

Evidence-Supported ASO Catalog

A measured orbital catalog for Space Data Network

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Technical whitepaper 2.3 | 12 October 2026

Numerical evidence cutoff: 11 October 2026

1 Summary

Space Data Network (SDN) builds a catalog of anthropogenic space objects (ASOs) from public and login-only sources. Object by object, it publishes the solution with the best measured accuracy for the intended use, with its uncertainty. Accuracy is measured against independent precise orbits, under plans fixed before the test data were read¹. Section 2 states the method step by step, with the rule that gives every object a covariance.

Object class	Catalog product	Measured (median)
GPS satellites	Analysis-centre orbit, propagated	3.5 cm at issue, 30 m a day later
Satellites with laser ranging	High-precision orbit propagation (HPOP) fitted to the ranges	7 m at the fit, 42 m after 7 days
Satellites with operator ephemerides	The operator’s ephemeris	Public element sets (OMMs) lie 0.6–5 km from it
Objects known only from public OMMs	SGP4 on the OMM	0.3–1.6 km at issue

For most objects the only public input is the OMM, and the catalog takes it as it is. What the catalog adds is a measured account of each input’s error, and screening that acts on it safely:

1. **Measured error as covariance.** An orbit propagated from an OMM’s epoch state carries a covariance equal to the error measured for its orbit regime and element-set age. That error is measured against independent orbits in every regime that has them: GNSS analysis-centre orbits, laser ranging, LEO precise orbits, operator ephemerides and radio-occultation receivers. A covariance is labeled calibrated only where held-out data confirm it (section 2.2).
2. **SDN’s own atmosphere.** Drag uses JB2008 or NRLMSISE-00 with an open correction in the form of the Space Force’s Dynamic Calibration of the Atmosphere, solved from public operator states. It explains 25–40 % of the density variation measured by satellites that did not calibrate it; 1–3-day position error is unchanged (ratios 0.98–1.02) (section 5.4).
3. **Maneuvers.** A detector reads each object’s element-set history for steps in orbital energy and plane, and reports each maneuver’s time and size. On held-out data it found 22 of 25 ISS burns and all 6 GPS maneuvers in precise orbits; geostationary station-keeping is harder, 4 of 11 (section 5.5).
4. **Better start states where data allow.** HPOP’s force models agree with Orekit within 1 cm over a day (steps of at most 30 s; 2.5 cm at 300 s, section 7). Fitted to laser ranges, HPOP stays 20–60 times better than SGP4 to 7 days; fitted to an arc of corrected OMMs, it halves SGP4’s error to two days in GPS (section 5.3). SGP4-XP sets that SDN fits to precise GNSS orbits err by a median 0.42 km over the seventh day, against 14 km for its SGP4 fits of the same orbits (exploratory, section 4).
5. **Screening that stays safe when the covariance is large.** A large covariance spreads a collision’s probability thin: on real OMM errors, a probability threshold of 1e-4 missed 2.7–16 % of true collisions. Where held-out data confirm the covariance, screening on the uncertainty region missed 0–0.4 %, at

the cost of more false alerts, and every event also carries the covariance-free maximum probability⁵⁰. Large uncertainty makes the screen cautious, not blind.

Three results go beyond published work:

1. An element-set correction learned on a LEO fleet carries to that fleet’s unseen satellites (25 % lower error at epoch) but not to other operators’ satellites, nor across GPS orbital planes; in GNSS a per-satellite bias holds 37 % of the along-track variance, against 1–5 % in LEO (section 5.3).
2. A density correction of the kind the Space Force’s drag model uses, solved from Planet’s public states, is scored on satellites that did not calibrate it (section 5.4).
3. Consecutive OMM errors are strongly correlated, and four published covariance constructions are overconfident (section 6).

Pre-registered hypotheses that failed are reported as not supported.

2 Method

The catalog is assembled object by object from the products of every source. Each object ends with a state, a covariance and its maneuvers.

2.1 Construction

1. **Read each source at its level.** Each record becomes the Space Data Standards (SDS) record of its kind, under the source’s own identifier: element sets as OMMs, ephemerides as OEMs, laser normal points and other measurements as observations (sections 3 and 4).
2. **Derive the same products from every source.** For every object a source covers, the method derives four records:
 1. An SGP4 element set (OMM): the source’s own, or one fitted to the source’s ephemeris (section 4).
 2. An SGP4-XP element set: an OMM in the extended-perturbation theory of the Space Force’s Astrodynamics Standards⁵², with its ballistic and radiation coefficients, fitted to the same data (section 4).
 3. A state with its covariance (OCM): the source’s state at its epoch, or the SGP4 epoch state of the handoff in section 4, with the covariance of section 2.2.
 4. The maneuvers in the source’s history (MNV), from the detector of section 5.5.

Sources are then compared like for like, and each can be propagated and shown on its own.

3. **Measure each source.** Each product is scored against independent precise orbits by object class, orbit regime and product age, under a plan fixed before its test data were read (sections 5 and 10). A source’s measured errors form its error model.
4. **Associate.** Crosswalks propose links between records of one object; ephemerides compared over shared intervals accept, reject or hold each link (section 8).
5. **Select.** For each object, regime and horizon, the catalog takes the product of the source with the lowest measured median error on a training window of at least 30 samples. Fusing sources was never better than selecting one (section 8).
6. **Attach covariance and maneuvers.** The selected product keeps its covariance and label (section 2.2). The object carries the maneuvers of all its sources, merged by time and size. A product whose epoch precedes a maneuver does not describe the orbit after it, so selection after a maneuver draws only on later products.
7. **Write the catalog.** A catalog record (CAT) per object, with its selected OMM, SGP4-XP OMM and OCM and its merged MNV records, each naming the source it came from.

2.2 Covariance for every object

Every object carries a covariance, from the first rule that applies:

1. **The operator supplies one.** The operator’s covariance, as supplied.
2. **An orbit fit made the product.** The fit’s formal covariance, scaled by the realism factor measured for that source and object class on held-out data. Unscaled, laser-range fits are 16–21 times too small in mean $d^2/3$ (section 6).
3. **The source has an error model for the object’s regime.** The source’s measured error at the element set’s age, mapped from radial, in-track and cross-track axes to Cartesian. The model is built from the errors of consecutive element sets against independent precise orbits, with their correlation, and calibrated by regime and age (section 6). AOE’s sets match Space-Track’s error at equal age (section 4) and take its model.
4. **Otherwise.** The same model pooled over all sources in the object’s regime.

Rules 3 and 4 cover every object with an element set, so no object goes without a covariance.

Each covariance carries a label: the rule, the source, the regime and age cell, and the verdict of held-out data for that cell. Calibrated means the realism rule of section 6 held on held-out data: mean $d^2/3$ in $[0.8, 1.25]$ and 95 % coverage in $[0.93, 0.97]$. Otherwise the label records the measured mean $d^2/3$ and coverage. The element-set model is calibrated in 2 of 35 regime-and-age cells, LEO above 800 km at issue and at half a day; the HPOP epoch state with per-regime P_0 and Q in 5 (section 6). Screening on the uncertainty region relies on calibrated cells, and every screening event also carries the covariance-free maximum probability, which needs no covariance⁵⁰.

Covariance propagates through HPOP’s state-transition matrix with per-regime process noise, or grows with element-set age in the model of rule 3 (section 6).

2.3 Evidence model

An orbit solution is an inference with five contributors:

1. The object’s physics
2. The dynamics model
3. The observations
4. The measurement model
5. The inference method

A provider’s ephemeris or element set already embeds the provider’s models and inference, so the catalog treats it as the provider’s estimate, not as an observation. Agreement between two products counts as independent confirmation only when their inputs are independent.

Orbit data sit at four processing levels, by analogy with Earth-science data levels. A higher level is more processed, not better: it inherits every flaw below it, and re-epoching adds no evidence. Each input is placed at its level.

Level	Content	SDN inputs
0	Raw sensor data	Detector counts, signal samples, images
1	Calibrated, time-tagged measurements	Laser normal points; radio Doppler; optical angles
2	Estimated states and ephemerides	Operator ephemerides; GNSS and laser-ranging precise orbits; Vimpel elements; ILRS predictions
3	Theory-specific mean elements fitted to level 1 or 2	OMMs from Space-Track and SpaceMapper; CelesTrak’s supplemental GP; SDN’s SGP4 companions

A solution states what produced it:

Field	Content
State and validity	State or ephemeris, epoch, applicable interval
Inputs	The products it rests on and their levels
Dynamics	Force model, environment inputs, parameters estimated, considered or assumed
Measurement model	Sensor geometry, timing, calibration, biases; unknown when a provider does not state it
Inference	Estimator or selection rule, weights, priors
Uncertainty	Covariance, its source and its calibration label

Physical validity rests on the measurements of sections 5 to 7.

3 Sources

The inventory² lists 97 public and login-only sources in eight groups, with access, terms, latency and use. Results draw on every source an experiment read; files are copied only where their terms allow, and the credits close this paper.

Group	Sources	Role
A. Precise orbits	IGS and ESA GNSS orbits; ILRS orbits and normal points; Sentinel-1, Swarm, GRACE-FO and CryoSat-2 precise orbits	Truth; the GNSS and laser-ranged products
B. Operator ephemerides	SpaceX Starlink (with covariance), Planet, NASA ISS, CMSE Tiangong, Intelsat; ILRS predictions	Operator products; drag and maneuver evidence
C. Catalogs and observations	Space-Track GP history (OMM) and SATCAT; JSC Vimpel; SpaceMapper AOE; SatNOGS Doppler	Element sets; other providers' catalogs; public observations
D. Density	Swarm and GRACE-FO densities; CHAMP and GRACE-A densities with the High Accuracy Satellite Drag Model (HASDM) ³	Density truth; the HASDM comparison
E. Space weather	Space Environment Technologies' (SET) JB2008 indices; GFZ Kp, ap and F10.7; NOAA SWPC forecasts	Model drivers, as issued
F. Earth orientation, gravity, ephemerides	IERS EOP; EGM2008, EGM96; FES2004; DE440	Frames and dynamics
G. Physical properties	GCAT; IGS satellite metadata	Priors for drag and radiation parameters
H. The High Accuracy Catalog (HAC) and HASDM	Special Perturbations (SP) vectors; real-time HASDM	The comparison target (section 10)

SpaceMapper's AOE catalog holds SGP4 element sets from its own ground and space sensors (channel KY, 19,202 objects on 11 October 2026) beside sets it relays from other catalogs⁴. AOE rewrites them every 3 hours; SDN reads them daily from the public web pages (section 4). SpaceMapper states no license, so the sets are cited, not copied. Doppler read from SatNOGS waterfall images made the ISS orbit 2.7–10.7 times worse than SGP4 E6.

4 Normalization and model dispatch

Vimpel osculating elements

Vimpel’s HEO product gives osculating elements in J2000⁵. The standard perifocal rotation turns them into a J2000 state at the same epoch⁶, with $\mu = 398,600.4418 \text{ km}^3/\text{s}^2$. Vimpel’s datefirst file maps its own object numbers to NORAD numbers, with the date each catalog first detected the object; each pair is a candidate link, accepted when the two orbits agree (section 8). An object the file does not map keeps the identifier `vimpel:<id>`, and no NORAD number is invented⁷. Velocity differenced from 600 s position samples departs from the analytic velocity by up to 1.1 km/s, so it serves only as a diagnostic.

AOE element sets

AOE’s KY sets are SGP4 mean elements: the catalog evaluates them through the same SGP4 as Space-Track’s OMMs, under the NORAD number AOE gives, or under `aoe:<id>` where it gives none. E15 scores them against independent orbits beside Space-Track’s, under a plan fixed before its test window E15. On 11 October 2026, its first training day:

Measure	Result
Difference from Space-Track	A median 1.70 km from Space-Track’s newest set at the same moment; 1.5 % within 100 m
Age at issue	Median 11.6 days: 7.4 in Starlink’s shells, 36 for the Chinese space station, 62 for Spire, 83 for Planet
Error at issue, Starlink (2,755 satellites, SpaceX ephemerides)	40.7 km median against Space-Track’s 2.14 km: 18.9 [16.7, 21.6] times, almost all set age
The same at matched age	1.07 [0.70, 1.55] times Space-Track’s error under half a day old; 1.03 [0.80, 1.26] at half a day to a day
Error at issue, GEO (76 satellites)	19.0 km against 6.69 km: 2.84 [1.77, 4.07] times
Coverage	45 of 82 Planet and 6 of 10 Spire satellites have no AOE set

AOE’s sets are therefore not copies of Space-Track’s: they are as accurate at the same age, and older on most objects.

The handoff contract

An OMM holds SGP4 mean elements, not osculating ones. The catalog evaluates SGP4 at zero elapsed time, transforms position and velocity from TEME to GCRF at the same instant, and starts HPOP from that state⁸. SGP4’s drag term B^* becomes the ballistic parameter

$$B = \frac{C_D A}{m} = \frac{2B^*}{\rho_0}$$

with ρ_0 from Spacetrack Report No. 3⁹; 0.01 m²/kg stands in where $B^* \leq 0$, and $\text{Cr} \cdot A/m$ is 0.02 m²/kg¹⁰. The handoff is valid; whether it helps is measured in section 5.3.

Levels of measurement of OMM elements

OMM fields mix nominal (catalog number), ordinal (element-set number), interval (epoch), ratio (mean motion) and circular (node, perigee, mean anomaly) scales, so the pipeline computes on SGP4-evaluated states, never on raw fields. The legacy two-line format quantizes angles to 0.0001°, about 12 m along track near 6,900 km: a resolution, not an accuracy.

Dispatch, frames and time

Each record is routed by its declared theory: mean elements to SGP4, osculating elements to the two-body conversion, states and ephemerides to frame transforms. Osculating elements offered to SGP4 are refused as a model mismatch. Frames follow the IERS Conventions (2010): IAU 2006/2000A, CIO-based, through ERFA, with IERS Earth orientation¹¹. TEME, EME2000, GCRF and ITRF stay distinct; epochs are UTC and integration runs on TT.

SDN's own OMMs

SDN fits its own OMMs to any source's ephemeris: operator ephemerides (SpaceX's MEME files, CCSDS OEM, Earth-fixed files), GNSS orbits (SP3), laser-ranging predictions (CPF) and its own HPOP solutions. Each fit gives two element sets over a declared interval, each scored on a held-out stretch before release: an SGP4 set with B*, which any SGP4 implementation reads, and an SGP4-XP set with its ballistic (BTERM) and radiation (AGOM) coefficients, propagated by the Astrodynamics Standards library⁵². CelesTrak's supplemental GP fits operator ephemerides with SGP4 the same way⁴⁸, Spacebook fits extended-perturbation element sets to its own orbits⁵¹, and the 18th Space Defense Squadron's eGP fits SP states⁴⁹. The fit RMS that CelesTrak publishes for each set is the benchmark.

Exploratory, on 24-hour fits to the same states XP: the median root-mean-square 3D position error (km) over the fit and over each later day, SGP4-XP / SGP4.

Ephemeris (windows)	Fit	Day 1	Day 3	Day 7
GPS, Galileo and GLONASS, ESA final orbits (98)	0.022 / 0.134	0.057 / 0.420	0.161 / 2.40	0.419 / 14.2
LAGEOS-1/2 and Etalon-1/2, ILRS orbits (36)	0.095 / 0.116	0.104 / 0.227	0.242 / 1.22	0.570 / 6.61
Seven low laser-ranged satellites, ILRS orbits (139)	0.371 / 0.389	0.735 / 0.977	1.16 / 5.10	
Starlink, SpaceX ephemerides (196)	0.539 / 0.534	3.67 / 5.92		
ISS, NASA ephemeris (14)	0.455 / 0.461	2.16 / 2.12	16.5 / 16.4	88.9 / 88.8

Starlink files span 2–3 days and the low laser-ranged arcs 4 days, which bounds their horizons. SGP4-XP converged on all 505 windows and SGP4 on 98 of the 120 GNSS windows; the GNSS row compares those 98. Where drag is weak the extended theory holds: 12 to 34 times closer at 7 days on GNSS, LAGEOS and Etalon. On the ISS, where drag and reboosts dominate, the two theories are equal.

5 Products by object class

Each row is one method: its originators, our measured result (median 3D position error unless stated) and the experiment. Every experiment froze its plan before reading its test window¹.

5.1 GNSS and laser-ranged satellites

Method	Prior art	Measured	Evidence
Newest ultra-rapid analysis-centre orbit at issue, propagated numerically beyond	IGS products ¹²	GPS, 32 satellites: 3.5 cm at issue, 336 m at 7 days; the latest public OMM 1.5–1.7 km	E3

Method	Prior art	Measured	Evidence
HPOP fitted to ILRS laser normal points	Laser-ranging orbit determination ¹³	Starlette, Stella, LARETS, WESTPAC, LARES: 7 m at the fit and 42 m at 7 days, against SGP4's 472 m and 685 m. One pass beats the OMM for a day; four passes beat it at every horizon to 7 days	E6

5.2 Operator- and provider-ephemeris objects

Method	Prior art	Measured	Evidence
Operator ephemeris, within its span	Operator orbit determination	GNSS analysis centres' predictions (IGS for GPS, ESA for GLONASS): 0.1 m from final orbits at 0–12 h	E4
SGP4 on the latest public OMM, against operator ephemerides	Dyreby et al. 2025 ¹⁴ ; Jankovic 2026 ¹⁵	At the file's start: Planet 0.59 km, ISS 0.82 km, GPS 1.23 km, Starlink 2.87 km, Intelsat 4.79 km; Starlink 13.8 km at 24 h	E4
Vimpel's state refined to Vimpel's ephemeris by one six-state correction	Weighted least squares ¹⁶	Withheld RMS 6.04–10.71 km before, 52.8–69.9 m after, on three 4-hour arcs: consistency with one provider, not accuracy	R77

5.3 Objects with public OMMs only

Method	Prior art	Measured	Evidence
SGP4 on the latest public OMM	Hoots and Roehrich 1980 ⁹ ; Vallado et al. 2006 ⁸	At issue: 0.31 km (laser-ranged LEO) to 1.57 km (GPS); by horizon in section 10	E3
Along-track correction at epoch (GPS)	Ly et al. 2020: 65 % ¹⁷ ; Hallgarten La Casta and Amato 2025 ¹⁸	RMS at epoch 2.04 → 0.79 km (61 % [53, 67]); the single-model form 8 %; worse than SGP4 by 7 days (2.55 against 1.88 km); its covariance fails the coverage gate. On an orbital plane outside the fit: 6 % [2, 10]	E1
The epoch correction learned on other objects, by regime (LEO: static covariates and a 48-hour fleet nowcast; MEO/GEO: the form of Ly et al.)	Ly et al. 2020 ¹⁷ ; Hallgarten La Casta and Amato 2025 ¹⁸	Unseen LEO satellites: 25 % [18, 32] lower error at epoch, 51 % for Planet's own satellites; other operators' satellites −2 % [−17, 10]; 9 % at 1 day, 1 % at 3 days. MEO and GEO 4 %, worse by more than 10 % for 64 of 135 objects. A per-satellite bias holds 37 % of the along-track variance in GNSS, 1–5 % in LEO	E16

Method	Prior art	Measured	Evidence
HPOP from the OMM's epoch state	Vallado et al. 2006 ⁸ ; Jankovic 2026 ¹⁵	Equal to SGP4 at epoch, then larger as the OMM's start-state error grows: at 24 h, 1.7 (GPS) to 11 (laser-ranged LEO) times SGP4's error; larger in all four regimes (GPS, LEO with precise orbits, laser-ranged LEO and MEO) by 72 h	E7
AOE's newest set	SpaceMapper ⁴	Starlink: 18.9 times Space-Track's error at issue, from set age; 1.03–1.07 times at matched age (section 4)	E15
HPOP fitted to an arc of OMM epoch states	Levit and Marshall 2011 ¹⁹	Better than SGP4 only at short horizons: 0.32–0.51 of its error to 12 h (laser-ranged LEO), 0.36–0.53 to 48 h on E1-corrected GPS sets; undecided beyond	E7
HPOP fitted to a 4- or 7-day arc of OMM epoch states with drag fitted (LEO)	Levit and Marshall 2011 ¹⁹	0.45 of SGP4's error at epoch and 0.39 at 6 h; 0.87 [0.62, 1.18] at 24 h and 1.40 [1.00, 1.92] at 72 h (not supported); laser-ranged spheres 0.28 at 24 h and 0.46 at 72 h. A fitted drag rate, weights with the measured correlation and the E13 density correction leave it unchanged	E16

The start state sets the limit. Over 6 days, HPOP leaves 0.2 km along track from a GPS satellite's IGS state and 8.4 km from its OMM epoch state (medians of 508 arcs)¹⁰. Laser ranges fix the start state, and the prediction then stays 20 to 60 times better than SGP4 to 7 days E6.

5.4 Drag regime

Density is scored by σ , the spread of $\ln(\text{observed}/\text{model density})$ on satellites outside the calibration; prediction by the 3-day position error relative to JB2008's (below 1 is better).

Method	Prior art	Measured	Evidence
JB2008 with SET's indices	Bowman et al. 2008 ²⁰	σ 0.155 (Swarm, GRACE-FO, 2026); 0.148 on CHAMP and GRACE-A in 2003 and 2008, where HASDM scores 0.078	E5
Temperature correction from accelerometer and precise-orbit densities, a stand-in for HASDM's calibration	Storz et al. 2005 ²¹ ; Doornbos 2012 ²²	σ 0.056, 64 % [57, 70] lower; 0.112 on HASDM's windows; forecast gain 9 % for one day; 3-day ratio 1.04 [0.96, 1.10]; inputs arrive 49–92 days late (E8)	E5
Temperature correction from the OMM decay of 48 catalogued objects	Picone et al. 2005 ²³ ; Gondelach and Linares 2020 ²⁴ ; Gershman 2026 ²⁵	σ 0.142, 8.4 % [−3.9, 18.3] lower (25 % required: not supported); 24.7 % lower in storms; as a forecast 16.8 % worse than JB2008; 3-day ratio 1.02; 0.270 on HASDM's windows	E8

An open, DCA-form correction from public operator states E13. HASDM’s Dynamic Calibration of the Atmosphere (DCA) corrects exospheric temperature every 3 hours from the drag of about 75–100 tracked calibration satellites, each with a constrained ballistic-coefficient correction²¹. E13 solves that form from public data alone: the common mode s of the daily drag of 36 Planet Doves, read through orbital energy, corrects JB2008’s temperature, with a ballistic coefficient held constant per satellite over a block and a forecast with a 48-hour time constant. Published work derives density from operator ephemerides and scores density alone^{26,27,28}, or assimilates commercial GPS states²⁹. E13 scores the correction on satellites that did not calibrate it, over ten months of Planet states against Swarm and GRACE-FO, with the storm of January 2026 in a held-out block. With x' the logarithmic residual of observed against JB2008 density in a 12-hour window,

$$R_1 = 1 - \frac{\text{sd}(x' - s)}{\text{sd}(x')}$$

Pre-registered test (threshold)	Test A, Jan–Mar 2026, Kp 8.7 storm	Test B, Apr–Jul 2026
H1: Swarm and GRACE-FO density spread explained, $R_1 (\geq 0.25)$	0.247 [0.137, 0.347]: not supported	0.401 [0.283, 0.501]: supported
H3: held-out Doves’ drag explained (≥ 0.2)	0.378 [0.223, 0.477]: supported	0.254 [0.135, 0.359]: supported
H4: Swarm position error ratio at 1 and 3 days (≤ 0.9)	1.02, 0.92: not supported	1.01, 1.00: not supported
H5: held-out Doves, the same	0.98, 0.97: not supported	1.00, 1.01: not supported
H6: control, correction shifted 7 days ($R_1 < 0.05$)	−0.149: passes	−0.082: passes

The correction does not follow storms. Exploratory, on one NRLMSISE-00 reference for every split: the fleet explains 0.47–0.48 of NRLMSISE-00’s larger spread, leaving residuals of 0.075–0.095 against 0.069–0.086 on JB2008.

5.5 Maneuver detection

The detector compares the trajectories of consecutive element sets at one instant, whatever propagator answers its queries: a crossing test and a robust likelihood-ratio test for steps in orbit-averaged energy and orbit plane, merged by default¹⁰. It builds on element-set time series³⁰ and the generalized likelihood ratio for jumps³¹. Thresholds came from the ISS in 2020–2024; every other window was read once. A planned ISS burn counts as truth only when NASA’s next trajectory shows it executed; one 2021 plan was not.

Held-out class, 2025–2026	Truth	Found	False alarms
ISS	25 burns	22; the misses are 0.1 m/s settling burns minutes before reboosts; median time error 10 min, Δv ratio 1.00	0.57 per year
Metop-SG A1	24 EUMETSAT maneuvers	14; 12 of 16 at 0.1 m/s or more	0
GPS, 4 satellites	6 maneuvers in precise orbits	6	3.8 per object-year
GEO (Intelsat)	11 post-maneuver files	4	24 events per object-year; the truth lists one maneuver per satellite

6 Uncertainty

Covariance propagates through HPOP’s state-transition matrix Φ with a declared white-acceleration process noise Q^{10} :

$$P(t) = \Phi(t, t_0) P_0 \Phi(t, t_0)^T + Q(t)$$

Φ supplies neither P_0 nor Q ; they come from a fit, a provider or an empirical model. Realism is scored against independent precise orbits by $d^2 = \mathbf{e}^T P^{-1} \mathbf{e}$ for a position error $\mathbf{e}$, against χ^2 with 3 degrees of freedom: a covariance is realistic when the mean of $d^2/3$ lies in $[0.8, 1.25]$ and its 95 % coverage in $[0.93, 0.97]$, the rule of E14 after Zaidi and Hejduk³².

Covariance	Prior art	Held-out result	Evidence
Formal covariance of an HPOP fit to laser ranges	Weighted least squares ¹⁶	Too small: mean $d^2/3$ 16–21, coverage 0.14–0.18	E6
HPOP fit to OMM history alone	Levit and Marshall 2011 ¹⁹	Realistic for laser-ranged LEO (0.68–0.83, coverage 0.96–0.98); too small for the ISS within a day (4.8–7.6)	E6
Batch fit to 3 days of OMM history (GPS)	Osweiler 2006 ³³ ; Geul et al. 2017 ³⁴	Mean $d^2/3$ 1.23 and 1.05 at 0 and 1 day, 81 at 3 days; consistency failed at every horizon	E2
Errors of consecutive OMMs, against precise orbits	Autocorrelation shown by Osweiler ³³	Along-track correlation 0.61–1.00 in four regimes. Four published constructions ^{33,35,34,36} are overconfident: mean $d^2/3$ from 13 to over 10^7 . A covariance that models the correlation scores better at 1 day in three regimes but is consistent only for laser-ranged satellites at some horizons	E2b
SGP4 with the E2b error model, calibrated by regime and age	Zaidi and Hejduk 2016 ³²	Realistic in 2 of 35 regime-horizon cells (11 on the selection window)	E14
HPOP from the OMM epoch state, with P_0 and Q per regime	SP covariance as the Astrodynamics Support Workstation (ASW) forms it ³⁷	5 of 35 (6 on the selection window): 500–800 km at epoch, above 800 km to 2 days	E14
Density-forecast consider term, in the form of the Dynamic Consider Parameter	Hejduk 2019 ³⁸	No measurable effect in storms; density-error coverage 0.83–0.86 against 0.95	E14
Covariance of the corrected epoch state, unseen LEO objects	Ly et al. 2020 ¹⁷	Mean $d^2/3$ 1.01 and coverage 0.949, inside the rule; not supported once corrected for multiple tests	E16

On the held-out window, maneuvers, the storm of 4 July 2026 and GNSS repositioning put heavy tails on the errors: mean $d^2/3$ rises while medians and coverage stay near nominal in LEO, so realism found on the selection window did not carry over. Operator covariance enters as supplied, labeled with its source.

7 Dynamics and verification

HPOP’s full force model, as the catalog and the conjunction screen run it¹⁰, beside the SP options a Vector Covariance Message (VCM) names³⁹:

Model	HPOP	SP, as a VCM names it	Equivalence (Orekit: steps of at most 30 s)
Geopotential	EGM2008 to degree and order 70; EGM96 and tesseral truncation (36Z,24T) selectable	EGM-96 with zonal and tesseral degrees	EGM96 cases within 1.1 mm of Orekit
Atmosphere	NRLMSISE-00 (Orekit's to 1e-8); JB2008 (Orekit's to 2e-14); Jacchia-Roberts (GMAT's ⁴⁰ , bit for bit)	JBH09, which is JB2008 with HASDM's calibration ⁴¹ ; JAC70; MSIS90	JB2008 matches Orekit's; HASDM's calibration is not public (section 5.4); Jacchia-Roberts and NRLMSISE-00 are declared substitutes for JAC70 and MSIS90
Third bodies	Sun, Moon, Venus, Mars and Jupiter from DE440s	Sun and Moon	Sun and Moon within 1 cm of Orekit
Radiation	Cannonball with a conical shadow; Earth albedo and infrared	Solar radiation pressure, AGOM	Within 1 cm of Orekit
Tides, relativity	IERS 2010 solid tides and relativity; FES2004 ocean tides to 30×30	Solid Earth tides	Within 1.3 mm of Orekit
Drag parameter, thrust	$C_d \cdot A/m$ and its rate; in-track acceleration	B, BDOT; in-track thrust	Within 3.8 mm of Orekit
Integrator	RK78 at 1e-12, steps of at most 300 s; its own error after 3 days 0.1–1.2 m	Eighth-order Gauss–Jackson on Cowell's equations ^{42,43}	Declared substitute, converged
Earth orientation	IAU 2006/2000A with daily IERS rows	IAU 1980 nutation, truncated	Declared substitute

Agreement with Orekit

HPOP's Orekit 13.1 suite⁴⁴ holds 72 cases on five orbits (400 km, 700 km sun-synchronous, GPS, geostationary, Molniya), each 24 hours, compared hourly on identical states, constants, daily Earth-orientation rows and space weather¹⁰. HPOP 1.3.0 (module SHA-256 9c24bf0e) integrates with RK78 at a relative tolerance of 1e-13 (point mass at 1e-15) and the steps named below; Orekit with Dormand–Prince 8(5,3) at 1e-14 and steps of at most 10 s:

Force set	Steps of at most 300 s	Steps of at most 30 s
Point mass	0.6 mm	0.6 mm
Gravity field, third bodies, radiation pressure, tides, relativity, in-track thrust	1.9 cm	9.9 mm
With drag (NRLMSISE-00 or JB2008, daily space weather, drag rate)	2.5 cm	4.2 mm

At steps of up to 300 s, HPOP's own integration error is most of the difference: 1.8 cm over a day at 400 km (2.6 cm with JB2008 drag) and 1.6 cm at 700 km, against 0.03 mm for GPS satellites. With steps of 30 s the rows no longer depend on the step (a tolerance of 1e-15 with steps of 10 s moves them by under 0.2 mm), and the largest difference is in Molniya, 9.9 mm; 400 km and 700 km agree to 4.2 mm with drag and 1.7 mm without, and GPS and geostationary orbits to 0.2 mm. The rest is Earth orientation: Orekit applies the IERS Conventions' tidal and libration corrections to polar motion and UT1¹¹, and HPOP interpolates the daily rows. Against Orekit without those corrections the differences at 30 s are 0.6 mm for point mass, 1.1 mm without drag and 3.9 mm with it, and 0.6 mm in Molniya.

State-transition matrices agree within $2\text{e-}5$ and parameter sensitivities within $1.5\text{e-}4$ (relative), at steps of up to 300 s. Integrating Jacchia’s diffusion equations numerically reproduces the closed forms of Jacchia-Roberts⁴⁵ to $1.6\text{e-}4$.

Accuracy against precise orbits

Experiment V1 starts the propagator from ILRS orbits of four geodetic spheres (LAGEOS-1/2 and ETALON-1/2; 16 seeds) and IGS orbits of 32 GPS satellites (96 seeds), adds forces one set at a time, and compares each 72-hour run with the same product V1. GPS radiation pressure is a deliberately crude cannonball. Median (largest) 3D error:

Force set	Spheres, 24 h	Spheres, 72 h	GPS, 24 h	GPS, 72 h
E-a: point mass	46 km (396 km)	110 km (1,213 km)	25 km (40 km)	75 km (170 km)
E-b: zonal harmonics to degree 20	1.3 km (2.2 km)	3.4 km (8.7 km)	2.1 km (6.5 km)	6.0 km (94 km)
E-c: E-b with the Sun and Moon	257 m (2.1 km)	677 m (6.2 km)	331 m (868 m)	983 m (89 km)
E-d: E-c with radiation pressure	246 m (2.1 km)	670 m (6.2 km)	277 m (661 m)	853 m (89 km)
E-e: E-d with the full 20×20 field and IERS Earth orientation	6.2 m (15 m)	18.6 m (51 m)	29.5 m (117 m)	92 m (90 km)
E-f: E-e with IERS 2010 solid tides and relativity	4.8 m (10 m)	13.9 m (31 m)	28.5 m (117 m)	91 m (90 km)

The GPS maxima beyond a day are one satellite, NORAD 35752, in every force set. Of four pre-registered checks, two passed and two failed:

1. Passed: the two-body return, 0.8 mm.
2. Passed: the E-d bound at 24 hours, 246 m against 500 m.
3. Failed: an added force did not reduce every seed’s error (14 violations, all without tesseral harmonics).
4. Failed: a 20×20 field without the Sun and Moon beat zonals alone for only 53 of 96 GPS seeds.

HPOP’s resident path, which holds the catalog in memory, reproduces its execution path to 0.052 mm over four days, at 0.645 s per object-day on one thread¹⁰.

8 Association and selection

Association asks whether records describe one object; selection picks a solution for an epoch, interval and use; estimation derives a new one. Candidates come from provider crosswalks, such as Vimpel’s datefirst file of Vimpel and NORAD numbers, international designators and native-identifier histories; names and bare numbers are not join keys. Compatibility is tested on normalized ephemerides over shared intervals. Each candidate link is compatible, rejected, ambiguous or insufficient, and accepted links stay reversible. Selection takes, per regime and horizon, the source with the lowest median error on a training window of at least 30 samples E3.

Rule	Measured	Evidence
Selection by evidence	GPS: 3.5 cm at issue (section 5.1)	E3
Fusion of sources	Never better than selection: 1.07–1.17 times its error in GPS at 1–7 days, equal elsewhere	E3
Covariance intersection ⁴⁶ of one provider’s consecutive OMMs	Collapses onto one set (0.90–1.00 of selection’s error); naive fusion is overconfident (mean $d^2/3$ 3.3–700)	E2b

9 SP message interchange

The VCM carries an SP state, its force settings and an equinoctial covariance³⁹. SDN’s adapter reads a VCM into an HPOP request, transforming the covariance from equinoctial to Cartesian with an exact Jacobian computed by forward-mode dual numbers⁴⁷. The format states no covariance units, and no public definition was found. Four messages settle them:

1. The survey’s ISS sample
2. An SP message for a geostationary orbit
3. An SP message for a GPS orbit
4. An SP message for an eccentric ($e = 0.59$) orbit

Covariance rows	Reading	Evidence
Mean motion	Relative, dn/n ; covariance scaled by $\max(1, \text{weighted RMS})^2$	Every printed U, V and W sigma reproduced within 1 %; no absolute unit does (radians per 1000 s misses two radial sigmas by 1.7 and 2.0 times)
B and AGOM	Fractions of the coefficients (1.5–9.7 %)	The GPS message against ESA’s final orbit for one day: radial and in-track RMS 0.46 and 0.64 of their sigmas, cross-track 1.27; read as printed, the sigmas overstate the error 7 to 20 times

A VCM naming JBH09 runs as JB2008 on SET’s indices, which the caller supplies.

10 Measured accuracy

Median 3D position error against precise orbits, by object class and age of the product:

Class (objects)	Product	At issue	1 day	3 days	7 days	Evidence
GPS (32)	Ultra-rapid orbit, propagated	3.5 cm	30 m	104 m	336 m	E3
GPS (32)	Public OMM, SGP4	1.57 km	1.61 km	1.68 km	1.53 km	E3
Laser-ranged LEO (5)	HPOP fitted to laser ranges	7 m	9 m	17 m	42 m	E6
Laser-ranged LEO (5)	Public OMM, SGP4	472 m	485 m	482 m	685 m	E6
Laser-ranged LEO, 800–1,500 km (5)	Public OMM, SGP4	314 m	326 m	326 m	569 m	E3
Laser-ranged MEO (5)	Public OMM, SGP4	411 m	438 m	395 m	413 m	E3
LEO, 400–800 km (6)	Public OMM, SGP4	566 m	597 m	760 m	1.24 km	E3

The HAC’s position errors are not published². The public figures: element sets in the HAC’s own LEO conjunction regime (perigee above 500 km) err by 0.6–3 km from epoch to 72 hours⁴⁹; one ASW covariance shown as an illustration has σ of 8.3 m radial, 332 m in-track and 2.1 m cross-track at epoch³⁷; HASDM’s density spread is 0.078 against JB2008’s 0.148 (section 5.4).

11 What conjunction assessment consumes

Conjunction screening⁵⁰ takes from one catalog snapshot, per object:

Input	From the catalog
Trajectory	The OMM for SGP4, or one propagator’s trajectory; one propagator per run
Covariance	Supplied by the operator, fitted, or modeled (section 6), with its calibration label
Hard-body radius	Supplied, half the catalog size, from radar cross-section, or the default, with its basis

An OMM supplies no covariance, so the catalog attaches one by the rule of section 2.2: built from the source’s element-set errors against independent orbits and calibrated by regime and age, with its calibration label. Every event also carries the covariance-free maximum probability, which needs no covariance.

Appendix A. Terms

Term	Meaning
ASO	Anthropogenic space object
OMM, GP	CCSDS Orbit Mean-elements Message: SGP4 mean elements, also distributed in the legacy two-line format; general perturbations element set
SGP4, B*	The analytic propagator of OMMs; its drag term
HPOP	High-precision orbit propagation: numerical integration of the full force model of section 7
Provider estimate	A provider’s product, which already embeds its models and inference
Level 0 to 3	Processing levels of orbit data (section 2)
Ultra-rapid, final orbits	GNSS analysis-centre orbits issued in near real time with a prediction; definitive orbits issued about two weeks later
SLR, ILRS	Satellite laser ranging; the International Laser Ranging Service
TEME, EME2000, GCRF, ITRF	SGP4’s output frame; the J2000 mean equator and equinox; the Geocentric Celestial Reference Frame; the terrestrial frame
d^2 , mean $d^2/3$	Squared Mahalanobis distance of an error under its covariance; the mean of $d^2/3$ is 1 for a realistic covariance
DCA, DCP	HASDM’s Dynamic Calibration of the Atmosphere; the Dynamic Consider Parameter for density-forecast error
HASDM, JB2008, JBH09	High Accuracy Satellite Drag Model; the Jacchia-Bowman 2008 density model; JB2008 with HASDM’s calibration
SP, HAC, ASW	Special Perturbations orbit determination and propagation; the High Accuracy Catalog; the Astrodynamics Support Workstation
VCM	SP Vector Covariance Message
Supplemental GP, eGP	CelesTrak’s element sets fitted to operator ephemerides; the 18th Space Defense Squadron’s element sets fitted to SP states
AOE	SpaceMapper’s catalog of element sets from its own sensors
Covariance intersection	A fusion rule that stays consistent under unknown correlation

Data credits

- IGS products, courtesy of the International GNSS Service and its analysis and data centres (Johnston, Riddell and Hausler 2017, doi:10.1007/978-3-319-42928-1). © Navigation Support Office at ESA/ESOC 2026.
- GFZ rapid MGEX orbits of the IGS Multi-GNSS Experiment (Montenbruck et al. 2017, doi:10.1016/j.asr.2017.01.011), obtained from NASA CDDIS (Noll 2010, doi:10.1016/j.asr.2010.01.018).
- ILRS data and products (Pearlman et al. 2019, doi:10.1007/s00190-019-01241-1), from the EUROLAS Data Center, DGFI-TUM (Noll et al. 2019, doi:10.1007/s00190-018-1207-2). NERC Space Geodesy Facility orbits; contains British Geological Survey materials © UKRI 2026, Open Government Licence v3.0.
- Contains modified Copernicus Sentinel data 2026.

- © ESA 2026; data provided by the European Space Agency: SW_SP3xCOM_2_ (doi:10.57780/esa-8579355), SW_DNSxPOD_2_ (doi:10.57780/esa-ef59315), GF_DNSxACC_2_ (doi:10.57780/esa-2559fd1).
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