### Time Systems

Five time systems are of primary interest for the IAS geometric algorithms: Terrestrial Time (TT), International Atomic Time (Temps Atomique International [TAI]), Universal Time—Coordinated (UTC), Universal Time—Corrected for polar motion (UT1), and Spacecraft Time (the readout of the spacecraft clock, derived from GPS time). Terrestrial time is the astronomic time system used for planetary and stellar ephemerides (e.g., star catalogs) and to model Earth precession and nutation. It is thus used in the conversion from Earth-centered inertial (ECI) of epoch J2000 coordinates to ECI true-of-date coordinates. Spacecraft Time is the time system used for the spacecraft time codes found in the Level 0R ancillary data (including image time codes). UTC is the standard reference for civil timekeeping. UTC is adjusted periodically by whole leap seconds to keep it within 0.9 seconds of UT1. UT1 is based on the actual rotation of the Earth and is needed to provide the transformation from stellar-referenced inertial coordinates (ECI true-of-date) to terrestrial-referenced Earth-centered Earth-fixed coordinates (ECEF). TAI provides a uniform, continuous time stream that is not interrupted by leap seconds or other periodic adjustments. It provides a consistent reference for resolving ambiguities arising from the insertion of leap seconds into UTC, which can lead to consecutive seconds with the same UTC time. Spacecraft time is based on GPS time, which is, itself, a fixed offset from TAI. The Explanatory Supplement to the Astronomical Almanac, mentioned previously, describes these and a variety of other time systems and their relationships. The following text describes the significance of each of these time systems, with respect to the IAS geometric algorithms.

1. Terrestrial Time

Epoch J2000 occurred at January 1, 2000 12:00:00 Barycentric Dynamical Time (TDB). Terrestrial Dynamical Time (TDT), known simply as Terrestrial Time (TT) since the IAU resolutions of 1991, is the time scale used for apparent geocentric ephemerides. At the time of the J2000 epoch, TT differed from TDB by approximately 73 microseconds (ref. Explanatory Supplement to the Astronomical Almanac). This small difference is ignored in the definition above, and the J2000 epoch is effectively taken to be January 1, 2000, 12:00:00 TT. The difference between TDB and TT is due to relativistic effects and is a periodic function containing terms as large as 1-2 milliseconds. This difference is accounted for by the USNO NOVAS software in its precession and nutation computations, but this is transparent to the time and coordinate system conversion logic that invokes the NOVAS functions.

Epoch J2000.0 TT is now considered to be the “standard epoch” for modern astrometric reference data (Ref. USNO Circular 179). TT is defined to be TAI + 32.184 seconds, so the J2000 epoch is 12:00:00 TT = 11:59:27.816 TAI + 32.184 sec. Furthermore, at the time of the J2000 epoch, TAI and UTC differed by 32 accumulated leap seconds, so 11:59:27.816 TAI = 11:58:55.816 UTC + 32.000 sec. Note that the relationship between TT and TAI is fixed, but the relationship between TT and UTC changes over time, with the offset increasing by one second each time a new leap second is declared. As of the date of this document, five additional leap seconds have been declared since the J2000 epoch: in January 2006, January 2009, July 2012, June 2015, and January 2017.

1. Spacecraft Time

In accordance with the Landsat Data Continuity Mission Spacecraft to Ground Interface Control Document (70-P58230P, Rev C), the L8 spacecraft clock reports time as TAI seconds since the spacecraft epoch, defined to coincide with the J2000 epoch:

January 1, 2000, 11:59:27.816 TAI.

Which is the same as the following:

January 1, 2000, 11:58:55.816 UTC.

Although L8 and L9 both use GPS as the time reference source, they use different GPS receivers. The L9 receiver is constrained to issue one-pulse-per-second (PPS) time marks only on whole GPS second boundaries. The ACS flight software operates on a 50 Hz cycle synchronized to the 1 PPS signals, with particular events (e.g., polling attitude sensors, computing attitude updates) occurring on predefined 50 Hz clock ticks. Using a clock epoch that is not aligned with GPS second boundaries would complicate the management of critical timing relationships in the flight software. As a result, the decision was made (by Orbital ATK) for L9 (still to be confirmed) that it would be simpler to define the spacecraft clock epoch as a whole number of seconds offset relative to TAI. This makes the offset between the spacecraft clock and the GPS system a whole number of seconds since the GPS epoch is aligned with TAI. The L9 spacecraft clock thus reports time as TAI seconds since the spacecraft epoch, defined as follows:

January 1, 2000, 11:59:28.000 TAI.

Which is the same as the following:

January 1, 2000, 11:58:56.000 UTC.

The L9 spacecraft clock epoch is thus 0.184 seconds later than the L8 spacecraft clock epoch. This “round off” offset has to be taken into account when converting L9 spacecraft time codes into seconds from J2000.0 TT for purposes of ECI to ECEF conversion.

The L8/9 flight software maintains the accuracy of the spacecraft clock, using time data from the on-board GPS receiver(s). The spacecraft clock is then used to time tag the spacecraft ancillary data and to provide a timing reference for the OLI and TIRS instruments. As noted above, spacecraft time is used to define the times at which the flight software generates filtered attitude and ephemeris estimates based on the input GPS, star tracker, and SIRU data. These estimates are included in the spacecraft ancillary data stream for use by ground processing. Also included in the ancillary data are the raw SIRU measurements. Individual SIRU observations are time tagged using a clock/counter internal to the SIRU itself, but the SIRU ancillary data also includes SIRU time synch events that make it possible to relate the SIRU clock to spacecraft time.

The spacecraft clock also provides time synchronization signals to the OLI and TIRS instruments once per second. Both instruments use the 1 PPS signals to regulate their internal clocks, thereby registering the image time codes to spacecraft time. Note that any instrument clock rate errors will manifest as (small) step discontinuities in the image time codes, which correspond to the 1 PPS updates. The resulting time code irregularities are corrected when the OLI and TIRS geometric models are created, as described below in the OLI LOS Model Creation algorithm and the TIRS LOS Model Creation algorithm.

1. UTC

As mentioned above, UTC is maintained within 0.9 seconds of UT1 by the occasional insertion of leap seconds. A table of leap seconds relating UTC to TAI is maintained in the L8/9 CPF to support the spacecraft time to UTC conversion. To convert spacecraft time to UTC, the number of additional leap seconds declared since the spacecraft epoch are subtracted from the reported spacecraft seconds since epoch and the result is added to the UTC representation of the epoch presented above. Leap second information is available from the International Earth Rotation Service (IERS) in their Bulletin C publications.

1. UT1

UT1 represents time with respect to the actual rotation of the Earth, and is used by the IAS algorithms, which transform inertial ECI coordinates or lines of sight to Earth-fixed ECEF coordinates. Failure to account for the difference between UT1 and UTC in these algorithms can lead to ground position errors as large as 400 meters at the equator (assuming the maximum 0.9-second UT1-UTC difference). The UT1-UTC correction typically varies at the rate of approximately 2 milliseconds per day, corresponding to an Earth rotation error of about 1 meter. Thus, UT1-UTC corrections should be interpolated or predicted to the actual image acquisition time to avoid introducing errors of this magnitude. The UT1-UTC offset, along with the polar wander Earth orientation parameters, can be obtained from IERS Bulletin B (for retrospective data) and Bulletin A (for predicted data). The L8/9 CPF also includes tables of the UT1-UTC and polar wander Earth orientation parameters.

1. TAI

Although the IAS algorithms do not operate directly in TAI, it underlies the definition of spacecraft time, as noted above. As such, it can be helpful to use TAI as a standard reference that can be related to UTC, using the CPF leap second file, and to spacecraft time, via the constant offset, to assist IAS operations staff in anomaly resolution.