1. Candidate VALUEs FOR SANA REGISTRY Pertaining to TIME SYSTEMs, reference frames, orbit elements and covariance-RELATED KEYWORDS

(Normative)

The values in this document represent the set of acceptable values for the TIME\_SYSTEM, REF\_FRAME, OEB\_FRAME, MAN\_REF\_FRAME, ORB\_REF\_FRAME, COV\_REF\_FRAME and STM\_REF\_FRAME keywords in the OPM, OMM, OEM and OCM. (For details and description of these time systems, see reference [L1]) If exchange partners wish to use different settings, the settings should be documented in the ICD.

* 1. TIME\_SCALES Metadata Keyword

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description and reference** | **Nomenclature** | **Default Units/Type** |
| BEIDOU | BeiDou Time (BDT) is a continuous time scale starting at 0h UTC on January 1st, 2006 and is synchronized with UTC within 100 ns< (modulo one second). |  |  |
| GALILEO | Galileo System Time (GST) is a continuous time scale maintained by the Galileo Central Segment and synchronized with TAI with a nominal offset below 50 ns. The GST start epoch is 0h UTC on Sunday, 22 August 1999 (midnight between 21 and 22 August). |  |  |
| GLONASS | GLONASS Time (GLONASST) is generated by the GLONASS Central Synchronizer and the difference between the UTC(SU) and GLONASST should not exceed 1 millisecond plus three hours[http://www.navipedia.net/index.php/Time\_References\_in\_GNSS - cite\_note-2](http://www.navipedia.net/index.php/Time_References_in_GNSS#cite_note-2) (the difference between Moscow Time and Greenwich Mean Time (GMT)), but http://www.navipedia.net/images/math/8/1/a/81a69207104f00baaabd6f84cafd15a0.png is typically better than 1 microsecond. Note: Unlike GPS, Galileo or BeiDou, GLONASS time scale implements leap seconds, like UTC. |  |  |
| GAST | Greenwich Apparent Sidereal Time is measured from the true vernal equinox relative to the Greenwich meridian, which includes secular and periodic contributions to the motion of the vernal equinox. |  |  |
| GMST | Greenwich Mean Sidereal Time (GMST) is defined as the Greenwich hour angle of the mean vernal equinox of date. |  |  |
| GPS | Global Positioning System Time (GPS) is the background (reference) time scale of that satellite-based navigation system; ideally, it is steered to lag TAI by nineteen (19) seconds, i.e., GPS Time = TAI - 19 s. GPS Time is natively expressed as elapsed time since the GPS epoch of 6 January 1980 00:00:00:00 UTC. The elapsed time is presented in terms of weeks and seconds into the week (1434:43214.000). |  |  |
| GPSZ | GPS time expressed as elapsed time since the GPS epoch of 6 January 1980 00:00:00:00 UTC. The elapsed time is presented in terms of Z counts (1.5 second increments) (578217609.333). Note that this differs from normal GPS convention where the Z count is represented as the number of whole weeks since the GPS epochs and the number of 1.5 second increments into the week. |  | 1.5s increments |
| NAVIC | NAVIC (Navigation with Indian Constellation) is an autonomous regional [satellite navigation](https://en.wikipedia.org/wiki/Satellite_navigation) system in the Indian Regional Navigation Satellite System (IRNSS) that will provide accurate real-time positioning and timing services. The system is expected to be fully operational in 2018.  |  |  |
| SCLK | Spacecraft Clock (receiver) (requires rules for interpretation in ICD) |  |  |
| TAI | International Atomic Time (TAI) is the practical realization of a uniform time scale based on atomic clocks and agrees with TT, except for a constant offset of 32.184s and the imperfections of existing clocks. Between TAI and TT the following relation holds: TAI = TT - 32.184sTAI provides a physical time scale affected by the Earth's gravitational and rotational potential, and deduced from a weighted average of various international frequency standards. Relative weighting is based on the historical stability of the individual standards. TAI is maintained by the Bureau International des Poids et Mesures (BIPM) and is the basis of other time scales. |  |  |
| TCB  | Barycentric Coordinate Time (TCB), where TCB is related to TT through a complex sequence of relativistic transformations. TCB - TDB ≈ 0.489seconds/year \* (year-1977.0) Note: TCB is intended to be the time scale for ephemerides in the solar system. |  |  |
| TDB | Barycentric Dynamical Time (TDB) is intended to serve as the independent argument of barycentric ephemerides and equations of motion. It is defined as being linearly related to Barycentric Coordinate Time (TCB) The linear relationship between TDB and TCB is chosen such that the rate of TDB closely matches TT for the time span covered by the JPL Development Ephemerides. TDB is sometimes designated as Barycentric Ephemeris Time (Teph) when used as the time scale of the JPL ephemerides. |  |  |
| TCG  | Geocentric Coordinate Time is defined in the context of the [general theory of relativity](https://en.wikipedia.org/wiki/General_relativity). It is defined by a 1991 IAU resolution. |  |  |
| TT | Terrestrial Time (TT) is a theoretically ideal time at the Earth geoid. A practical realization is TT = TAI + 32.184 s. TT has also been known as Terrestrial Dynamical Time (TDT) when considered as a coordinate time for geocentric orbits. TT is the successor of pre-relativistic Ephemeris Time (ET). |  |  |
| UT1 | Universal Time (UT1) is the angular measure of Earth rotation inferred from observations. UT1 is the Earth-rotation angle determined by VLBI of selected radio point sources and interpolated by tracking of GPS satellites. UT1 provides a sequentially increasing continuum that is everlasting and widely apparent, and serves as the astronomical basis of civil time of day. The angular rate of modern-day UT1 has been defined to closely follow Newcomb's convention for mean solar time, based on the mean motion of the Sun reduced from 19th-century observations. |  |  |
| UTC | Coordinated Universal Time (UTC) is a broadcast time standard providing both astronomical time of day and atomic-time interval. UTC is kept within +/-0.9 s of UT1 by the introduction of leap seconds and is therefore a legally recognized proxy for Universal Time in most countries. UTC is always offset from TAI by an integer number of seconds, and is thus a carrier of precision frequency and time interval for broadcast standards based on the SI second. Note: Zulu time is synonymous with UTC. |  |  |

If another timescale is used than presented in the above table, an ICD should be used to fully specify the interpretation of the timescale.

The following figure depicts the relationships between many of these time scales.



The figure below provides an overview of the differences between the most relevant time scales described in references [1] and [5].

NOTE – Periodic terms in Barycentric Coordinate Time (TCB) and Barycentric Dynamical Time (TDB)have been exaggerated by a factor of 100 to make them discernible.



Differences between Relevant Time Scales between 1950 and 2020

* 1. Reference Frame KEYWORDs

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description and reference** | **Nomenclature** | **Default Units/Type** |
| ALIGN\_CB | **For all central bodies except Earth, where the central body shall be defined via an accompanying “CENTER\_NAME”.** An **inertial** frame obtained by evaluating the central body’s fixed (rotating) frame at some specified epoch, rather than evolving in time.  |  |  |
| ALIGN\_EARTH | **For the Earth system only,** an **inertial** frame obtained by evaluating the Earth’s fixed (rotating) frame at some specified epoch, rather than evolving in time.  |  |  |
| B1950 | **For the Earth system only,** these inertial axes are associated with the FK4 star catalog and its theory modeling the mean equator and mean equinox. The epoch is the beginning of the Besselian year 1950, corresponding to 31 Dec 1949 22:09:46.866 or JD 2433282.4234591. The B1950 axes are realized by a constant rotation offset from the J2000 axes, using a formula available from the Explanatory Supplement to the Astronomical Almanac. |  |  |
| CIRS | **Celestial Intermediate Reference System.** Details in IERS TN32 5.11 and TN36 p. 47 and Vallado [L-18]. Essentially the transformation for precession/nutation is based on the Celestial Intermediate Pole realized with the IAU2000A model rather than IAU1976/80 |  |  |
| DTRFyyyy | The DTRFyyyy is the inertial realization of the ITRS computed at DGFI-TUM. Only two other VLBI centers compute these realizations, the others being IGN in Paris and JPL in Pasadena. The DTRF considering corrections for non-tidal atmospheric and hydrological loading, as of year “yyyy” (e.g. 2000). | e.g., DTRF2000 |  |
| EFG | Earth-Fixed Greenwich (EFG) rotating frame. The EFG reference frame is defined as the Earth Fixed frame after polar motion is removed. Some sources refer to this as a pseudo-Earth Fixed frame.  | E, F, G, Edot, Fdot, Gdot |  |
| GCRFyyyy | The Geocentric Celestial Reference Frame is the realization of the Geocentric Celestial Reference System per IERS conventions 2003 and 2010 (McCarthy et al.). The GCRF is the standard inertial coordinate system for the Earth, with origin at the geocenter (i.e Earth’s center of mass location). The GCRF is the geocentric counterpart of the ICRF. | e.g., GCRF2000 |  |
| GTOD | **The Greenwich True-of-Date (GTOD) rotating coordinate system.** This is realized as a rotating, right-handed, Cartesian system with the origin at the center of the Earth. The orientation of this system is specified with the xy plane in the Earth’s true of date Equator, the z axis directed along the Earth’s true of date rotational axis and is positive north, the positive x axis directed toward the prime meridian, and the y axis completing the right-handed system.Greenwich True of Date is also referred to as ‘True of Date Rotating (TDR)’ or ‘Greenwich Rotating Coordinate Frame.’. |  |  |
| FIXED\_CB | **The rotating fixed frame for all central bodies except Earth, where the central body shall be defined via an accompanying “CENTER\_NAME”.** The Fixed frame is the frame in which its topography is expressed. For gaseous planets (Jupiter, Saturn, Uranus, Neptune), the Fixed frame identifies the planet’s magnetic field instead. The Earth’s Moon realizes its Fixed frame (by default) as its MeanEarth frame; all other central bodies realize their Fixed frames using the transformational algorithm and parameters contained in Report of the IAU/IAG Working Group on cartographic coordinates and rotational elements: 2009, B.A. Archinal et al., Celest. Mech Dyn Astr 109 (2), 101-135 (DOI: 10.1007/s10569-010-9320-4). |  |  |
| EME2000 | ??? |  |  |
| ICRFyyyy | The International Celestial Reference Frame is the realization of the International Celestial Reference System per IERS conventions 2003 and 2010 (McCarthy et al.) and is the standard Barycentric reference system. The ICRF is periodically reevaluated, such that each realization must be annotated (i.e., year “yyyy” as 2000). The ICRF axes are defined as the inertial (i.e., kinematically non-rotating) axes associated with a general relativity frame centered at the solar system barycenter (often called the BCRF). The IAU (International Astronomical Union) is the authority for the definition of the ICRF. The ICRF frame is realized by its transformational algorithm between it and the Earth Fixed frame.Note that the term ‘ICRF coordinate system’ is not restricted to the system whose origin is at the solar system barycenter--- rather, the term describes a coordinate system whose origin is determined from context (i.e., for a central body, its center of mass location) whose axes are aligned with the axes of the BCRF. In fact, the IAU uses the term GCRF to refer to the system with origin at the geocenter (i.e Earth’s center of mass location) with axes parallel to the BCRF. [Note that ‘aligned’ here refers to directions in Euclidean space – not in a curved space governed by general relativity.] | e.g., ICRF2000 |  |
| Inertial\_CB | **Inertial definition for all central bodies except the Moon, Sun and Earth, where the central body shall be defined via an accompanying “CENTER\_NAME”.** Each central body defines its own Inertial frame computed as a constant rotation from the ICRF frame. Earth and Sun both define their Inertial frames as ICRF itself (i.e., no rotation) and do not provide an additional frame named Inertial. Due to potential vagaries in definition, the use of “Inertial\_CB” is not recommended unless a more definitive frame is not available or applicable (i.e. ICRF2000, J2000) |  |  |
| ITRFyyyy | The rotating Earth-fixed frame obtained by a transformation from ICRF which includes precession, nutation, and rotation effects, as well as pole wander and frame corrections. International Terrestrial Reference Frame solution as of year “yyyy” (e.g. 1993, 1997, 2000) | e.g., ITRF2000 |  |
| J2000 | The **quasi-inertial frame** Mean Equator and Mean Equinox of the J2000 epoch (JD 2451545.0 TDB which is 1 Jan 2000 12:00:00.000 TDB). The J2000 frame is realized by the transformational algorithm (also known as the FK5 IAU76 theory) between it and the Earth Fixed frame. The algorithm uses the 1976 IAU Theory of Precession, the 1980 Nutation model, and the Greenwich Mean apparent Sidereal Time (expressed as a function of time in UT1), updated by IERS Technical Note No. 21 to include an adjustment to the equation of the equinoxes.Note that the term ‘J2000 coordinate system’ is not restricted to the system whose origin is at Earth’s center--- rather, the term describes a coordinate system whose origin is determined from context (i.e., for a central body, its center of mass location) whose axes are parallel to the axes of the J2000 system defined at the Earth. |  |  |
| J2000A | The **quasi-inertial frame** Mean Equator and Mean Equinox of the J2000 epoch (JD 2451545.0 TDB which is 1 Jan 2000 12:00:00.000 TDB). The J2000 frame is the realization using the IAU 2000A by Mathews et al. (IERS TN 32 and 36)Note that the term ‘J2000A coordinate system’ is not restricted to the system whose origin is at Earth’s center--- rather, the term describes a coordinate system whose origin is determined from context (i.e., for a central body, its center of mass location) whose axes are parallel to the axes of the J2000 system defined at the Earth. |  |  |
| J2000\_ECLIPTIC | The **quasi-inertial frame** mean ecliptic system evaluated at the J2000 epoch. The mean ecliptic plane is defined as the rotation of the J2000 XY plane about the J2000 X axis by the mean obliquity defined using FK5 IAU76 theory. |  |  |
| MOD\_CB | **Mean of Date quasi-inertial frame definition for all central bodies except Earth and Moon, where the central body shall be defined via an accompanying “CENTER\_NAME”.**  The same computation as TOD\_CB except that when the Fixed frame Z axis is computed, any oscillatory terms in the formulas for the right ascension and declination are ignored. |  |  |
| MOD\_EARTH | **Mean of Date quasi-inertial frame definition for the Earth.**  Mean Equator and Mean Equinox of date. The transformation between J2000 and MeanOfDate is computed using a sequence of Euler rotations. Rotation angles are computed using cubic polynomials of time past the J2000 epoch in JED according to the 1976 IAU Theory of Precession angles and rates, as found in the US Naval Observatory circular No. 163. The MeanOfDate Z axis is the Earth’s mean spin axis; the MeanOfDate X axis defines the mean vernal equinox |  |  |
| MOD\_MOON | **Mean of Date quasi-inertial frame definition for the Moon.**  The Z axis aligns with the IAU2003 Z axis, and the X axis aligns with the vector that is the cross product of the ICRF Z axis and the IAU2003 Z axis, evaluated at each given time. However, when computing the IAU2003 Z axis, the oscillatory terms are ignored. |  |  |
| MOE\_CB | **Mean of Epoch** **quasi-inertial frame** definition for all central bodies except Earth, **where the central body shall be defined via an accompanying “CENTER\_NAME”.** The MeanOfDate system evaluated at some specified epoch, rather than evolving in time. This frame does not rotate with respect to the Inertial frame. |  |  |
| MOE\_EARTH | **Mean of Epoch quasi-inertial frame definition for the Earth**. The Earth’s MeanOfDate system evaluated at some specified epoch, rather than at each given time. This frame does not rotate with respect to the J2000 frame. |  |  |
| MOON\_ME | **Moon Mean Earth (ME) rotating frame.** This is the preferred lunar frame for associating lunar topography. It is defined as a constant rotation from a PrincipalAxes frame. Typically, the X axis pointed along the mean direction to the center of the Earth and the Z axis pointing to the mean direction of rotation. The ME frame is typically used to specify the location of objects on the Moon.  |  |  |
| MOON\_MEIAUE | **Moon-Centered, Moon Mean Equator and IAU-Node of Epoch quasi-inertial frame** as specified in [L11, Fig. 6-2].  |  |  |
| MOON\_PA403 | **Moon Principal Axis (PA) rotating frame**. This frame is aligned with the Moon’s principal inertia axes with the Z axis along the maximum inertia and the X axis along the minimum inertia. The PA frame is developed in conjunction with the development of the ephemerides for the Moon: hence, the frame depends on the source JPL DE file being used. The PA frame is used as the basis for Lunar gravity models, in the numerical integration of the planetary ephemerides, and as the reference for modern moon gravity solutions. Euler angles supplied as part of the JPL DE planetary ephemerides relate the MOON\_PA frame to ICRF. |  |  |
| MOON\_PA430 | **Moon Principal Axis (PA) rotating frame.** The Z axisaligns with the Fixed Z axis, and the X axis aligns with the vector that is the cross product of the ICRF Z axis and the Fixed Z axis, evaluated at each given time. The TrueOfDate frame is very close to the Mean Lunar Equator and IAU Node of Date (Lunar Constants and Model Document, JPL D-32296, Sept 2005). If the Moon’s Fixed frame were to be set to use the IAU2003 frame, then the two frames would be identical. |  |  |
| MOON\_PA421 | **Moon Principal Axis (PA) rotating frame.** Alternative definition of the Moon fixed axes: IAU2003 axes, which is based on the formulation in the IAU 2003 report, and the principal (fixed) axes as defined in the DE data set DE421. |  |  |
| MOON\_PA421 | **Moon Principal Axis (PA) rotating frame.** Alternative definition of the Moon fixed axes: IAU2003 axes, which is based on the formulation in the IAU 2003 report, and the principal (fixed) axes as defined in the DE data set DE421. |  |  |
| TEMEOFDATE | **For the Earth system only, specifies True Equator Mean Equinox of date quasi-inertial frame.** This is an intermediate quasi-inertial frame associated with the transformation from Earth’s MeanOfDate to Earth’s TrueOfDate axes. The TEMEOfDate Z axis is aligned with the TrueOfDate Z axis; the TEMEOfDate X axis is close to (but not identical to) the MeanOfDate X axis. This is the underlying frame upon which the NORAD Two-Line Element Sets (TLEs) are based. |  |  |
| TEMEOFEPOCH | **For the Earth system only, specifies the quasi-inertial True Equator Mean Equinox of epoch frame.** Earth’s TEMEOfDate frame evaluated at some specified epoch rather than evolving in time. The frame does not rotate with respect to the J2000 frame. |  |  |
| TIRS | **Terrestrial Intermediate Reference System.** Details in IERS TN32 5.11 and TN36 p. 47 and Vallado [L-18]. Essentially the transformation for precession/nutation is based on the Celestial Intermediate Pole realized with the IAU2000A model rather than IAU1976/80 |  |  |
| TOD\_CB | **True of Date quasi-inertial frame definition for all central bodies except Earth and Moon, where the central body shall be defined via an accompanying “CENTER\_NAME”.**  The Z axis aligns with the central body’s Fixed Z axis, and the X axis aligns with the vector that is the cross product of the ICRF Z axis and the Fixed Z axis, evaluated at each given time. If the cross product is zero, then the Y axis aligns with the cross product of the Fixed Z axis and the ICRF X axis. |  |  |
| TOD\_EARTH | **True of Date quasi-inertial frame definition for the Earth.**  True Equator and True Equinox of date. The transformation between Earth’s MeanOfDate to Earth’s TrueOfDate axes uses the mean obliquity, the nutation in longitude, and the nutation in obliquity, computed according to the 1980 Nutation model, and then applies the update to the equation of the equinoxes. By default, the nutation values are obtained by interpolating values contained in the JPL DE file rather than evaluating the model directly. The TrueOfDate Z axis would be the Earth’s spin axis if pole wander were ignored; the TrueOfDate X axis defines the true vernal equinox. |  |  |
| TOD\_MOON | **True of Date quasi-inertial frame definition for the Moon.**  The Z axis aligns with the Fixed Z axis, and the X axis aligns with the vector that is the cross product of the ICRF Z axis and the Fixed Z axis, evaluated at each given time. The TrueOfDate frame is very close to the Mean Lunar Equator and IAU Node of Date (Lunar Constants and Model Document, JPL D-32296, Sept 2005). If the Moon’s Fixed frame were to be set to use the IAU2003 frame, then the two frames would be identical. |  |  |
| TOE\_CB | **True of Epoch definition for all central bodies except Earth and Moon, where the central body shall be defined via an accompanying “CENTER\_NAME”.** The central body’s TrueOfDate system (TOD\_CB) evaluated at some specified epoch, rather than evolving over time. This frame does not rotate with respect to the ICRF frame. |  |  |
| TOE\_EARTH | **True of Epoch definition for the Earth**. The Earth’s TrueOfDate system (TOD\_EARTH) evaluated at some specified epoch, rather than evolving over time. This frame does not rotate with respect to the ICRF frame. |  |  |
| TOE\_MOON | **True of Epoch definition for the Moon**. The Moon’s TrueOfDate system (TOD\_MOON) evaluated at some specified epoch, rather than evolving over time. This frame does not rotate with respect to the ICRF frame. |  |  |
| TRUE\_ECLIPTIC | **The true ecliptic system, evolving in time.** The true ecliptic plane is defined as the rotation of the J2000 XY plane about the J2000 X axis by the true obliquity defined using FK5 IAU76 theory. |  |  |
| UVW\_GI | **Launch go-inertial reference frame**, with U in local horizon plane along inertial launch azimuth (downrange), W along the geodetic vertical and V completing the set (cross-range). In typical use the go-inertial epoch should be specified in an accompanying comment field. |  |  |

The relationships between many of these reference frames are portrayed in [L-18] in the figure below:



* 1. Relative reference FRAME KEYWORDS

In addition to the above reference frames, maneuver and covariance data can be specified in the following relative frames:

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description and reference** | **Nomenclature** | **Default Units/Type** |
| EQW | Equinoctial Coordinate System, a quasi-inertial frame with E aligned with the ascending node direction, W along the orbital angular momentum vector () and Q completing the set () | EQW |  |
| LVLH | ‘LVLH’ stands for ‘Local Vertical Local Horizontal’. The Z-axis of the LVLH frame is a unit vector collinear and opposite sign of the gravicentric satellite position (planet center, spacecraft gravity center), the Y-axis is a unit vector collinear with but the opposite sign of the orbital kinetic momentum (normal to orbit plane), and the X-axis is the unit vector equal to   | MTA |  |
| NSW | “NADIR, Sun, Normal” – This rotating frame aligns the x-axis in the NADIR direction, the y-axis as much as possible toward the Sun while still being normal to the x-axis, and the z-axis completing the right-hand set | NSW |  |
| NTW | A local orbital coordinate rotating frame that has the x-axis along the Tangential (or velocity) vector, z-axis (“W”) along the orbital angular momentum vector (), and N completing the right handed system (i.e., for a circular orbit “N” generally points in the Nadir direction and for an eccentric orbit, “N” points as close to Nadir as possible while still being normal to the T-W plane). Note that while this frame has the same axes defined as in the TNW frame, the ordering of axes is different. | NTW |  |
| PQW | Perifocal Coordinate System, a quasi-inertial frame with P axis pointing to perigee, W along the orbital angular momentum vector () and Q completing the set () | PQW |  |
| RSW | A Radial, Along track, Cross track, local orbital coordinate rotating frame, where the R axis always points out from the satellite along the central body’s radius vector to the satellite as it moves through the orbit. The S axis is in the direction of (but not necessarily parallel to) the velocity vector and is perpendicular to the radius vector. The W axis is aligned with the orbit angular momentum vector.Note that this RSW frame is also referred to as:Gaussian Coordinate System ‘Radial, In-track, Cross-track” (**RIC**)‘Radial, Transverse, Normal’ (**RTN**)QSW**UVW** (as employed in Conjunction Data Messages) | RSW |  |
| TNW | A local orbital coordinate Tangential, Normal, Cross track rotating frame that has the x-axis along the Tangential (or velocity) vector, z-axis (“W”) along the orbital angular momentum vector (), and N completing the right handed system (i.e., for a circular orbit “N” generally points in the Nadir direction and for an eccentric orbit, “N” points as close to Nadir as possible while still being normal to the T-W plane). Note that while this frame has the same axes defined as in the NTW frame, the ordering of axes is different (TNW). | TNW |  |
| TOPOHORIZ | The SEZ system rotates with the observing site. The local horizon forms the fundamental plane, with the S axis pointing due south from the site (even in the Southern Hemisphere). The E axis points east from the site and is undefined at the North or South Poles. The Z axis (zenith) points radially outward from the site, along the site’s geodetic local vertical. | SEZ |  |
| VNC | A local orbital coordinate Velocity, Normal, Co-normal rotating frame that has the x-axis along the Velocity (or tangential) vector, y-axis Normal to the orbit along the orbital angular momentum vector (), and z-axis is the “Co-normal” direction completing the right handed system (i.e., for a circular orbit “C” points in the radius vector direction whereas for an eccentric orbit, “C” points as close to radial as possible while still being normal to the V-N plane). Note that while this frame has the same axes defined as in the NTW frame, the ordering of axes is different (i.e., TWN).**Note that the VNC reference frame is also synonymous with the VNB frame**, where the “Co-Normal” moniker has been replaced by “Bi-Normal” (per some astrodynamics tool naming conventions) | VNC |  |

* 1. Attitude Control and spacecraft System Reference Frame KEYWORDS

In addition to the above reference frames, the following attitude control and spacecraft systems reference frames may be specified:

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description and reference** | **Nomenclature** | **Default Units/Type** |
| ACC\_i | Accelerometer reference frame (‘i’ = 0→9) | ACTUATOR\_1 |  |
| ACTUATOR\_i | Actuator reference frame (‘i’ = 0→9): could denote reaction wheels, solar arrays, thrusters, magnetic torque rods, etc. | ACTUATOR\_1 |  |
| AST\_i | Autonomous Star Tracker Reference Frame (‘i’ indicates the sensor number if there is more than one) | AST\_5 |  |
| CSS\_ij | Coarse Sun Sensor (‘i’ = 0→9, ‘j’ = 0→9) | CSS\_9 |  |
| DSS\_i | Digital Sun Sensor (‘i’ = 0→9) | DSS\_1 |  |
| ESA\_i | Earth Sensor Assembly Reference Frame (‘i’ indicates the sensor number if there is more than one) | ESA\_3 |  |
| GYRO\_i | Gyroscope Reference Frame (‘i’ = 0→9) | GYRO\_9 |  |
| IMU\_i | Inertial Measurement Unit Frame (‘i = 0→9) | IMU\_2 |  |
| INSTRUMENT\_i | Instrument ‘c’ reference frame (‘i’ = 0→9) | INSTRUMENT\_3 |  |
| MTA | Magnetic Torque Assembly | MTA |  |
| RATE\_FRAME | The frame of reference in which the Euler rates are specified. | REF\_FRAME\_AREF\_FRAME\_B |  |
| REF\_FRAME\_A | Name of the reference frame that defines the starting point of a transformation.  | SC\_BODY\_9, ICRFyyyy |  |
| REF\_FRAME\_B | Name of the reference frame that defines the ending point of a transformation. | INSTRUMENT\_2,AST\_3 |  |
| RWA\_i | Reaction Wheel Assembly Frame (‘i’ =0→9) | RWA\_1 |  |
| SA\_i | Solar Array Coordinate Frame (‘i’ =0→9) | SA\_7 |  |
| SC\_BODY\_i | Spacecraft Body Frame (‘i’ = 0→9); requires clear specification via ICD | SC\_BODY\_1 |  |
| SENSOR\_i | Sensor ‘x’ reference frame (‘i’ = 0→9) | SENSOR\_6 |  |
| STARTRACKER\_i | Star Tracker Reference Frame (‘i’ = 0→9) | STAR TRK\_3 |  |
| TAM\_i | Three Axis Magnetometer Reference Frame (‘i’ = 0→9) | TAM\_2 |  |
|  |  |  |  |

* 1. Element Set KEYWORDS

Orbit element states and/or time histories may be specified in the following element sets.

Orbit elements shall be interpreted as osculating elements unless pre-coordinated between the message originator and recipient to contain mean elements (e.g. singly- or doubly-averaged elements based upon Kozai, Brouwer or other theories).

It is not allowed to specify non-inertial reference frames when employing inertial element sets, or to specify inertial reference frames when employing non-inertial element sets.

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description and reference** | **Nomenclature** | **Default Units/Type** |
| ADBARV | Spherical 6-element set comprised of: right ascension +E°, declination +N°, inertial flight path angle measured from the radial direction to inertial velocity direction (e.g. 90° for circular orbit), inertial azimuth angle, measured from local North to projection of inertial velocity in local horizontal plane, radius magnitude and velocity magnitude) |  | ,  |
| CARTP | Cartesian 3-element position (only) orbit state | X, Y, Z |  |
| CARTPV | Cartesian 6-element position and velocity orbit state | X, Y, Z, XD, YD, ZD | ,  |
| CARTPVA | Cartesian 9-element position, velocity and acceleration orbit state | X, Y, Z, XD, YD, ZD, XDD, YDD, ZDD | , ,  |
| DELAUNAY | Delaunay elements employ a set of canonical action-angle variables, which are commonly used in general perturbation theories. The element set consists of three conjugate action-angle pairs. Lower case letters represent the angles while upper case letters represent the conjugate actions. Delaunay variables coordinate type is not available if a Fixed coordinate system is selected. Elements L, G and H are expressed in terms of distance squared divided by time, where distance is measured in standard units and time is measured in seconds, where “L” is related to the two-body orbital energy, “G” is the magnitude of the orbital angular momentum, “H” is the Z component of the orbital angular momentum. The elements l, g and h are angles, where l is the mean anomaly, g is the argument of perigee and h is the right ascension of the ascending node.  | L, G, H, l, g, h | ,  |
| DELAUNAYMOD | Modified Delaunay variables, where the L, G and H “action” variables of the Delaunay element set defined above are divided by the square root of the central-body gravitational constant, yielding a geometric version of the Delaunay set that is independent of the central body. | Lm, Gm, Hm, lm, gm, hm | ,  |
| EIGVAL3EIGVEC3 | 12-element eigenvalue/eigenvector representation time history corresponding to the 3x3 position covariance time history, with each line containing Time, the three (major, medium and minor) eigenvalues IN DESCENDING ORDER, and the corresponding three eigenvectors matching the major, medium and minor eigenvalues | EigMaj, EigMed, EigMin,EigVecMaj,EigVecMed,EigVecMin | , , |
| EQUIN | Equinoctial elements (Broucke and Cefola, 1972) are popular because they do not suffer from the singularity problems that classical and other elements do. This standardized equinoctial seven-element set is adopted from the definition contained in Vallado [L9, 4th Ed.]. The first six equinoctial elements have a singularity for exact 180º inclinations, which is overcome by the addition of a seventh element which specifies the retrograde factor [fr = ±1, where fr = 1 denotes direct orbits (inclination<=90°), -1 for retrograde orbits (inclination>90°)]. Note that some centers switch the retrograde factor (-1) only for exact retrograde orbits (switching the singularity for that case to an inclination of 0º), while others switch this retrograde factor to (-1) for any/all retrograde orbits. | [a, af, ag, L=, χ, ψ,  | , ,,,  |
| EQUINMOD | Modified equinoctial seven-element set, where semi-major axis has been replaced by semi-latus rectum “p” = a (1-e2), and where Mean Anomaly has been replaced by True Anomaly in the “L” term. The seventh element specifies the retrograde factor [fr = ±1] as defined in Vallado [L9]. | [p = a(1-e2), af, ag, , χ, ψ,  | , ,,,  |
| GEODETIC | Geodetic elements (longitude, geodetic latitude, fixed frame flight path angle, fixed frame azimuth, altitude above oblate spheroid, and velocity relative to the fixed frame |  | ,  |
| KEPLER | Keplerian 6-element classical set (semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of perigee and true anomaly) |  | , , |
| KEPLERM | Keplerian 6-element classical set (semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of perigee and mean anomaly) |  | , , |
| LDBARV | Modified spherical 6-element set (Earth longitude +E°, declination +N°, inertial flight path angle measured from the radial direction to inertial velocity direction (e.g. 90° for circular orbit), inertial azimuth angle, measured from local North to projection of inertial velocity in local horizontal plane, radius magnitude and velocity magnitude) |  | ,  |
| POINCARE | Canonical counterpart of equinoctial 6-element set. See Vallado [L9])  | gp, hp, Lp, Gp, Hp | ,, ,  |

* 1. Additional COVARIANCE SET KEYWORDS

In addition to the above orbit element sets, covariance data can be specified in the following orbit sets:

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description and reference** | **Nomenclature** | **Default Units/Type** |
| TADBARV | 7x7: Time & Spherical 6-element set (: right ascension +E°, declination +N°, inertial flight path angle measured from the radial direction to inertial velocity direction (e.g. 90° for circular orbit), inertial azimuth angle, measured from local North to projection of inertial velocity in local horizontal plane, radius magnitude and velocity magnitude) errors | T,  | , ,  |
| TCARTP | 4x4: Time & Cartesian 3-element position (only) errors (X, Y, Z) errors | T, X, Y, Z | ,  |
| TCARTPV | 7x7: Time & Cartesian 6-element position and velocity errors (X, Y, Z, XD, YD, ZD) errors | T, X, Y, Z, XD, YD, ZD | , ,  |
| TCARTPVA | 10x10: Time & Cartesian 9-element position, velocity and acceleration errors (X, Y, Z, XD, YD, ZD, XDD, YDD, ZDD) errors | T, X, Y, Z, XD, YD, ZD, XDD, YDD, ZDD | , , ,  |
| TDELAUNAY | 7x7: Time & Delaunay 6-element set (as defined above) errors | T, L, G, H, l, g, h | , ,  |
| TDELAUNAYMOD | 7x7: Time & Modified Delaunay variables errors, where the L, G and H “action” variables of the Delaunay element set defined above are divided by the square root of the central-body gravitational constant, yielding a geometric version of the Delaunay set that is independent of the central body. | T, Lm, Gm, Hm, lm, gm, hm | , ,  |
| TEIGVAL3EIGVEC3 | 13-element eigenvalue/eigenvector representation time history corresponding to the 3x3 position covariance time history, with each line containing Time, the three (major, medium and minor) eigenvalues IN DESCENDING ORDER, and the corresponding three eigenvectors matching the major, medium and minor eigenvalues | T, EigMaj, EigMed, EigMin,EigVecMaj,EigVecMed,EigVecMin | , , , |
| TEQUIN | 7x7: Time & Equinoctial 6-element set ([ahkλpq ] = [a, ag, af, L=, χ, ψ] as defined in Vallado [L9], omitting from the set) errors | [a, af, ag, L=, χ, ψ,  | , , ,,,  |
| TEQUINMOD | 7x7: Time & Equinoctial 6-element modified set ([pfghkL ] = [a(1-e2), af, ag, χ, ψ, ] per Vallado [L9], omitting from the set) errors | T, [p = a(1-e2)], af, ag, , χ, ψ | , , ,, |
| TGEODETIC | 7x7: Time & geodetic elements (longitude, geodetic latitude, fixed frame flight path angle, fixed frame azimuth, altitude above oblate spheroid, and velocity relative to the fixed frame) errors | T,  | , ,  |
| TKEPLER | 7x7: Time & Keplerian 6-element classical set (semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of perigee and true anomaly) errors | T,  | , , , |
| TKEPLERM | 7x7: Time & Keplerian 6-element classical set (semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of perigee and mean anomaly) errors | T,  | , , , |
| TLDBARV | 7x7: Time & modified spherical 6-element set (Earth longitude +E°, declination +N°, inertial flight path angle measured from the radial direction to inertial velocity direction (e.g. 90° for circular orbit), inertial azimuth angle, measured from local North to projection of inertial velocity in local horizontal plane, radius magnitude and velocity magnitude) errors | T,  | , ,  |
| TPOINCARE | 7x7: Time & canonical counterpart of equinoctial 6-element set errors. See Vallado [L9])  | T, gp, hp, Lp, Gp, Hp | , ,, ,  |

* 1. ATTITUDE AND SPACECRAFT CONVENTIONS

The following definitions are relevant to spacecraft attitude and dynamics [L-19].

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description and reference** | **Nomenclature** | **Default Units/Type** |
| Direction Cosine Matrix  | Represents the orientation of a frame B with respect to a frame A, the coordinate transformation from frame A to frame B. | MBA | N/A |
| Quaternion | The first three elements form the vector part of the quaternion, the fourth is the scalar element. Defined as:where e1,e2,e3 are the three elements of the Euler rotation axis (unit vector) and  is the Euler rotation angle. The quaternion represents the coordinate transformation from frame A to frame B. | Q=[Q1,Q2,Q3,QC] | N/A, N/A, N/A, N/A |
| Quaternion Derivative | Rate of change of the quaternion.  |  | second-1 |
| Angular Velocity  | The rotational rate of frame B with respect to frame A. The vector direction is the instantaneous axis of rotation of frame B with respect to frame A and the vector magnitude is the instantaneous rate of this rotation. The subscript indicates the frame in which the angular velocity is resolved. ‘SC’ refers to the spacecraft body frame. |  | radians/second |
| Euler Angles | Euler angles are used to represent a rotation from an initial frame A to a final frame B as a product of three successive rotations about reference unit vectors, the angles of these rotations are the Euler angles. There are 12 possible sequences. The rotation sequence and the rotation angles are specified when providing the final transformation matrix (direction cosine matrix). For example, MBA=M312=M3()M1()M2(). M2() is the first rotation of  about the 2nd axis of the initial frame A. M1() is the second rotation of the angle  about the 1st axis of the intermediate frame, M3() is the 3rd rotation of the angle  around the 3rd axis of the second intermediate frame, completing the transformation into the final frame B. Mathematically this is written as | M312() |  |
| Euler Rates | The time derivatives of the Euler angle representation. They represent the rotation rates of the individual transformations represented in the three angle Euler angle rotation sequence. The transformation between Euler rates and angular velocity is not orthogonal. The angles are written in the same order as the Euler angle sequence, with a dot to indicate differentiation. |  | radians/second |
| Inertia | The moment of inertia tensor, a symmetric 3x3 matrix. Expressed in a coordinate frame attached to the center of mass of a spacecraft body. The subscript indicates the frame in which the inertia is resolved and the superscript indicates the component.  |  | kilogram-meters2 |
| Angular Momentum | Defined for a rigid body as the product of the inertia and the angular velocity. If a spacecraft contains devices which contribute angular momentum they are added to the momentum generated by the spacecraft body. The subscript indicates the coordinate frame in which the momentum is resolved. The superscript indicates what elements are included in the momentum. For example, ‘W’ indicates a reaction wheel, ‘B’ indicates just the spacecraft body, ‘C’ indicates the total system momentum, momentum about the system center of mass.Note that in the 2nd equation above the ISC includes the inertia of the wheels transverse to their spin axes, but not the inertia along the spin axes. The second term is the momentum contribution of the wheels along their spin axes only, the momentum along the transverse direction is included in the first term (see Markley and Crassidis).  |  | Newton-meter-seconds |
| Torque Vector | Torque is the rate of change of angular momentum. For example,  | TSC | N-m |
| Nutation | The angle between a spacecraft principal moment of inertia axis and the angular momentum vector. |  | radians |
| Spin Axis | The axis about which a spacecraft is spinning, often closely aligned with the major principal axis of inertia. | RA,DEC | radians |
| Spin Rate | The rotation rate about the Spin Axis. |  | radians/second  |
| Phase | Rotation angle about the Spin Axis |  | radians |

* 1. Center\_Name values

The following values may be used to specify the gravitational central attracting body using the “CENTER\_NAME” keyword.

Values are color-coded as follows:

* blue: orbiters, impactors and landers
* yellow: flybys (Voyager 2 generated most entries)
* red: proposed missions
* green: Lagrange points (Lissajous, halo and Lyapunov orbits)

SANA CENTER\_NAME registry

|  |  |  |
| --- | --- | --- |
| **SANA entry proposal** | **JPLS SSD name** | **example of orbiting spacecraft** |
| **Sun, planets and associated dynamical points** |
| SUN | Sun [Sol] | *STEREO A* and *STEREO B* (NASA), *Kepler* (NASA) |
| SOLAR SYSTEM BARYCENTER | Solar System Barycenter [SSB] |
| MERCURY | Mercury | *Mariner 10* (NASA) flyby, *MESSENGER* (NASA) flyby and orbit, *BepiColombo* (ESA/JAXA) planned orbit |
| MERCURY BARYCENTER | Mercury Barycenter |
| VENUS | Venus | *Venus Express* (ESA) |
| VENUS BARYCENTER | Venus Barycenter |
| EARTH | Earth [Geocenter] |  |
| EARTH BARYCENTER | n/a |
| SUN-EARTH L1 | L1 [S-E-M Lagrangian] | *Deep Space Climate Observatory* (NOAA), *SOHO* (ESA) |
| SUN-EARTH L2 | L2 [S-E-M Lagrangian] | *Planck* and *Herschel* (ESA) |
| EARTH-MOON L1 | n/a | none |
| EARTH-MOON L2 | n/a | *Chang'e 5-T1* (CNSA) before lunar orbit |
| MARS | Mars | first flyby *Mariner 4* (NASA), first orbiter *Mars 2* (USSR), first lander *Viking 1* (NASA) |
| MARS BARYCENTER | Mars Barycenter |
| JUPITER | Jupiter | orbited by *Galileo* (NASA) and *Juno* (NASA) |
| JUPITER BARYCENTER | Jupiter Barycenter |
| SATURN | Saturn | orbited by *Cassini* (NASA) |
| SATURN BARYCENTER | Saturn Barycenter |
| URANUS | Uranus | *Voyager 2* (NASA) flyby |
| URANUS BARYCENTER | Uranus Barycenter |
| NEPTUNE | Neptune | *Voyager 2* (NASA) flyby |
| NEPTUNE BARYCENTER | Neptune Barycenter |
| **Satellites** |
| MOON | Moon [Luna] |  |
| PHOBOS | Phobos (MI) | three failed missions + proposed missions |
| DEIMOS | Deimos (MII) | proposed missions |
| IO | Io (JI) | *Voyager 1* & *Voyager 2* (NASA) flyby |
| EUROPA | Europa (JII) | *JUICE* (ESA) and Europa Clipper (NASA) planned flyby; *Voyager 1* & *Voyager 2* (NASA) flyby |
| GANYMEDE | Ganymede (JIII) | *JUICE* (ESA) planned orbit; *Voyager 1* (NASA) flyby |
| CALLISTO | Callisto (JIV) | *JUICE* (ESA) planned flyby; *Voyager 1* (NASA) flyby |
| AMALTHEA | Amalthea (JV) | *Voyager 1* & *Voyager 2* (NASA) flyby |
| MIMAS | Mimas (SI) | *Voyager 1* & *Voyager 2* (NASA) flyby |
| ENCELADUS | Enceladus (SII) | *Cassini* (NASA) flyby ; several proposed missions by ESA/NASA/DLR; *Voyager 1* (NASA) flyby |
| TETHYS | Tethys (SIII) | *Voyager 1* & *Voyager 2* (NASA) flyby |
| DIONE | Dione (SIV) | *Voyager 2* (NASA) flyby |
| RHEA | Rhea (SV) | *Voyager 1/2* (NASA) flyby |
| TITAN | Titan (SVI) | *Huygens* (ESA) lander; *Voyager 1* (NASA) flyby |
| HYPERION | Hyperion (SVII) | *Voyager 1/2* (NASA) flyby |
| IAPETUS | Iapetus (SVIII) | *Voyager 2* (NASA) flyby |
| PHOEBE | Phoebe (SIX) | *Cassini* (NASA) flyby |
| JANUS | Janus (SX) | *Voyager 2* (NASA) flyby |
| EPIMETHEUS | Epimetheus (SXI) | *Voyager 2* (NASA) flyby |
| HELENE | Helene (SXII) | *Voyager 2* (NASA) flyby |
| TELESTO | Telesto (SXIII) | *Voyager 2* (NASA) flyby |
| CALYPSO | Calypso (SXIV) | *Voyager 2* (NASA) flyby |
| ATLAS | Atlas (SXV) | *Voyager 2* (NASA) flyby |
| PANDORA | Pandora (SXVII) | *Voyager 2* (NASA) flyby |
| ARIEL | Ariel (UI) | *Voyager 2* (NASA) flyby |
| UMBRIEL | Umbriel (UII) | *Voyager 2* (NASA) flyby |
| TITANIA | Titania (UIII) | *Voyager 2* (NASA) flyby |
| OBERON | Oberon (UIV) | *Voyager 2* (NASA) flyby |
| MIRANDA | Miranda (UV) | *Voyager 2* (NASA) flyby |
| TRITON | Triton (NI) | *Voyager 2* (NASA) flyby |
| LARISSA | Larissa (NVII) | *Voyager 2* (NASA) flyby |
| PROTEUS | Proteus (NVIII) | *Voyager 2* (NASA) flyby |
| CHARON | Charon (PI) | *New Horizons* (NASA) flyby during Pluto flyby |
| **Minor planets and asteroids** |
| PLUTO | Pluto (134340) | *New Horizons* (NASA) flyby |
| PLUTO BARYCENTER | Pluto Barycenter | *New Horizons* (NASA) flyby |
| 1 CERES | 1 Ceres | Orbited by *Dawn* (NASA) |
| 4 VESTA | 4 Vesta | Orbited by *Dawn* (NASA) for 2 months |
| 21 LUTETIA | 21 Lutetia | *Rosetta* (ESA) flyby |
| 243 IDA | 243 Ida | *Galileo* (NASA) flyby |
| 253 MATHILDE | 253 Mathilde | *NEAR Shoemaker* (NASA) flyby |
| 433 EROS | 433 Eros (1898 DQ) | *NEAR Shoemaker* (NASA) flyby, orbit and landing |
| 951 GASPRA | 951 Gaspra (1916 S45) | *Galileo* (NASA) flyby |
| 2867 STEINS | 2867 Steins (1969 VC) | *Rosetta* (ESA) flyby |
| 4179 TOUTATIS | 4179 Toutatis (1989 AC) | *Chang'e 2* (CNSA) flyby |
| 5525 ANNEFRANK | 5535 Annefrank (1942 EM) | *Stardust* (NASA) flyby |
| 9969 BRAILLE | 9969 Braille (1992 KD) | *Deep Space 1* (NASA) attempted flyby |
| 132524 APL | 132524 APL (2002 JF56) | *New Horizons* (NASA) flyby |
| 25143 ITOKAWA | 25143 Itokawa (1998 SF36) | *Hayabusa* (JAXA) landing |
| 16 PSYCHE | 16 Psyche | *Psyche* (NASA) planned orbit (2026) |
| 617 PATROCLUS | 617 Patroclus (1906 VY) | *Lucy* (NASA) planned flyby (2033) |
| 3200 PHAETHON | 3200 Phaethon (1983 TB) | *DESTINY+* (JAXA) planned flyby (2024) |
| 3548 EURYBATES | 3548 Eurybates (1973 SO) | *Lucy* (NASA) planned flyby (2027) |
| 11351 LEUCUS | 11351 Leucus (1997 TS25) | *Lucy* (NASA) planned flyby (2028) |
| 15094 POLYMELE | 15094 Polymele (1999 WB2) | *Lucy* (NASA) planned flyby (2027) |
| 21900 ORUS | 21900 Orus (1999 VQ10) | *Lucy* (NASA) planned flyby (2028) |
| 52246 DONALDJOHANSON | 52246 Donaldjohanson (1981 EQ5) | *Lucy* (NASA) planned flyby (2025) |
| 65803 DIDYMOS | 65803 Didymos (1996 GT) | *AIDA* (ESA) proposed impact |
| 101955 BENNU | 101955 Bennu (1999 RQ36) | *OSIRIS-REx* (NASA) planned sample return (en route) |
| 162173 RYUGU | 162173 Ryugu (1999 JU3) | *Hayabusa 2* (JAXA) planned sample return (en route) |
| 486958 2014 MU69 | 486958 (2014 MU69) | *New Horizons* (NASA) planned flyby |
| **Comets** |
| 21P/GIACOBINI-ZINER | Comet 21P/Giacobini-Zinner [2013] | *ICE* (NASA) flyby |
| 1P/HALLEY | Comet 1P/Halley | flyby by *Vega 1* (USSR), *Vega 2* (USSR), *Suisei* (JAXA), *Sakigake* (JAXA) and *Giotto* (ESA) |
| 26P/GRIGG-SKJELLRUP | Comet 26P/Grigg-Skjellerup [2014] | *Giotto* (ESA) flyby |
| 19P/BORRELLY | Comet 19P/Borrelly | *Deep Space 1* (NASA) flyby |
| 81P/WILD 2 | Comet 81P/Wild 2 | *Stardust* (NASA) flyby and coma sample return |
| 9P/TEMPEL 1 | Comet 9P/Tempel 1 | *Deep Impact* (NASA) flyby and impactor, *Stardust* (NASA) flyby |
| 103P/HARTLEY 2 | Comet 103P/Hartley 2 [2010] | *EPOXI* (NASA) flyby |
| 67P/CHURYUMOV-GERASIMENKO | Comet 67P/Churyumov-Gerasimenko [2010] | *Rosetta* (ESA) orbit and impact, *Philae* (ESA) lander |

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