ISO 11233: Orbit Determination

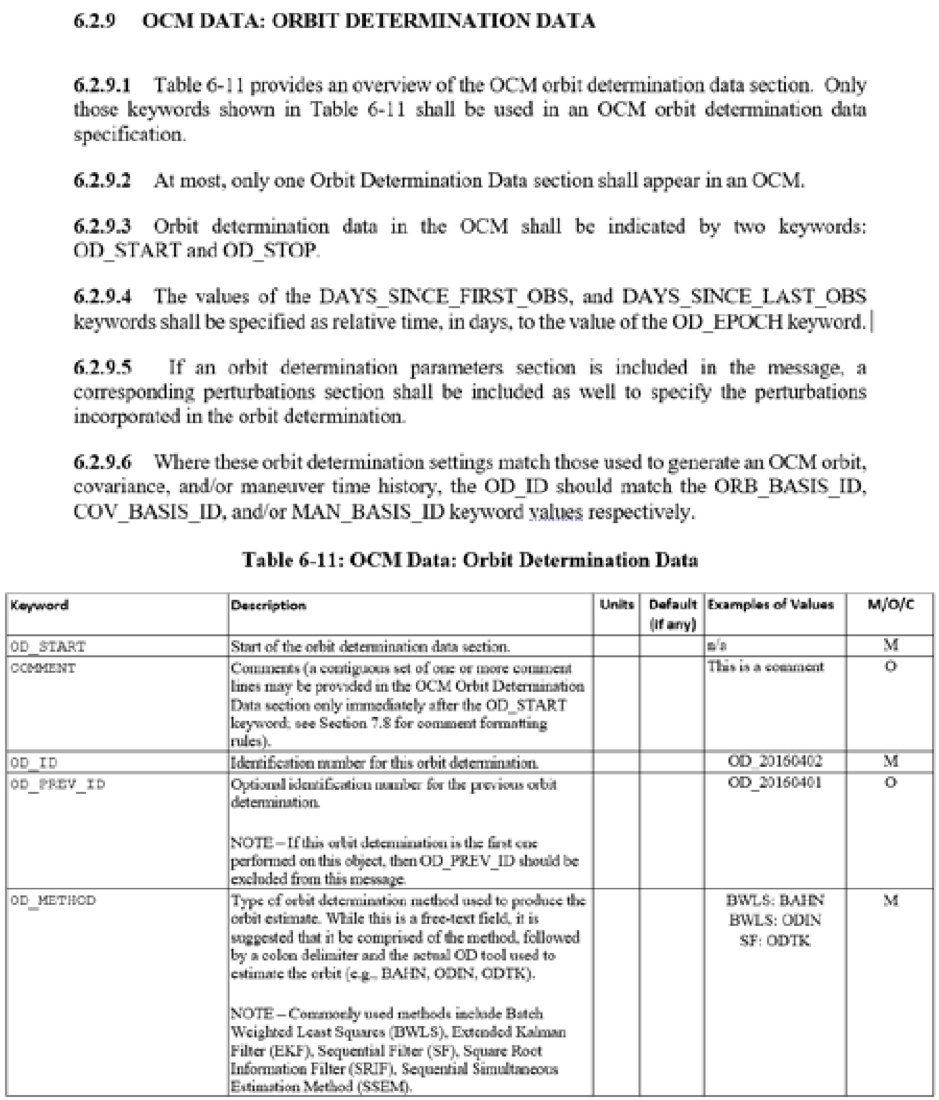
17 May 2021

- Comments received from Dan Oltrogge (21-Feb-2018): Regarding ISO/TR 11233 (Orbit determination and estimation), I've had our technical experts and US TAG members consider this technical report's merits from both technical and completeness perspectives. While we see this document as a bit "harmless" since it is a technical report only, our conclusion is that this document should be cancelled for the following reasons:
  - The current content is incomplete, omitting major components pertaining to reference frames, force model parameters, element sets, atmosphere models, etc. and spending woefully insufficient time discussing OD techniques and how to communicate them to others (i.e., only a paragraph on LS and filter methods);
  - This technical report contains normative (i.e., "shall") content (which TRs should not contain);
  - It would take a substantial amount of work to make the existing ISO/TR 11233 worthy of use and commercially useful, in our opinion; we believe that our effort would be better spent on other endeavors at this time.
  - And most importantly, the new Orbit Comprehensive Message (OCM), which is nearing completion, has an entire data block devoted to conveying orbit determination metadata and content. As a joint CCSDS/ISO standard, we propose that this OCM content be used to meet the needs of what ISO/TR 11233 was originally intended to be.

June 2018 WG3 meeting

- During WG3 Jun-2018 meeting, the discussion continued as follows: Concerning ISO/TR 11233, the WG3 convenor reminded that WG3 participants decided Nov-17 to confirm the document until its 5-years systematic review [action 48-02 closed], and that 11233 is a technical report to provide guidance in orbit estimation.
- The orbit messages standard (SC13/CCSDS responsibility) is a message format standard with fields to be filled, however not addressing with sufficiently technical information how the information is derived.
  - RESPONSE: ISO 26900 contains more than just message formats; technical information also provided.

OCM (ISO 26900) now nearing completion



6.2.9 OCM DATA: ORBIT DETERMINATION DATA

6.2.9.1 Table 6-11 provides an overview of the OCM orbit determination data section. Only those keywords shown in Table 6-11 shall be used in an OCM orbit determination data specification.

6.2.9.2 At most, only one Orbit Determination Data section shall appear in an OCM.

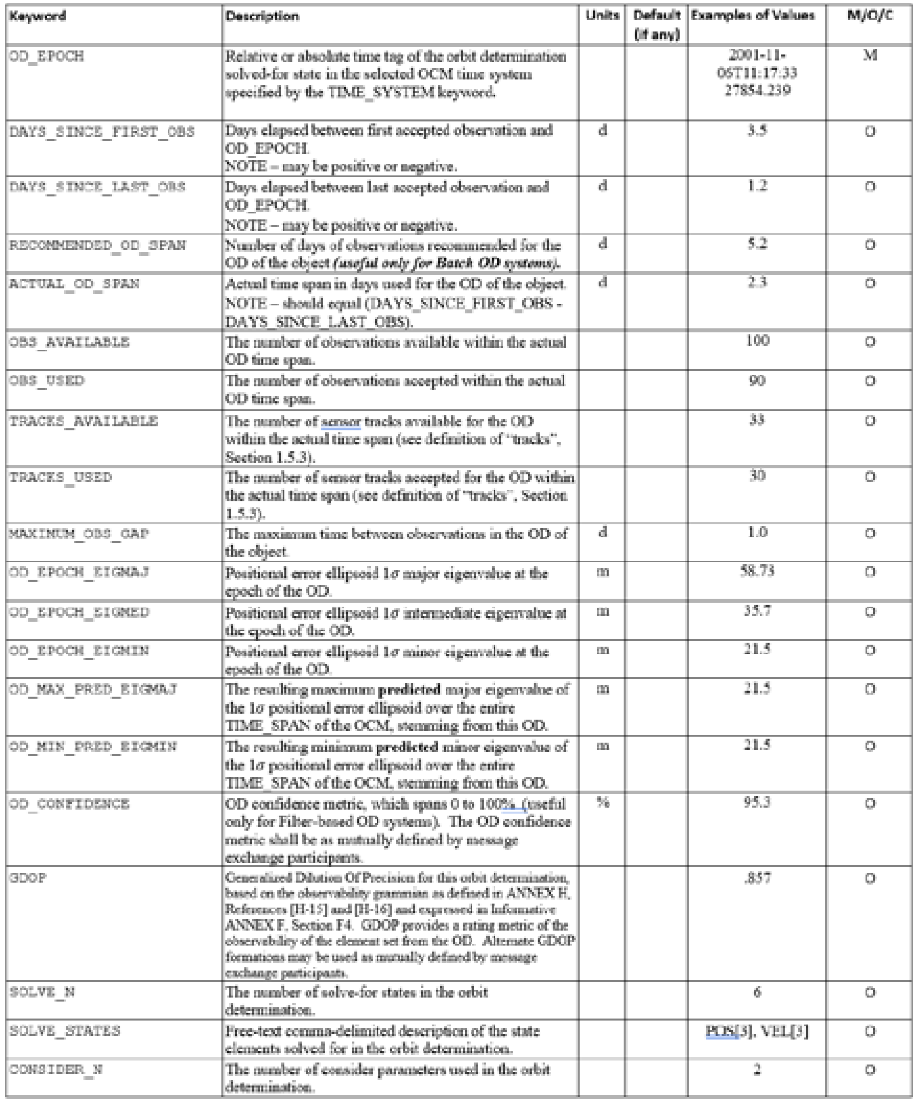
6.2.9.3 Orbit determination data in the OCM shall be indicated by two keywords: OD_START and OD_STOP.

6.2.9.4 The values of the DAYS_SINCE_FIRST_OBS, and DAYS_SINCE_LAST_OBS keywords shall be specified as relative time, in days, to the value of the OD_EPOCH keyword.

6.2.9.5 If an orbit determination parameters section is included in the message, a corresponding perturbations section shall be included as well to specify the perturbations incorporated in the orbit determination.

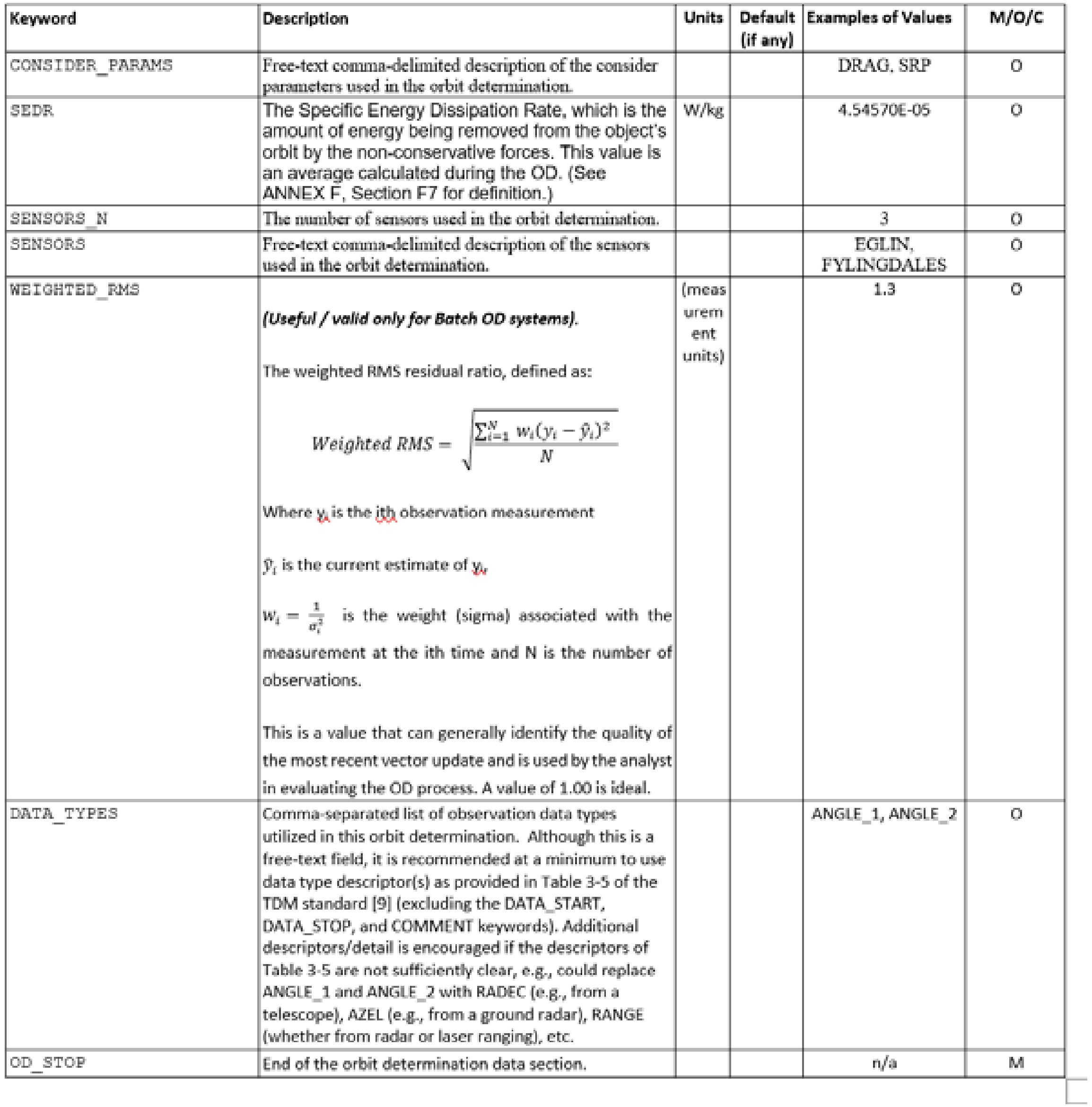
6.2.9.6 Where these orbit determination settings match those used to generate an OCM orbit, covariance, and/or maneuver time history, the OD_ID should match the ORB_BASIS_ID, COV_BASIS_ID, and/or MAN_BASIS_ID keyword values respectively.

Table 6-11: OCM Data: Orbit Determination Data



Keyword	Description	Units	Default (if any)	Examples of Values	M/O/C
`OD_START`	Start of the orbit determination data section.			n/a	M
`COMMENT`	Comments (a contiguous set of one or more comment lines may be provided in the OCM Orbit Determination Data section only immediately after the OD_START keyword; see Section 7.8 for comment formatting rules).			This is a comment	O
`OD_ID`	Identification number for this orbit determination.			OD_20160402	M
`OD_PREV_ID`	Optional identification number for the previous orbit determination. NOTE – If this orbit determination is the first one performed on this object, then OD_PREV_ID should be excluded from this message.			OD_20160401	O
`OD_METHOD`	Type of orbit determination method used to produce the orbit estimate. While this is a free-text field, it is suggested that it be comprised of the method, followed by a colon delimiter and the actual OD tool used to estimate the orbit (e.g., BAHN, ODIN, ODTK). NOTE – Commonly used methods include Batch Weighted Least Squares (BWLS), Extended Kalman Filter (EKF), Sequential Filter (SF), Square Root Information Filter (SRIF), Sequential Simultaneous Estimation Method (SSEM).			BWLS: BAHN BWLS: ODIN SF: ODTK	M
`OD_EPOCH`	Relative or absolute time tag of the orbit determination solved-for state in the selected OCM time system specified by the TIME_SYSTEM keyword.			2001-11-06T11:17:33 27854.239	M
`DAYS_SINCE_FIRST_OBS`	Days elapsed between first accepted observation and OD_EPOCH. NOTE – may be positive or negative.	d		3.5	O
`DAYS_SINCE_LAST_OBS`	Days elapsed between last accepted observation and OD_EPOCH. NOTE – may be positive or negative.	d		1.2	O
`RECOMMENDED_OD_SPAN`	Number of days of observations recommended for the OD of the object ***(useful only for Batch OD systems).***	d		5.2	O
`ACTUAL_OD_SPAN`	Actual time span in days used for the OD of the object. NOTE – should equal (DAYS_SINCE_FIRST_OBS - DAYS_SINCE_LAST_OBS).	d		2.3	O
`OBS_AVAILABLE`	The number of observations available within the actual OD time span.			100	O
`OBS_USED`	The number of observations accepted within the actual OD time span.			90	O
`TRACKS_AVAILABLE`	The number of sensor tracks available for the OD within the actual time span (see definition of "tracks", Section 1.5.3).			33	O
`TRACKS_USED`	The number of sensor tracks accepted for the OD within the actual time span (see definition of "tracks", Section 1.5.3).			30	O
`MAXIMUM_OBS_GAP`	The maximum time between observations in the OD of the object.	d		1.0	O
`OD_EPOCH_EIGMAJ`	Positional error ellipsoid 1σ major eigenvalue at the epoch of the OD.	m		58.73	O
`OD_EPOCH_EIGMED`	Positional error ellipsoid 1σ intermediate eigenvalue at the epoch of the OD.	m		35.7	O
`OD_EPOCH_EIGMIN`	Positional error ellipsoid 1σ minor eigenvalue at the epoch of the OD.	m		21.5	O
`OD_MAX_PRED_EIGMAJ`	The resulting maximum **predicted** major eigenvalue of the 1σ positional error ellipsoid over the entire TIME_SPAN of the OCM, stemming from this OD.	m		21.5	O
`OD_MIN_PRED_EIGMIN`	The resulting minimum **predicted** minor eigenvalue of the 1σ positional error ellipsoid over the entire TIME_SPAN of the OCM, stemming from this OD.	m		21.5	O
`OD_CONFIDENCE`	OD confidence metric, which spans 0 to 100% (useful only for Filter-based OD systems). The OD confidence metric shall be as mutually defined by message exchange participants.	%		95.3	O
`GDOP`	Generalized Dilution Of Precision for this orbit determination, based on the observability grammian as defined in ANNEX H, References [H-15] and [H-16] and expressed in Informative ANNEX F, Section F4. GDOP provides a rating metric of the observability of the element set from the OD. Alternate GDOP formations may be used as mutually defined by message exchange participants.			.857	O
`SOLVE_N`	The number of solve-for states in the orbit determination.			6	O
`SOLVE_STATES`	Free-text comma-delimited description of the state elements solved for in the orbit determination.			POS[3], VEL[3]	O
`CONSIDER_N`	The number of consider parameters used in the orbit determination.			2	O

OCM (ISO 26900) now nearing completion



Keyword	Description	Units	Default (if any)	Examples of Values	M/O/C
CONSIDER_PARAMS	Free-text comma-delimited description of the consider parameters used in the orbit determination.			DRAG, SRP	O
SEDR	The Specific Energy Dissipation Rate, which is the amount of energy being removed from the object's orbit by the non-conservative forces. This value is an average calculated during the OD. (See ANNEX F, Section F7 for definition.)	W/kg		4.54570E-05	O
SENSORS_N	The number of sensors used in the orbit determination.			3	O
SENSORS	Free-text comma-delimited description of the sensors used in the orbit determination.			EGLIN, FYLINGDALES	O
WEIGHTED_RMS	***(Useful / valid only for Batch OD systems).*** The weighted RMS residual ratio, defined as: $Weighted\ RMS = \sqrt{\frac{\sum_{i=1}^{N} w_i (y_i - \hat{y}_i)^2}{N}}$ Where y_i is the ith observation measurement $\hat{y}_i$ is the current estimate of y_i, $w_i = \frac{1}{\sigma_i^2}$ is the weight (sigma) associated with the measurement at the ith time and N is the number of observations. This is a value that can generally identify the quality of the most recent vector update and is used by the analyst in evaluating the OD process. A value of 1.00 is ideal.	(measurement units)		1.3	O
DATA_TYPES	Comma-separated list of observation data types utilized in this orbit determination. Although this is a free-text field, it is recommended at a minimum to use data type descriptor(s) as provided in Table 3-5 of the TDM standard [9] (excluding the DATA_START, DATA_STOP, and COMMENT keywords). Additional descriptors/detail is encouraged if the descriptors of Table 3-5 are not sufficiently clear, e.g., could replace ANGLE_1 and ANGLE_2 with RADEC (e.g., from a telescope), AZEL (e.g., from a ground radar), RANGE (whether from radar or laser ranging), etc.			ANGLE_1, ANGLE_2	O
OD_STOP	End of the orbit determination data section.			n/a	M

COMSPOC

Much of ISO 11233 now discussed (green) or in common text (blue)

New ODM Annex F8

F8 ORBIT DETERMINATION (OD) PARAMETERS

Satellite orbit determination (OD) estimates the position and velocity of an orbiting object from discrete observations. The set of observations includes external measurements from terrestrial or space-based sensors and measurements from instruments on the satellite itself. Satellite orbit propagation estimates the future state of motion of a satellite whose orbit has been determined from past observations. Though a satellite's motion is described by a set of ideal equations of motion representing physical hypotheses, the observations used in OD are subject to systematic and random uncertainties. Therefore, OD and propagation are probabilistic and can only approximately describe the satellite's motion. The degree of approximation that can be tolerated depends on the intended use of the orbital information.

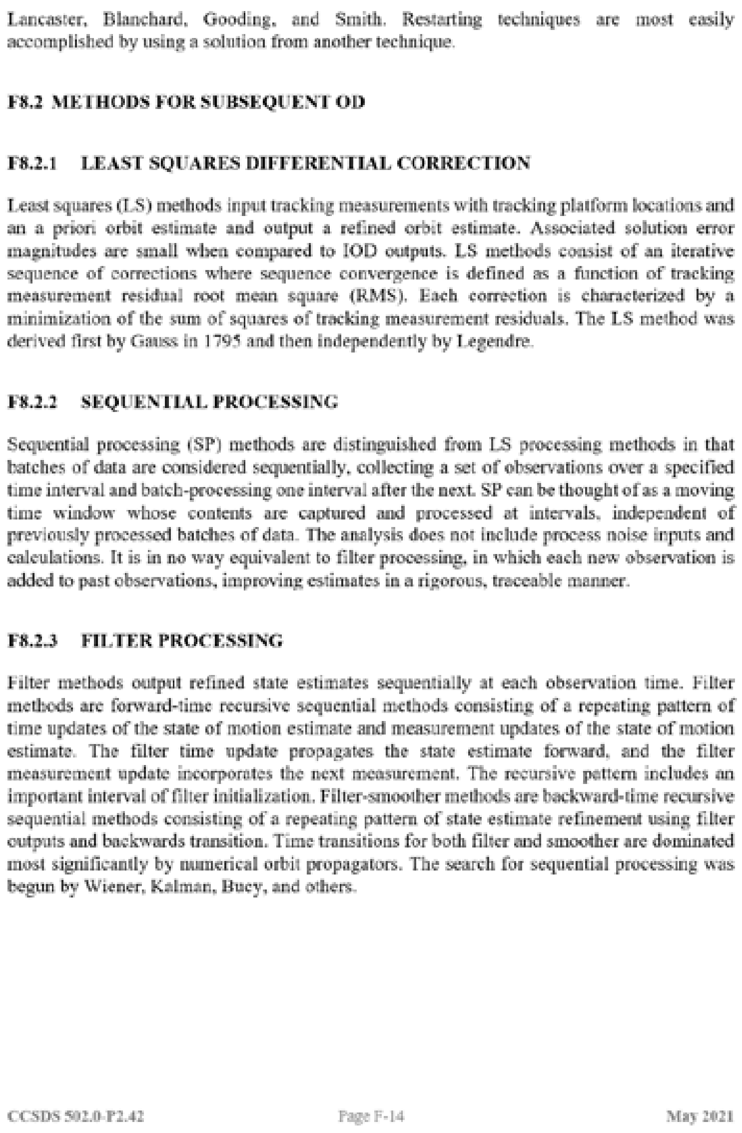
Satellite owners/operators employ different techniques to determine orbits from active and passive observations, such that the same data inputs lead to different predictions when they are used in different models. Satellite owners/operators often accept orbit descriptions developed using physical models that others employ. Differences in orbit predictions caused using different physical models and numerical techniques can be significant.

A spacecraft is influenced by a variety of external forces, including terrestrial gravity, atmospheric drag, multibody gravitation, solar radiation pressure, tides, and spacecraft thrusters. Selection of forces for modelling depends on the accuracy and precision required from the OD process and the amount of available data. The complex modelling of these forces results in a highly nonlinear set of dynamical equations. Many physical and computational uncertainties limit the accuracy and precision of the spacecraft state that can be determined. Similarly, the observational data are inherently nonlinear with respect to the state of motion of the spacecraft and some influences might not have been included in models of the observation of the state of motion.

Satellite OD and propagation are stochastic estimation problems because observations are inherently noisy and uncertain and because not all phenomena that influence satellite motion are clearly discernible. Estimation is the process of extracting a desired time-varying signal from statistically noisy observations accumulated over time. Estimation encompasses data smoothing, which is statistical inference from past observations; filtering, which infers the signal from past observations and current observations; and prediction or propagation, which employs past and current observations to infer the future of the signal.

F8.1 INITIAL OD (IOD)

Initial OD (IOD) methods input tracking measurements with tracking platform locations, and output spacecraft position and velocity estimates. No a priori orbit estimate is required. Associated solution error magnitudes can be very large. IOD methods are sometimes nonlinear methods and are often trivial to implement. Measurement editing is typically not performed during IOD calculations because there are insufficient observations. Operationally, the OD process is frequently begun, or restarted, with IOD. IOD methods were derived by various authors: LaPlace, Poincaré, Gauss, Lagrange, Lambert, Gibbs, Herrick, Williams, Stumpp,



Lancaster, Blanchard, Gooding, and Smith. Restarting techniques are most easily accomplished by using a solution from another technique.

F8.2 METHODS FOR SUBSEQUENT OD

F8.2.1 LEAST SQUARES DIFFERENTIAL CORRECTION

Least squares (LS) methods input tracking measurements with tracking platform locations and an a priori orbit estimate and output a refined orbit estimate. Associated solution error magnitudes are small when compared to IOD outputs. LS methods consist of an iterative sequence of corrections where sequence convergence is defined as a function of tracking measurement residual root mean square (RMS). Each correction is characterized by a minimization of the sum of squares of tracking measurement residuals. The LS method was derived first by Gauss in 1795 and then independently by Legendre.

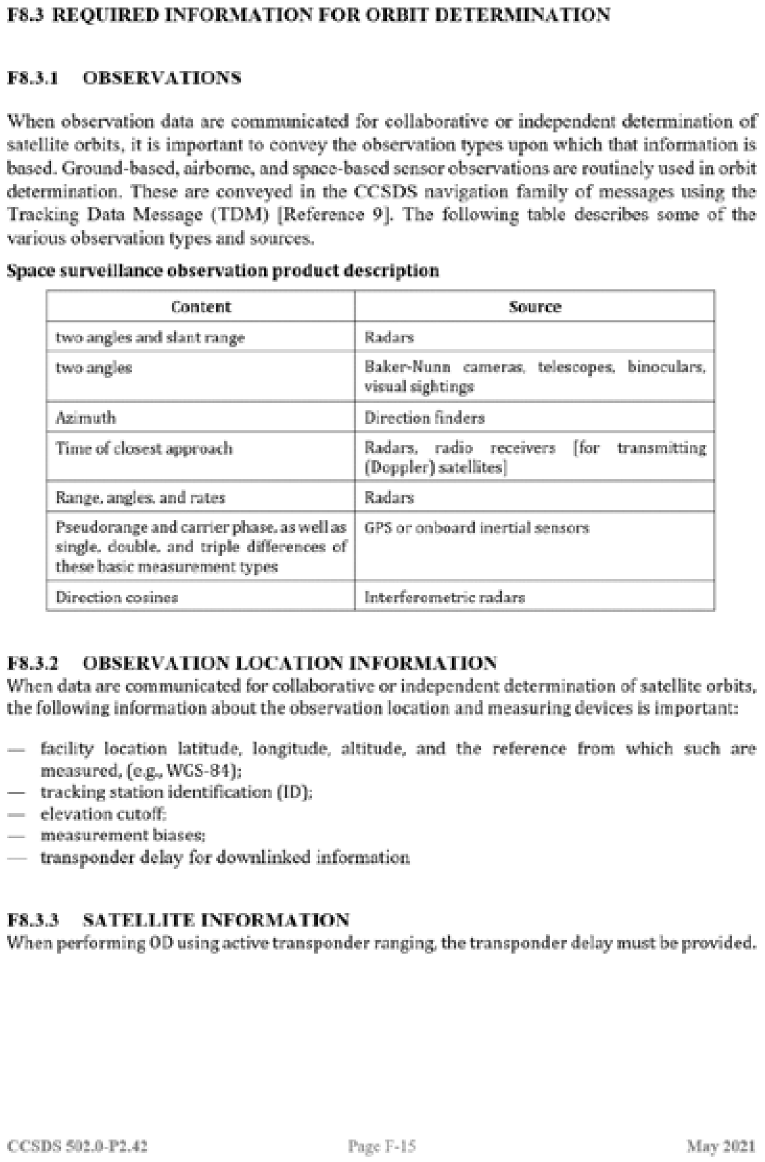
F8.2.2 SEQUENTIAL PROCESSING

Sequential processing (SP) methods are distinguished from LS processing methods in that batches of data are considered sequentially, collecting a set of observations over a specified time interval and batch-processing one interval after the next. SP can be thought of as a moving time window whose contents are captured and processed at intervals, independent of previously processed batches of data. The analysis does not include process noise inputs and calculations. It is in no way equivalent to filter processing, in which each new observation is added to past observations, improving estimates in a rigorous, traceable manner.

F8.2.3 FILTER PROCESSING

Filter methods output refined state estimates sequentially at each observation time. Filter methods are forward-time recursive sequential methods consisting of a repeating pattern of time updates of the state of motion estimate and measurement updates of the state of motion estimate. The filter time update propagates the state estimate forward, and the filter measurement update incorporates the next measurement. The recursive pattern includes an important interval of filter initialization. Filter-smoother methods are backward-time recursive sequential methods consisting of a repeating pattern of state estimate refinement using filter outputs and backwards transition. Time transitions for both filter and smoother are dominated most significantly by numerical orbit propagators. The search for sequential processing was begun by Wiener, Kalman, Bucy, and others.

New ODM Annex F8



F8.3 REQUIRED INFORMATION FOR ORBIT DETERMINATION

F8.3.1 OBSERVATIONS

When observation data are communicated for collaborative or independent determination of satellite orbits, it is important to convey the observation types upon which that information is based. Ground-based, airborne, and space-based sensor observations are routinely used in orbit determination. These are conveyed in the CCSDS navigation family of messages using the Tracking Data Message (TDM) [Reference 9]. The following table describes some of the various observation types and sources.

Space surveillance observation product description

Content	Source
two angles and slant range	Radars
two angles	Baker-Nunn cameras, telescopes, binoculars, visual sightings
Azimuth	Direction finders
Time of closest approach	Radars, radio receivers [for transmitting (Doppler) satellites]
Range, angles, and rates	Radars
Pseudorange and carrier phase, as well as single, double, and triple differences of these basic measurement types	GPS or onboard inertial sensors
Direction cosines	Interferometric radars

F8.3.2 OBSERVATION LOCATION INFORMATION

When data are communicated for collaborative or independent determination of satellite orbits, the following information about the observation location and measuring devices is important:

- facility location latitude, longitude, altitude, and the reference from which such are measured, (e.g., WGS-84);
- tracking station identification (ID);
- elevation cutoff;
- measurement biases;
- transponder delay for downlinked information

F8.3.3 SATELLITE INFORMATION

When performing OD using active transponder ranging, the transponder delay must be provided.

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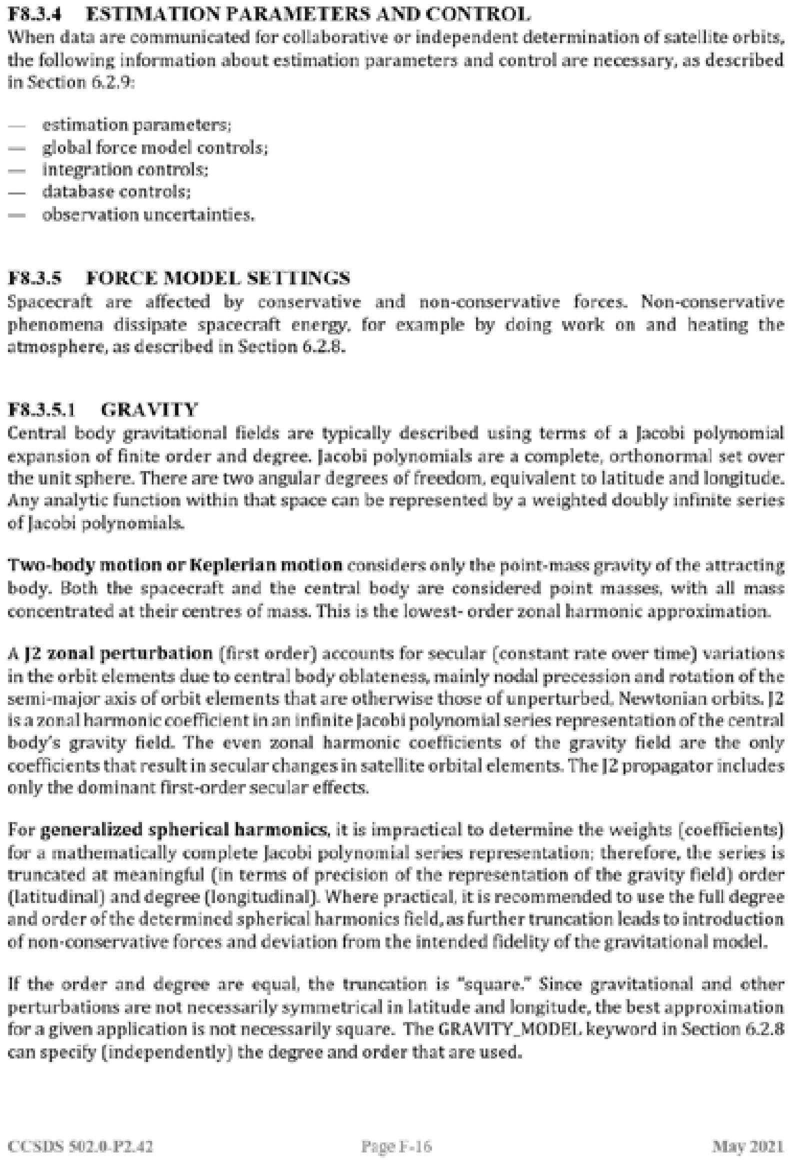

F8.3.4 ESTIMATION PARAMETERS AND CONTROL

When data are communicated for collaborative or independent determination of satellite orbits, the following information about estimation parameters and control are necessary, as described in Section 6.2.9:

- estimation parameters;
- global force model controls;
- integration controls;
- database controls;
- observation uncertainties.

F8.3.5 FORCE MODEL SETTINGS

Spacecraft are affected by conservative and non-conservative forces. Non-conservative phenomena dissipate spacecraft energy, for example by doing work on and heating the atmosphere, as described in Section 6.2.8.

F8.3.5.1 GRAVITY

Central body gravitational fields are typically described using terms of a Jacobi polynomial expansion of finite order and degree. Jacobi polynomials are a complete, orthonormal set over the unit sphere. There are two angular degrees of freedom, equivalent to latitude and longitude. Any analytic function within that space can be represented by a weighted doubly infinite series of Jacobi polynomials.

Two-body motion or Keplerian motion considers only the point-mass gravity of the attracting body. Both the spacecraft and the central body are considered point masses, with all mass concentrated at their centres of mass. This is the lowest- order zonal harmonic approximation.

A **J2 zonal perturbation** (first order) accounts for secular (constant rate over time) variations in the orbit elements due to central body oblateness, mainly nodal precession and rotation of the semi-major axis of orbit elements that are otherwise those of unperturbed, Newtonian orbits. J2 is a zonal harmonic coefficient in an infinite Jacobi polynomial series representation of the central body's gravity field. The even zonal harmonic coefficients of the gravity field are the only coefficients that result in secular changes in satellite orbital elements. The J2 propagator includes only the dominant first-order secular effects.

For **generalized spherical harmonics**, it is impractical to determine the weights (coefficients) for a mathematically complete Jacobi polynomial series representation; therefore, the series is truncated at meaningful (in terms of precision of the representation of the gravity field) order (latitudinal) and degree (longitudinal). Where practical, it is recommended to use the full degree and order of the determined spherical harmonics field, as further truncation leads to introduction of non-conservative forces and deviation from the intended fidelity of the gravitational model.

If the order and degree are equal, the truncation is "square." Since gravitational and other perturbations are not necessarily symmetrical in latitude and longitude, the best approximation for a given application is not necessarily square. The GRAVITY_MODEL keyword in Section 6.2.8 can specify (independently) the degree and order that are used.

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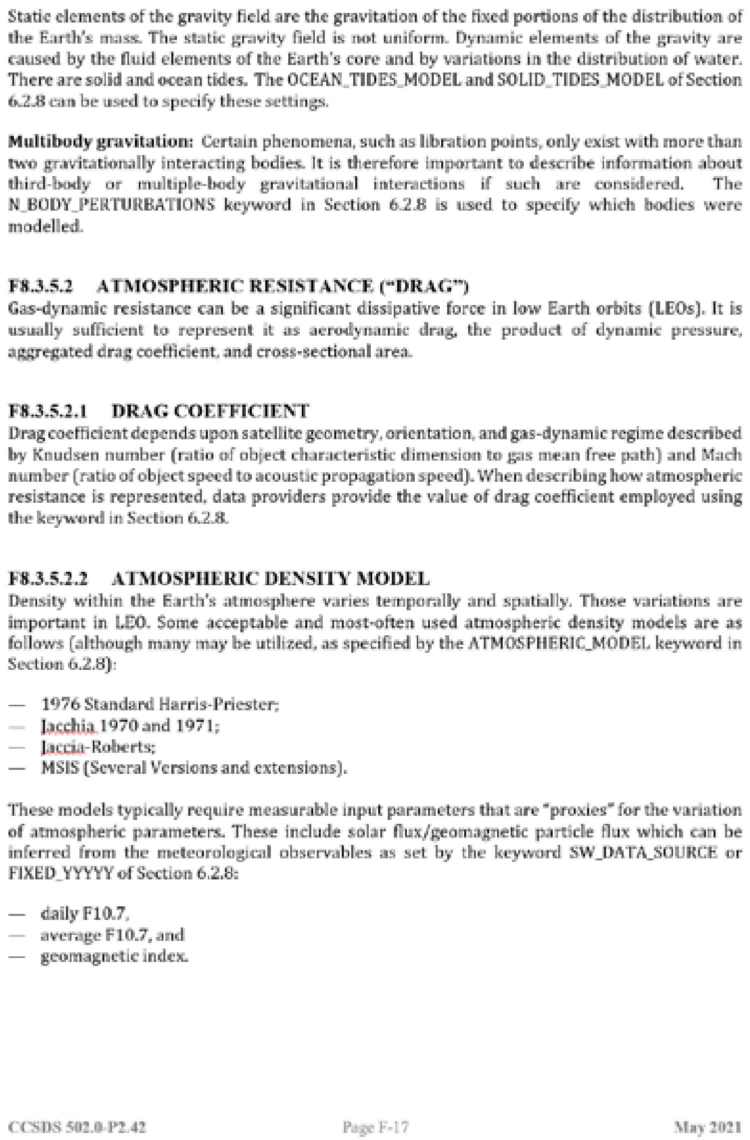
New ODM Annex F8



Static elements of the gravity field are the gravitation of the fixed portions of the distribution of the Earth's mass. The static gravity field is not uniform. Dynamic elements of the gravity are caused by the fluid elements of the Earth's core and by variations in the distribution of water. There are solid and ocean tides. The OCEAN_TIDES_MODEL and SOLID_TIDES_MODEL of Section 6.2.8 can be used to specify these settings.

Multibody gravitation: Certain phenomena, such as libration points, only exist with more than two gravitationally interacting bodies. It is therefore important to describe information about third-body or multiple-body gravitational interactions if such are considered. The N_BODY_PERTURBATIONS keyword in Section 6.2.8 is used to specify which bodies were modelled.

F8.3.5.2 ATMOSPHERIC RESISTANCE ("DRAG")

Gas-dynamic resistance can be a significant dissipative force in low Earth orbits (LEOs). It is usually sufficient to represent it as aerodynamic drag, the product of dynamic pressure, aggregated drag coefficient, and cross-sectional area.

F8.3.5.2.1 DRAG COEFFICIENT

Drag coefficient depends upon satellite geometry, orientation, and gas-dynamic regime described by Knudsen number (ratio of object characteristic dimension to gas mean free path) and Mach number (ratio of object speed to acoustic propagation speed). When describing how atmospheric resistance is represented, data providers provide the value of drag coefficient employed using the keyword in Section 6.2.8.

F8.3.5.2.2 ATMOSPHERIC DENSITY MODEL

Density within the Earth's atmosphere varies temporally and spatially. Those variations are important in LEO. Some acceptable and most-often used atmospheric density models are as follows (although many may be utilized, as specified by the ATMOSPHERIC_MODEL keyword in Section 6.2.8):

- 1976 Standard Harris-Priester;
- Jacchia 1970 and 1971;
- Jaccia-Roberts;
- MSIS (Several Versions and extensions).

These models typically require measurable input parameters that are "proxies" for the variation of atmospheric parameters. These include solar flux/geomagnetic particle flux which can be inferred from the meteorological observables as set by the keyword SW_DATA_SOURCE or FIXED_YYYYY of Section 6.2.8:

- daily F10.7,
- average F10.7, and
- geomagnetic index.

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F8.3.5.3 RADIATION PRESSURE

Momentum transfer from photons to satellites can be an important force for HEOs. Radiation pressure depends on the area and surface characteristics of the satellite and the nature of the incident radiative fluxes. The Sun is the predominant direct source of electromagnetic radiation, but the Earth and the Moon also emit and reflect electromagnetic radiation. The keywords provided in Section 6.2.8 (SHADOW_BODIES, SRP_MODEL, ALBEDO_MODEL, ALBEDO_GRID_SIZE) allow the user to specify radiation pressure settings used in the OD and orbit propagation regarding:

- solar radiation pressure coefficient;
- area-to-mass ratio;
- satellite bidirectional reflectance function (BDRF) or equivalent;
- shadow and shape factor models;
- eclipse models (cylindrical, dual-cone);
- Albedo and intensity at the satellite.

F8.3.6 ORBIT PROPAGATION

Orbit propagation or prediction has evolved synchronously with advances in computational capability. Initially, force models were greatly simplified, and most important non-gravitational forces were approximated analytically. These generally linearized approaches were valid only over short intervals or for small variations from two-body Keplerian motion.

Even when more precise numerical integration became feasible, execution times were often too long, and computation was too expensive to employ numerical integration on a regular basis. Several semi-analytical techniques emerged that reduced numerical complexity (with some compromise to precision) by providing formulae from which significant elements of the propagation workflow could be extracted.

Purely numerical techniques are not used frequently. These suffer only the physical approximations made in describing important phenomena and numerical phenomena common to all discrete computations. Analytical, numerical, and semi-analytical orbit propagation techniques are distinguished. Semi-analytical and analytical approaches are specific "propagators". This subclause applies to numerically derived orbit predictions.

F8.3.7 ORBIT ELEMENTS

Orbit elements are the sets of parameters that emerge from the smoothing, filtering, or predictive estimation schemes. Six independent quantities and orbit elements describe the orbit of a satellite. A seventh variable designates the satellite location at a specific time of interest (epoch). There are many different sets of orbit elements (see orbit element set type; selected per ANNEX , Section B7). Each is best suited for a particular application, such as aiming antennas, ea manipulation in various coordinate systems, or estimating orbits from different types of measurements.

The traditionally used set of orbital elements is called the set of Keplerian elements; Keplerian elements parameters can be encoded as text in several formats. In semi-analytical propagation, mean orbit elements are often used, the most common of them is as conveyed in the NASA/NORAD "two-line elements" (TLE) format, originally designed for use with 80-column punched cards (but still in use because it is the most common format).

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Suggested path

- As stated previously, recommend retiring ISO 11233.
  - Current content is not comprehensive and would require much enhancement to be useful/relevant.
- Suggest moving remaining unique orbit determination content from ISO 11233 into ISO 26900 Informative Annex F: “Technical material and conventions for ODM data”
  - CCSDS NAV WG convener supportive of this ODM change.
- Can then retire ISO 11233.