latitute (=North)+
OBSGEO-L=             -70.3976 / [deg] Tel geodetic longitude (=East)+
OBSGEO-H=            2530.0000 / [m]   Tel height above reference ellipsoid
CRDER3  =               0.0819 / random error in timings from fit
CSYER3  =               0.0100 / absolute time error
PC1_1   =    0.999999971570892 / WCS transform matrix element
PC1_2   =    0.000238449608932 / WCS transform matrix element
PC2_1   =   -0.000621542859395 / WCS transform matrix element
PC2_2   =    0.999999806842218 / WCS transform matrix element
CDELT1  =  -9.48575432499806E-5 / Axis scale at reference point
CDELT2  =   9.48683176211164E-5 / Axis scale at reference point
CDELT3  =              13.3629 / Axis scale at reference point
PV1_1   =                   1. / ZPN linear term
PV1_3   =                  42. / ZPN cubic term
END
```

Table 5. Header extract of an image where Time is emtangled with Space

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

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

Table 6. Header extract of an image where Time is entangled with Space needing a PC matrix

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

SIMPLE  =                    T /Written by IDL:  Fri Sep 25 14:01:44 2009
BITPIX  =                  -32 /Real*4 (floating point)
NAXIS   =                    4 /
NAXIS1  =                   20 / Wavelength
NAXIS2  =                  120 / Longitude
NAXIS3  =                  143 / Latitude
NAXIS4  =                    1 / Time (degenerate)
DATE    = ’2009-09-25’         /
BUNIT   = ’erg/cm^2/s/sr/Angstrom’ /
DATE-OBS= ’1998-10-25T16:59:41.823’ /
DATEREF = ’1998-10-25T16:59:41.823’ /
TIMESYS = ’UTC     ’           / We will use UTC
CTYPE1  = ’WAVE    ’           /
CUNIT1  = ’Angstrom’           /
CRPIX1  =              10.5000 /
CRVAL1  =              629.682 /
CDELT1  =           0.11755400 /
CTYPE2  = ’HPLN-TAN’           /
CUNIT2  = ’arcsec  ’           /
CRPIX2  =              60.5000 /
CRVAL2  =              897.370 /
CDELT2  =            2.0320000 /
CTYPE3  = ’HPLT-TAN’           /
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 7. Header extract of a binary table (event list) with two time columns

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

COMMENT      ----------  Globally valid key words  ----------------

TIMESYS = ’TT      ’           / Time system   REPEATED FOR CLARITY    ###
MJDREF  =  50814.000000000000  / MJD zero point for (native) TT        ###
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

COMMENT      ----------  First Time Column  -----------------------

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

TCTY1A  = ’UTC     ’           / UTC  ELAPSED seconds since MJDREFA
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  = 0.46184717           / But TCG is already ahead of TT at MJDREFB
TCDE1B  = 1.0000000006969291   / And it keeps running faster

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 = ’TTYPE21,TTYPE22’    / Reference direction is found in cols 21 and 22
TCNA20  = ’Barycentric Dynamical Time’ / This is TDB
TCUNI20 = ’s       ’
TCRPX20 = 0.0                  / MJDREF is the true zero point for Barytime ...
TCRVL20 = 0.0                  / ...and relative time is zero there
TCDLT20 = 1.0                  / 1 s is 1 s
```

Table 7 (cont’d)

```
123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

TCRD20  =  1.0000000000000E-09 / Relative error
TCSY20  =  5.0000000000000E-05 / Absolute error

TCTY20C = ’TCB     ’           / TCB
TCNA20C = ’Barycentric Coordinate Time’ / This is TCB
TCUN20C = ’s       ’           / still in seconds
TCRP20C = 0.0                  / MJDREF is the reference point
TCRV20C = 10.27501057          / But TCB is already ahead of TDB at MJDREF
TCDE20C = 1.00000001550505     / And it keeps running faster

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
```