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To: Distribution

From: R. DeMajistre

Subject: TIMED Position and Attitude Geometry Description

Introduction

In an effort to control costs and simplify ground system processing, the TIMED mission is not post-processing spacecraft telemetry on the ground for use by the instrument teams. The uses of an on-board GPS receiver and a robust attitude determination system have all but eliminated the need for operational post-processing analysis of spacecraft position and attitude. The lack of post-processing does, however, require the science and instrument teams to have a firm understanding of the information produced by the spacecraft. It is the purpose of this memo to communicate the basic conventions that are used by the spacecraft subsystems for the communication of spacecraft position and attitude.

Scope

This memo details the coordinate systems, attitude specification and timing conventions and summarizes the major modes and states of the Navigation and Attitude systems aboard TIMED. This memo should give enough information for the development of algorithms for pointing determination and other geometric tasks required by the science and instrument teams. It does not, however, discuss telemetry formats, thus cannot be used as a specification for telemetry processing software.

References

Reference 1 **–** "TIMED General Instrument Interface Specification," *APL Document 7363-9050, May 1998.*

Reference 2 **–** *Hoffinann-Wellenhoff B, H. Lichtenegger and J. Collins,* **GPS Theory and Practice,** Spinger-Verlag Wein, *New York, 1997.*

Reference 3 **–** *Wertz, James,* **Spacecraft Attitude Determination and Control,** *Kluwer Academic Publishers, Boston, 1990.*

Reference 4 **– The Astronomical Almanac For the Year 1995,** *U.S. Government Printing Office, 1995.*

Reference 5 **–** *"TIMED GPS Navigation System (GNS) External Software lCD," APL Document 7363-9332B, Apr. 1998.*

TIMED Coordinate Systems

Several different coordinate systems are used to describe position and attitude for TIMED. The following coordinate systems are commonly used by the various spacecraft subsystems. Table 1 provides a summary of the systems used for TIMED.

Name	**Common Coordinate References**	**Definition**	**Notes**
Earth Centered Inertial (ECI/CIS)	(x,y,z) Cartesian (ρ,α) right ascension, declination	Z along Earth's rotation axis X towards Vernal equinox	Referenced to expected positions on Jan. 1, 2000. Axes parallel to J2000 system
Earth Centered Earth Fixed (ECEF/CTS)	(x,y,z) Cartesian (λ,ϕ,r) longitude, latitude, radius (λ,ϕ,a) longitude, latitude, altitude	Z along Earth's rotation axis X along ray from Earth's center to Greenwich Meridian	System rotates with the Earth. Z axis is slightly displaced from ECI Z axis. Displacement is a function of time.

Name	**Common Coordinate References**	**Definition**	**Notes**
Geodetic Coordinates	(λ,ϕ,a) longitude, latitude, altitude	Longitude and latitude are the angular coordinates of the surface normal that passes through point of interest. Altitude is the length of the normal	Uses WGS-84 ellipsoid as shape model. This is not a Cartesian system. Identical to ECEF system if a spherical Earth is assumed.
Spacecraft Body Fixed	(x,y,z) Cartesian	Defined by optical cubes	
Nominal Orbit Relative (NOR)	(x,y,z) Cartesian	Z axis is local radius vector, directed downward Y axis perpendicular to orbit plane X axis either toward ram or wake	Direction of X determined by ground command. Spacecraft commanded to align the Spacecraft Body Fixed system with this frame. Valid only during nominal operations
Local Vertical Local Horizontal (LVLH)	(x,y,z) Cartesian (r,p,y) roll, pitch, yaw (α,ε) azimuth, elevation	Z axis is local radius vector, directed upward Y axis perpendicular to orbit plane X axis toward	
East North Up (ENU)	(x,y,z) Cartesian	Z axis is parallel to local surface normal. X axis eastward	

Table 1. Summary of coordinate systems. Detailed descriptions of these systems are given below in the text.

Earth Centered Inertial (ECI)

Unless otherwise noted, all inertial (non-rotating) coordinates reference a system where the origin is the Earth's center of mass, and the Z and X axes are parallel to the J2000 system. In this system, the z-axis points along the Earth's rotation axis at the standard epoch of January 1, 2000. The x-axis points towards the vernal equinox at the same epoch. Some TIMED documentation, following Reference 2, refers to this system as the Conventional Inertial System or CIS.

Earth Centered Earth Fixed (ECEF)

The Earth Centered Earth Fixed (ECEF) system is also a Cartesian system whose origin is the Earth's center of mass. In this system the z-axis is oriented along the Earth's rotation axis and the x-axis is defined by the Greenwich meridian. This system spins with respect to ECI at a rate of one revolution per sidereal day. There is also a small slow drift of the z-axis of this system with respect to the ECI z-axis. The conversion between ECEF and ECI coordinates must account for the Earth's rotation rate, planetary nutation, precession and polar motion. The polar motion correction is small and is sometimes neglected. Reference 2 and Reference 4 provide conversion algorithms between these systems. Reference 2 refers to this as the Conventional Terrestrial System (CTS).

It should be noted that the rotation axis of the Earth exhibits a slight quasi-periodic geographic variation of about 9 meters. This effect is often referred to as polar motion (e.g., Reference 2). This effect is corrected by the GNS subsystem, and referenced to the mean pole in the year 1905. In its conversions between ECEF and Ed, the attitude system does not take this effect into account. The magnitude of the effect is small enough so that this difference should be insignificant.

Geodetic Coordinates

Geodetic coordinates are given in longitude, latitude and altitude referenced to the WGS 84 ellipsoid. The characteristics of this ellipsoid are given in Table 2 and described in Reference 2 and Reference 4. This system is similar to the ECEF system, though the geodetic system is not Cartesian. This system is described in detail in Reference 4; this reference also contains algorithms to convert from ECEF to geodetic coordinates and geodetic coordinates.

Parameter	**Value**
Equatorial Radius (a)	6378.137 km
Flattening (1/f)	298.257223563

Table 2. WGS 84 ellipsoid parameters

Spacecraft body fixed

The spacecraft body fixed coordinate system is discussed in Reference 1 section 6. The nominal Z and Y axes are normal to the sides of the spacecraft where GUVI and SABER are mounted respectively. Reference 1 states that "The specific body frame will be defined by an optical cube mounted on the optical bench. All scientific and attitude instruments will be aligned relative to this cube". Alignment measurements will be conducted during integration and test of the TIMED spacecraft. The instrument teams must monitor changes to the alignment after launch.

Nominal Orbit Relative (NOR)

During nominal on orbit operations, the attitude system will attempt to align the spacecraft body fixed axes with the nominal orbit relative coordinate system. Both of these coordinate systems have the same origin. The Z axis of the nominal orbit relative coordinate system points toward the center of the Earth (anti-parallel to the local radius vector, not the surface normal) in an inertial frame. The X and Y axes are constructed as follows:

Equation 1

$$\hat{\mathbf{y}} = \pm \frac{\hat{\mathbf{z}} \times \mathbf{v}}{\sqrt{\left|\hat{\mathbf{z}} \times \mathbf{v}\right|^2}}$$

Equation 2

$$\hat{\mathbf{x}} = \hat{\mathbf{y}} \times \hat{\mathbf{z}}$$

In the above equations, **v** is the velocity vector in an inertial frame. The sign in Equation 1 is changed at approximately six-week intervals by a spacecraft command to keep the +Y axis from pointing towards the sun.

In a perfectly circular orbit, the X axis of this system would point along (or anti-parallel to) the velocity vector. The residual eccentricity of the orbit will cause the velocity vector to differ slightly from the direction of the X axis.

Local Vertical Local Horizontal (LVLH)

The local horizontal local vertical (LVLH) system is identical to the nominal orbit relative system when the sign on the right hand side of Equation 1 is positive. This system is only defined by the position and velocity of the spacecraft, whereas the nominal orbit relative system is defined by position, velocity and commanded attitude of the spacecraft.

East-North-Up (ENU)

East-North-Up (ENU) is a right handed Cartesian system defined by the spacecraft position in geodetic coordinates. The origin of the system is the center of mass of the spacecraft. The Z axis (up) is parallel to the local altitude vector (surface normal). The X axis (east) is defined by

Equation 3

$$\hat{\mathbf{x}}_{ENU} = \frac{\hat{\mathbf{z}}_{ECEF} \times \hat{\mathbf{z}}_{ENU}}{\sqrt{\left|\hat{\mathbf{z}}_{ECEF} \times \hat{\mathbf{z}}_{ENU}\right|^2}}$$

and the Y axis (north) completes the system. This system is undefined when the spacecraft is directly over the Earth’s poles.

Spacecraft Attitude

Spacecraft attitude specifies the orientation of the spacecraft body fixed coordinate system with respect to another known coordinate frame. Under most circumstances, the attitude control system will attempt to align the spacecraft body fixed axes with the nominal orbit relative axes. We assume that all the coordinate systems listed above (with the exception of the spacecraft body fixed system) are either known *a priori* (e.g., ECI, ECEF) or require only knowledge of the position and velocity vectors of the spacecraft (e.g. ENU, LVLH). Thus, once the orientation of the body fixed coordinate system is known with respect to another coordinate system, its orientation can be found in all systems. For most purposes, knowledge of the spacecraft attitude is required so that a vector represented in spacecraft body fixed coordinates (such as a line of sight unit vector) can be transformed into a physically meaningful coordinate system.

For TIMED, spacecraft attitude is specified in either quaternions or roll, pitch and yaw angles. The former can be used to transform vectors into ECI coordinates, the latter can be used to transform vectors into either LVLH or nominal orbit relative coordinates.

Quaternions

Quaternions, as well as several other representations of spacecraft attitude are described in detail in chapter 12 of Reference 3 under the name *Euler symmetric parameters.* They can be viewed as a four-element object from which the rotation matrix from ECI into spacecraft body fixed coordinates can be calculated. Given a vector in spacecraft body fixed coordinates, $\mathbf{P}_{bf}$, and the quaternion $\mathbf{q}=[q_1, q_2, q_3, q_4]^T$ we wish to find the vectors representation in ECI coordinates $\mathbf{P}_{eci}$. We can do this by constructing the following transform

Equation 4

$$\mathbf{P}_{eci} = \mathbf{A}_q \mathbf{P}_{bf}$$

Where the rotation matrix $\mathbf{A}_q$ is constructed from the quaternion as

Equation 5

$$\mathbf{A}_q = \begin{vmatrix} q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 + q_2q_4) \\ 2(q_1q_2 + q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_2q_3 - q_1q_4) \\ 2(q_1q_3 - q_2q_4) & 2(q_2q_3 + q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2 \end{vmatrix}$$

or alternatively

Equation 6

$$\mathbf{q} = \begin{vmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{vmatrix} \equiv \begin{vmatrix} \mathbf{q}_0 \\ q_4 \end{vmatrix}$$

$$\mathbf{Q(q}_0) \equiv \begin{vmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{vmatrix}$$

$$\mathbf{A}_q = (q_4^2 - \mathbf{q}_0^2)\mathbf{1} + 2\mathbf{q}_0\mathbf{q}_0^T + 2q_4\mathbf{Q(q}_0)$$

Reference 3 describes additional computational properties of quaternions that may be of interest.

Roil, Pitch and Yaw Angles (RPY)

The RPY angles describe a transformation between the actual spacecraft body fixed system and the NOR system. The RPY angles are essentially the Euler angles for rotations about the x,y,z axes respectively (see Reference 3). Under most circumstances, these angles will be very small, since the spacecraft is generally commanded to be aligned with the NOR system. The TIMED attitude system will use small angle approximations to determine these angles.

Because small angles are assumed:

1. the transformation is independent of the order of the rotations.

2. when the spacecraft is far from the NOR system (+/- 5 degrees or so), the RPY angles should not be used (and will not be supplied). Note that if additional spacecraft maneuvers are implemented, the implementation of the roll, pitch and yaw angles will need to be re-examined.

Under the assumption of small angles, and labeling the roll, pitch and yaw angles as ϕ,θ and ψ, respectively, we can write the transformation of body fixed coordinates to NOR as

Equation 7

$$\mathbf{P}_{bf} = \frac{\mathbf{A}_{\phi,\theta,\psi}\mathbf{P}_{NOR}}{\sqrt{\left|\mathbf{A}_{\phi,\theta,\psi}\mathbf{P}_{NOR}\right|^{2}}}$$

Where

Equation 8

$$\mathbf{A}_{\text{ö,è,ø}} = \begin{vmatrix} 1 & \psi & -\theta \\ -\psi & 1 & \phi \\ \theta & -\phi & 1 \end{vmatrix}$$

Again, since the other systems are given *a priori*, vectors in the NOR system can be transformed into the desired frame of reference.

Attitude Rates

Attitude rates are reported at the same frequency as the quaternions and the RPY angles. The rates, ω_x, ω_y, ω_z, are defined as the components of the inertial angular velocity vector in instantaneous spacecraft body fixed coordinates. To illustrate this representation, for a circular orbit with perfect attitude control, the attitude rate vector would be [0,+/- 1/T, 0], where T is the period of the orbit. That is, the spacecraft rotates once around its Y axis every orbit.

These rates can be used to estimate the spacecraft attitude during the time between two reported quaternions (see Reference 3). For short time intervals At, the attitude at q(t+ At) can be approximated as

Equation 9

$$\mathbf{q}(t+\Delta t) \cong [1+\frac{1}{2}\mathbf{W}\Delta t]\mathbf{q}(t)$$

$$\mathbf{W} = \begin{vmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{vmatrix}$$

Spacecraft Timing

Time on the TIMED spacecraft is measured in GPS time, which is the number of seconds elapsed since midnight on January 6, 1980 (Julian date 2444244.5). A straightforward description of GPS time and other time systems is given in Reference 2. A summary of this description is presented here.

Summaries of various relevant systems of time reference are given in Table 3. The time systems are labeled as atomic or dynamical based on whether they are based on an atomic clock reference or the motion of celestial bodies. We will treat each of these systems in the order given in the table.

Time System	**Reference**	**Purpose**
GPS Time	Atomic	TIMED spacecraft time
UTC	Atomic	Calendar time and proxy for dynamical time
UT1	Dynamical	Measure of solar time
GAST	Dynamical	Used to relate inertial and rotational coordinate systems

Table 3. Time systems relevant to TIMED

GPS Time

GPS time provides a monotonic count of the number of seconds since the GPS epoch (6-jan-1980). All time tagged telemetry on the TIMED spacecraft references GPS time. The GNS and C&DH subsystems on board the spacecraft provide coordination for time distribution. Time is distributed on the spacecraft every second on the second.

In the event that the GNS subsystem loses contact with the GPS, the spacecraft will be able to propagate time using on board oscillators. When contact with the constellation is restored, any drift that has occurred will be corrected for by a steering of the time signal by the C&DH. Details of the various modes of the GNS will be described in another section.

UTC

Whereas GPS time provides a monotonic count of seconds since an epoch, UTC is periodically adjusted to account for the difference between atomic and dynamical times. Dynamical time has a slow drift with respect to atomic time. When the cumulative drift exceeds 0.9 seconds, a second is added to (or subtracted from) UTC on a pre-defined date. These are the so-called leap seconds. Leap seconds may be added on either January 1 or July 1 of each year. A table of leap seconds is maintained at the US Naval Observatory, and a complete list of leap seconds can be found on the web at ftp://maia.usno.navy.mil/ser7/tai-utc.dat. UTC should be used to derive calendar time, and is also used as a proxy for UT1 dynamical time.

The following algorithm can be used to convert from GPS time to UTC using the data from the above USNO FTP site for a GPS time on a given date.

1) Locate the entry in the table immediately before the given date

2) Find the (TAI-UTC) value for that entry

3) UTC= [GPS time]-[(TAI-UTC)-19]

In the data file, the atomic reference is TAI, which starts from a different epoch than GPS time. During the period between the TAI epoch and the GPS epoch, the equivalent of 19 leap seconds were added, thus the 19 appears in number 3 above.

As an example, during the period between July 1, 1997 and January 1,1999, UTC lags GPS time by 12 seconds. At midnight on Jan. 1 1999, a leap second will be inserted, and UTC will lag GPS by 13 seconds. Thus it can be seen that at rare intervals, UTC is not unique or sequential.

UT1

UTC is a compromise between atomic times, such as GPS times, and dynamical times like UT1. Seconds in UT1 are related to the length of the Solar day rather than atomic decay. UTC is maintained so that the difference between UT1 and UTC is always less than 1 second. Thus the angular error between UT1 and UTC is less than 360/86400 or about 0.004 degrees. UTC is thus an adequate proxy for UT1, so the details of the drift of the Earth's rotation rate need not be tracked.

GAST

Greenwich apparent sidereal time, or GAST, is the quantity used in most algorithms for transformation between inertial reference frames and frames of reference which co-rotate with the earth. GAST is essentially a measure of the position of the Greenwich meridian with respect to the celestial reference frame. Reference 2 provides algorithms for transformations using GAST, as well as algorithms for deriving GAST from UT1. For the purposes of TIMED data processing UTC may be substituted into this algorithm for UT1.

G&C System Modes, States and Events

The TIMED attitude system will operate in one of three modes:

1) Operational

2) Nadir Pointing

3) Safe

Under most circumstances, the G&C should be in operational mode. With the exception of brief periods of time during yaw maneuvers and solar panel rotations, the attitude system is within its operating specifications when it is in the operational mode. Since the G&C sensors provide attitude information in an inertial reference frame, information about the relative position of the Earth with respect to the satellite is required from the GNS subsystem to maintain operational attitude. Thus the maintenance of the operational attitude mode requires that both the G&C and GNS subsystems meet their operational requirements.

When, because of an anomalous circumstance, the performance of the G&C subsystem is degraded, or the information about the spacecraft's position from the GNS is either unreliable or temporarily unavailable, the attitude system will be placed in nadir pointing mode. In this mode, the G&C maintains a relaxed operational attitude. In this mode, operational pointing will be maintained to within 5 degrees or so. The instruments may continue to operate while the spacecraft is in this mode, but the data acquired may not be useful.

When the G&C determines that it is unable to maintain the relaxed attitude of the nadir-pointing mode, it will place the spacecraft in safe mode. In this mode, the -Y axis is pointed to within +/-10 degrees of the sun. The instruments will be shut off shortly after the initiation of this mode. It takes the spacecraft roughly 20 minutes to achieve the sun pointing orientation; it also takes roughly 20 minutes to move from the sun pointing orientation to the operational orientation.

The two events that are signaled by the G&C in operational mode are the solar panel rotation and the yaw maneuver. The solar panels will be rotated approximately daily to maintain maximum exposure of the panels to the sun as the orbit precesses. During these rotations, the jitter specifications may be violated. The solar panel rotation event begins 15 seconds before the actual rotation begins, and continues until pointing accuracy is restored.

Approximately every six weeks, the spacecraft will perform a 180-degree yaw about its z-axis (see above). Clearly, during the period of the yaw maneuver, the spacecraft will not be in one of its operational orientations, and the pointing specifications do not apply. The yaw maneuver event begins sixty seconds before the actual rotation, and continues until pointing accuracy is restored.

GNS System Modes, States and Events

The GNS subsystem will operate in the following modes

1) GPS Navigation

2) Non-GPS navigation

3) Separation Sequence

Under most circumstances, the GNS subsystem will be in GPS navigation mode. This is the mode where the GNS uses the GPS constellation to determine the spacecraft's position and velocity. This is the only mode that is certified where the spacecraft position knowledge specification is met.

When, under anomalous circumstances, information is not available from the GPS constellation, the GNS will be placed in non-GPS mode. In this mode, the GNS propagates state vectors that have been uploaded from the ground system. Other modes will not be used when the instruments are gathering data. In a broad-brush sense, only data taken in GPS navigation mode should be trusted.

In addition to the navigation mode identifier, the GNS also supplies a "time precision word". This is a 2 bit word with the possible values [raw, course, semi-precise and precise]. Only data marked as precise is within the specifications.

The GNS subsystem also provides several event flags for processing on board. These flags are as follows:

SAA event flag: This flag is set when the spacecraft sub-point is within an area designated by the SAA. The SAA boundaries are loadable, and thus the definition of the region can be changed if necessary. The provisional boundary is the octagonal boundary defined by UARS/SOLSTICE.

Polar Region event flag: This flag is set when the absolute value of the spacecraft sub-point latitude exceeds a given value. This value has not been determined yet.

Day/Night event flag: This flag is toggled each time the spacecraft sub-point crosses the terminator. Note that this flag does not indicate whether or not the spacecraft is in eclipse.

Time Jump event flag: This flag indicates that the C&DH and GNS subsystems are synchronizing their clocks. This flag should only be set after spacecraft separation or after a GNS reset.

Conclusion

This memo presents the conventions necessary for the ground processing of the spacecraft position and attitude information reported by the TIMED spacecraft. The information here has been culled from the references and conversations from the subsystem developers.

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