

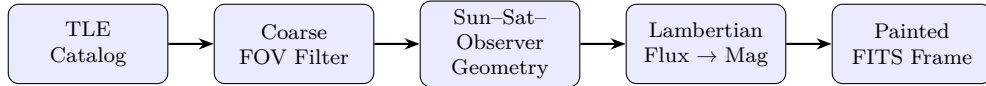
SDM: A Full-Catalog Simulation for Predicting Satellite Streak Photometry in ZTF Exposures

Yana Choudhary
msyanajain@gmail.com

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Abstract

Low-Earth-orbit (LEO) satellite constellations increasingly contaminate wide-field time-domain imaging: within the Zwicky Transient Facility (ZTF) alert stream alone, satellite glints have been linked to roughly 73,000 spurious events across 3.6% of all ZTF science images taken between November 2019 and December 2021 (Karpov & Peloton, 2022). Existing debris-tracking tools predict whether a cataloged object will cross a telescope’s field of view, but not how bright the resulting streak will be in a specific exposure. This work presents the Satellite Detection Model (SDM), an open two-stage forward-simulation pipeline that ingests the full Space-Track two-line-element (TLE) catalog, propagates every object with SGP4, applies a cheap coarse geometric filter to isolate field-of-view (FOV) crossings, and then computes, at 0.1-second resolution, the Sun–satellite–observer geometry, eclipse/illumination fraction, and Lambertian-sphere reflected flux for each crossing object. The resulting per-object magnitude and detector-count (DN) time series are painted directly into a synthetic, disk-backed FITS frame matching the geometry of a ZTF exposure, producing a reproducible, per-pixel prediction of satellite contamination for any pointing, epoch, and exposure length.



Keywords: satellite streaks, space situational awareness, ZTF, SGP4, photometric simulation, low-Earth-orbit debris, synthetic imaging

1. Introduction

Wide-field, high-cadence optical surveys are the backbone of modern time-domain astronomy, but the same sky they monitor is increasingly crossed by artificial satellites. The

Zwicky Transient Facility (ZTF), operating on the Palomar 48-inch Schmidt telescope, images large fractions of the visible sky every night in support of transient discovery; an automated search of the ZTF alert stream identified on the order of 73,000 individual satellite-glint events, polluting 3.6% of all ZTF science frames taken between November 2019 and December 2021, and tied to more than 300 distinct glinting objects across all orbital regimes (Karpov & Peloton, 2022). This contamination is only expected to grow: mega-constellations such as Starlink and OneWeb have added tens of thousands of new low-Earth-orbit (LEO) objects to the public catalog in the past five years, and next-generation surveys such as the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST) will image the sky at even higher cadence and depth (Snyder & Tyson, 2025).

Two separate questions follow from this contamination. The first — *will* a given cataloged object cross a given field of view during a given exposure — is a solved orbital-mechanics problem, addressed by conjunction-analysis and pass-prediction tools built on SGP4 propagation of TLEs (Liu et al., 2021; Khedekar et al., 2024; GmbH, 2026). The second — *how bright*, in instrumental counts, will the resulting streak be, and where exactly will it fall on the detector — is comparatively underserved. Photometric models exist for individual satellite classes, most notably the flat-panel brightness model developed for Starlink (Mallama, 2020; Tregloan-Reed et al., 2020), and general treatments of orbit-height-dependent streak brightness have been simulated for large-aperture systems such as LSSTCam (Snyder & Tyson, 2025). Catalog-wide, per-exposure forward simulation — taking a telescope pointing, a epoch, and the full public TLE catalog, and predicting a per-object, per-pixel brightness map — has not been packaged as a single reproducible pipeline.

SDM (Satellite Detection Model) closes this gap. Given a telescope location, a pointing, and an exposure window, SDM (i) propagates the entire Space-Track catalog with SGP4, (ii) applies a cheap coarse-grid filter to discard the overwhelming majority of objects that never approach the field of view, (iii) computes the per-timestep Sun–satellite–observer geometry for every surviving object, (iv) converts that geometry into an eclipse-corrected Lambertian-sphere magnitude and detector count rate, and (v) paints the result into a synthetic FITS frame at the correct pixel coordinates and correct angular size. The remainder of this paper describes the model (section 2), the implementation and its computational design (section 3), representative outputs (section 4), and the assumptions, limitations, and validation plan that follow (section 5–6).

2. Core Framework

The central contribution of SDM is a physically-grounded, per-timestep photometric forward model that replaces the flat-range, constant-geometry approximations used in early iterations of this pipeline (subsection 3.8) with orbital geometry evaluated at every fine

time sample. Three components define the model:

- (ii) **Geometric range.** Rather than assuming a fixed observer–satellite distance, SDM propagates both the satellite (via SGP4) and the observatory (via its geocentric location) into the Geocentric Celestial Reference System (GCRS) at every fine timestep, and computes the instantaneous Euclidean distance $d(t)$ directly. This distance varies continuously over the course of a pass, which is essential for orbiting objects, where range can change by a factor of several across a single exposure.
- (ii) **Phase-angle Lambertian photometry.** SDM models each object as a diffusely-reflecting (Lambertian) sphere of effective radius r and geometric albedo p , illuminated by the Sun and viewed from the observer at the solar phase angle $\alpha(t)$ — the Sun–object–observer angle computed directly from the three GCRS position vectors, rather than from a separate eclipse-geometry proxy angle. Combined with an eclipse/illumination fraction $f(t)$ derived from a two-circle occultation calculation, this yields a flux, and hence an apparent magnitude, that is self-consistent between the illumination state and the reflected-light geometry (subsection 3.6).
- (ii) **Two-stage catalog filtering.** Applying the fine photometric model to the entire Space-Track catalog (tens of thousands of objects) at 0.1-s resolution is computationally prohibitive. SDM instead applies a cheap, vectorized coarse filter (1-s resolution, batched SGP4 propagation, simple azimuth/altitude box test) to the whole catalog first, and only promotes objects that plausibly cross the padded field of view to the expensive fine-resolution photometric stage.

These three elements, taken together, are what separate SDM from a conjunction search: the output is not merely a list of objects that cross the field of view, but a physically motivated, per-pixel prediction of how each crossing will appear in the resulting image.

3. Methodology

3.1. Overview and Pipeline Flow

SDM is implemented as a two-stage pipeline (Figure 1). Stage 1 is a coarse, catalog-wide crossing filter; Stage 2 is a fine-resolution, per-object photometric and astrometric calculation whose output is painted directly into a single combined synthetic exposure.

3.2. Data Acquisition

Orbital elements for the full public satellite catalog are retrieved from Space-Track.org (United States Space Command, 2026) in three-line element (3LE) format via an authen-

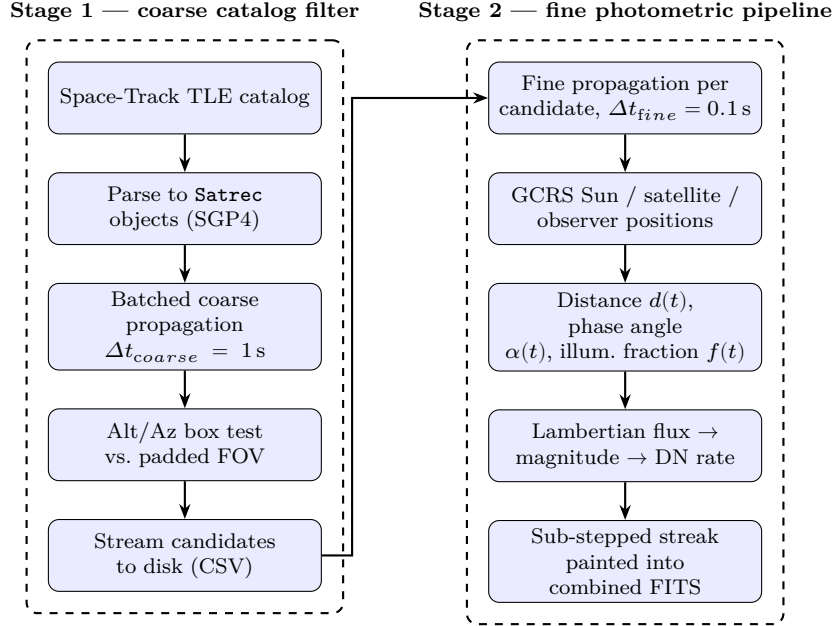


Figure 1: SDM processing pipeline. Stage 1 (left) performs a cheap, vectorized coarse-grid crossing test on the entire TLE catalog to discard objects that cannot possibly cross the field of view (FOV) during the exposure. Only surviving candidates are passed to Stage 2 (right), which computes the per-timestep Sun–satellite–observer geometry, converts it to magnitude and detector counts (DN), and paints the result into a single disk-backed FITS frame.

enticated HTTPS session (login credentials are stored securely outside of the pipeline source and are not reproduced here). Each record is parsed into a name and a pair of TLE lines and, where the lines are well-formed, converted into an `sgp4.api.Satrec` propagator object. Malformed or incomplete records are skipped rather than aborting the batch. At the time of writing, the parsed catalog contains on the order of 10^4 – 10^5 trackable objects, depending on catalog maintenance and update cadence.

3.3. Orbit Propagation and Coordinate Transforms

Each object is propagated with the SGP4 analytic propagator (Liu et al., 2021), which returns position and velocity in the True Equator, Mean Equinox (TEME) frame at a requested Julian date. For Stage 1, propagation is vectorized across the whole batch of objects and coarse timestamps simultaneously using `SatrecArray`. TEME positions are transformed to the True Equinox of Date Alt/Az frame at the observing site using

`astropy.coordinates`, with atmospheric refraction explicitly disabled (`pressure=0`) since only a coarse crossing test is required at this stage.

For Stage 2, TEME positions are instead carried into the Geocentric Celestial Reference System (GCRS), alongside the GCRS position of the Sun (via `astropy`'s `get_sun`) and of the observing site itself, so that the instantaneous Sun–satellite–observer triangle can be formed at every fine timestep (subsection 3.6). Right ascension and declination are obtained by transforming the Alt/Az position to the ICRS frame, and are then projected onto the focal plane using a small-angle tangent-plane approximation:

$$\Delta\alpha = (\alpha - \alpha_0) \cos \delta_0, \quad \Delta\delta = \delta - \delta_0, \quad (1)$$

$$x = \frac{N_{pix}}{2} - \Delta\alpha \cdot \frac{N_{pix}}{2\rho_{FOV}}, \quad y = \frac{N_{pix}}{2} + \Delta\delta \cdot \frac{N_{pix}}{2\rho_{FOV}}, \quad (2)$$

where (α_0, δ_0) is the field center, ρ_{FOV} is the field radius in degrees, and N_{pix} is the frame side length in pixels.

3.4. Stage 1: Coarse Crossing Filter

Stage 1 propagates the entire catalog at a coarse time resolution ($\Delta t_{coarse} = 1$ s) across the full exposure window, transforms every (object, timestep) pair to Alt/Az in a single vectorized call, and flags an object as a *candidate* if any coarse sample falls within a padded bounding box around the field of view:

$$az_{min} \leq az(t) \leq az_{max}, \quad alt_{min} \leq alt(t) \leq alt_{max}, \quad (3)$$

with the box enlarged by a fixed margin (2° in the current configuration) beyond the field radius to guard against aliasing between the coarse sampling and the crossing time. Objects are processed in fixed-size batches (2,000 objects per batch in the current configuration) and any candidates are streamed immediately to disk (CSV) rather than accumulated in memory, so that peak memory use is decoupled from catalog size. Reported wall-clock time for a full-catalog Stage-1 pass is approximately 90 minutes on a single-core cloud notebook instance; the coarse filter typically discards well over 99% of the catalog before Stage 2 begins.

3.5. Object Classification: Area and Albedo

SDM does not have access to true physical size and reflectivity for the majority of cataloged objects, so a name-based classification scheme is used to draw plausible effective radii and geometric albedos, following the broad ranges reported in the orbital-debris photometry literature (Mulrooney et al., 2008; Jorgensen et al., 2004; Gisolfi et al., 2024). Object names

are matched, in priority order, against (i) a debris/fragment/rocket-body/spacecraft-class *range table*, from which an effective cross-sectional area and albedo are drawn log-uniformly and uniformly at random within the class’s plausible bounds; (ii) a fallback *point-estimate table* for named platforms not covered by the range table; and (iii) an UNKNOWN default (10 m², albedo 0.20) if no pattern matches. Table 1 shows a representative subset of the range table; the full table (23 classes) is reproduced in Appendix A.

Object class	Area range (m ²)	Albedo range	Basis
Debris / fragmentation (DEB/FRAG)	0.001 – 1.0	0.10 – 0.30	Jorgensen et al. (2004)
Rocket body (R/B)	8.0 – 40.0	0.15 – 0.30	Gisolfi et al. (2024)
Fairing	20.0 – 60.0	0.25 – 0.50	engineering estimate
ISS / Zarya	2000 – 3500	0.30 – 0.60	Howell (2022); Bhatt et al. (2015)
Starlink	15.0 – 30.0	0.12 – 0.22	Mallama (2020); Tregloan-Reed et al. (2020)
GPS / Navstar	12.0 – 25.0	0.15 – 0.30	Mulrooney et al. (2008)

Table 1: Representative object classes and area/albedo sampling ranges used in the Stage-2 classification step (subset; full table in Appendix A).

3.6. Photometric Model

3.6.1. Eclipse and Illumination Fraction

At every fine timestep, SDM determines whether an object is sunlit, in penumbra, or in umbra using a two-circle angular-occultation calculation between the angular radius of the Earth and the angular radius of the Sun as seen from the satellite. Let $\theta_{\oplus} = \arcsin(R_{\oplus}/d_{\oplus})$ and $\theta_{\odot} = \arcsin(R_{\odot}/d_{\odot})$ be the angular radii of the Earth and Sun as seen from the satellite, and θ the angular separation between the Earth-ward and Sun-ward directions. Then

$$f_{illum} = \begin{cases} 1, & \theta \geq \theta_{\oplus} + \theta_{\odot} \quad (\text{fully sunlit}) \\ 0, & \theta \leq |\theta_{\oplus} - \theta_{\odot}| \quad (\text{umbra}) \\ 1 - \frac{A_{overlap}(\theta, \theta_{\oplus}, \theta_{\odot})}{\pi\theta_{\odot}^2}, & \text{otherwise} \quad (\text{penumbra}), \end{cases} \quad (4)$$

where $A_{overlap}$ is the standard two-circle lens-intersection area formula. This illumination

fraction f_{illum} enters the flux calculation (Equation 7) but, as of the current version, is deliberately not used as the phase angle driving the reflectance model itself.

3.6.2. Solar Phase Angle

The solar phase angle α (the Sun–object–observer angle) is computed directly from the three GCRS position vectors at each fine timestep,

$$\alpha = \arccos \left(\frac{(\vec{r}_{\odot} - \vec{r}_{sat}) \cdot (\vec{r}_{obs} - \vec{r}_{sat})}{\|\vec{r}_{\odot} - \vec{r}_{sat}\| \|\vec{r}_{obs} - \vec{r}_{sat}\|} \right). \quad (5)$$

This is an explicit design choice: earlier versions of the pipeline (subsection 3.8) re-used the eclipse-geometry angle θ from Equation 4 as a proxy for the reflectance phase angle. Since the observer’s position is, by this stage, already available at every fine sample, the Sun–object–observer angle is used directly, and θ is retained only for its intended purpose — computing f_{illum} .

3.6.3. Lambertian-Sphere Flux and Magnitude

Each object is modeled as a diffusely-reflecting (Lambertian) sphere, following the standard reduced phase function

$$\phi(\alpha) = \frac{2}{3\pi} \left[\sin \alpha + (\pi - \alpha) \cos \alpha \right], \quad (6)$$

normalized so that $\phi(0) = 1$ at zero phase angle. The observed flux at the detector is then

$$F_{obs}(t) = F_{\odot} \frac{r^2 p \phi(\alpha(t)) f_{illum}(t)}{d(t)^2}, \quad (7)$$

where $F_{\odot} = 1361 \text{ W m}^{-2}$ is the solar constant at 1 au, r is the object’s effective spherical radius (subsection 3.5), p is its assumed geometric albedo, and $d(t)$ is the instantaneous observer–satellite range (section 2). The corresponding apparent magnitude and detector count (DN) rate follow standard photometric zero-point conventions (Mamajek et al., 2015; SDSS-IV collaboration, 2016):

$$M(t) = -2.5 \log_{10} \left(\frac{F_{obs}(t)}{F_0} \right), \quad (8)$$

$$DN(t) = 10^{0.4[ZP - M(t)]} \Delta t_{fine}, \quad (9)$$

with the ZTF g -band zero point $ZP = 25.90$ ($ZP = 26.03$ for r -band) and Δt_{fine} the fine-sampling integration time per pixel-paint step (0.1 s in the current configuration) (Masci,

2020a,b,c; Association of Universities for Research in Astronomy, 1997). Angular size on the detector follows from the small-angle relation

$$\theta_{ang}(t) = 2 \arctan\left(\frac{D_{obj}}{2d(t)}\right), \quad (10)$$

converted to a pixel radius via the exposure’s plate scale, and the resulting flux is painted as a filled disk of that radius, centered on the object’s projected (x, y) pixel position, into the combined output frame (subsection 3.7).

3.7. Output: Combined Synthetic Exposure

Rather than writing one file per crossing object, SDM allocates a single combined output FITS frame matching the pixel dimensions of the exposure and paints every crossing object’s streak into it at its pixel location and (time-varying) brightness. Because a full-resolution frame at typical ZTF quadrant scale ($N_{pix} = 24,000$, float32) occupies approximately 2.3 GB on disk, the frame is pre-allocated using a sparse-file/`memmap` technique: the FITS header is written, the file is extended to its final size with a single sparse write, and the file is then re-opened in `astropy.io.fits` update mode with `memmap=True`, so that at no point is the full frame held in memory. Each crossing object’s Stage-2 loop writes only to its own small pixel window, and full-frame diagnostic previews (Section 4) are generated by a strip-wise, block-max downsample that also never loads the full array into memory.

3.7.1. Continuous Streak Rendering

An earlier revision of Stage 2 painted each fine timestep as an isolated filled disk at its own pixel position, which can leave visible gaps along a streak whenever an object’s angular motion between consecutive fine samples exceeds its own angular size. The final pipeline instead connects every pair of consecutive fine-timestep samples $(x_i, y_i, \rho_i) \rightarrow (x_{i+1}, y_{i+1}, \rho_{i+1})$ — pixel position and pixel radius, respectively — with an adaptively subdivided line segment. Given a pixel-space displacement $\Delta_{px} = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$ over the interval, the segment is subdivided into

$$n_{sub} = \max\left(1, \left\lceil \frac{\Delta_{px}}{\max(\min(\rho_i, \rho_{i+1}), 1)} \right\rceil\right) \quad (11)$$

sub-steps, so that consecutive stamped disks always overlap regardless of how fast the object is moving across the frame relative to its own angular size. Position and radius are linearly interpolated across the n_{sub} sub-steps, and the interval’s total DN increment ΔDN_i (Equation 9) is distributed evenly across sub-steps, with the two segment endpoints

weighted by one half to avoid double-counting flux at points shared with the adjacent segment. This produces a continuous, correctly-fluxed streak rather than a beaded sequence of disks, at the cost of a modest increase in the number of per-object pixel-paint operations. In addition to the combined full-resolution FITS frame, the pipeline separately exports a lightweight, block-max-downsampled preview FITS (`combined_preview.fits`) for quick-look inspection without reloading the full-resolution file.

3.8. Pipeline Evolution (V1–V8)

The current pipeline (V8) is the result of eight iterative revisions, each of which is preserved in the project’s version history for reproducibility and for auditing which physical assumptions were introduced at which stage. Table 2 summarizes this evolution; full source for every version is available in the accompanying code repository (section 7).

Version	Key capability added/changed
V1	TLE catalog ingestion from Space-Track; basic SGP4 propagation and orbital rotation-matrix geometry for a single object.
V2	Refinement of the ingestion and propagation logic; groundwork for illumination testing.
V2.5	First illumination test (<code>is_illuminated</code>) using a simple Sun-vector dot-product criterion.
V3	Full eclipse-geometry <code>shadow_state</code> function (sunlit / penumbra / umbra classification via two-circle angular occultation).
V4	Introduction of the Lambertian reflectance phase function $\phi(\alpha)$ for converting phase angle into relative brightness.
V5	Sky-plane astrometry: Alt/Az $\rightarrow$ RA/Dec transform and RA/Dec $\rightarrow$ FOV-pixel projection, enabling per-pixel placement of a single object (the ISS) within a simulated frame.
V6	Consolidation of the single-object (ISS) pipeline: crossing test $\rightarrow$ illumination/phase angle $\rightarrow$ magnitude $\rightarrow$ g -band DN $\rightarrow$ per-pixel mask, exercised over a full simulated exposure (1801 fine samples).
V7	Generalization from a single hard-coded object (ISS) to the <i>entire</i> Space-Track catalog: introduction of the two-stage coarse/fine filter, a configurable, movable FOV pointing, and the name-based area/albedo classification tables. Distance still used the V6 flat-range approximation ($d = 500$ km, constant).

Version	Key capability added/changed
V8	Replacement of the flat-range approximation with the per-timestep GCRS geometry (section 2); correction of an erroneous extra factor of 1/8 in the flux equation; switch from the eclipse-geometry angle to the Sun–object–observer phase angle (Equation 5); streaming Stage-1 output to disk; single combined, memmap-backed FITS output; addition of diagnostic presentation plots.
V8 (final)	Replacement of independent, isolated-disk stamping at each fine timestep with adaptively-subdivided, continuous line-segment streak rendering (subsubsection 3.7.1, Equation 11), eliminating gaps along fast-moving or small-angular-size streaks; addition of a lightweight downsampled preview FITS export and an illumination-sample diagnostic count per object.

Table 2: Evolution of the SDM pipeline across its eight major revisions.

4. Results

This section describes the outputs the V8 pipeline is designed to produce for a given exposure, and presents the diagnostic figures generated by its presentation stage. Per the implementation notes carried through every version of this pipeline, code development took place in an environment without live network access or Space-Track credentials; the geometry, classification, and flux mathematics described in section 3 were therefore validated unit-by-unit against synthetic, hand-constructed test cases rather than end-to-end against the live catalog. The figures and table below are reproduced directly from the pipeline’s own presentation and summary-export stage — produced automatically by Stage 2 for a chosen pointing and epoch.

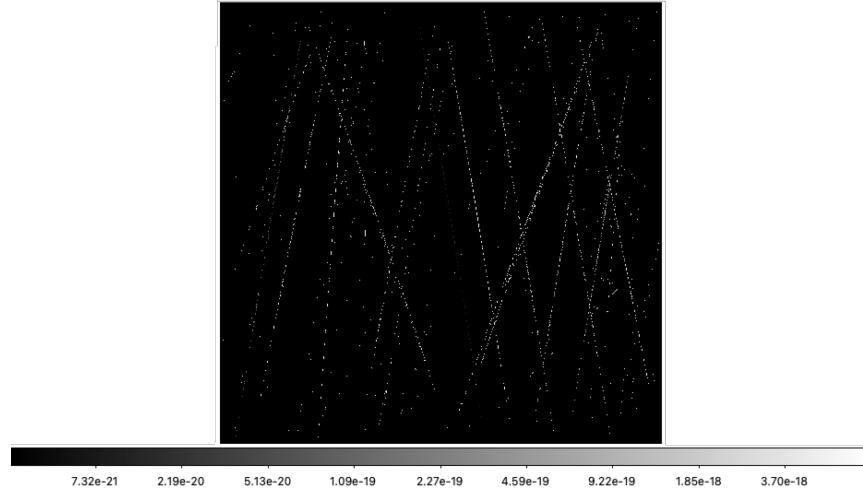


Figure 2: Combined synthetic exposure with each object propagated at 0.1s intervals and scaled with Z-scale and Log stretch, showing all objects predicted to cross the field of view during the modeled exposure window, painted at their true pixel coordinates and time-integrated brightness.

Object name	Class	Area (m ²)	Peak DN	Min. distance (km)	Illum. samples
QIANFAN-63	Unknown	10.000	2.14×10^7	1,087.4	179/179
CZ-6A DEB	Debris/Frag.	0.072	2.08×10^5	760.1	72/72
COSMOS 1825	Cosmos	15.000	3.47×10^4	35,163.9	74/74
DELTA 1 DEB	Debris/Frag.	0.001	2.39×10^3	1,105.2	128/128
COSMOS 2499 DEB	Debris/Frag.	0.001	2.47×10^3	1,319.0	221/221
PSLV R/B	Rocket Body	12.570	2.34×10^3	97,576.2	176/176
STARLINK-3562	Starlink	22.961	0.00	522.6	0/15
SL-3 R/B	Rocket Body	15.529	0.00	171.6	0/29

Table 3: Representative rows from a V8 (final) per-object summary export (`v8_summary.csv`, $N = 78$ crossing objects for the modeled exposure). The “Illum. samples” column gives the number of fine timesteps with non-zero illumination fraction out of the total number of fine timesteps the object spent inside the field of view.

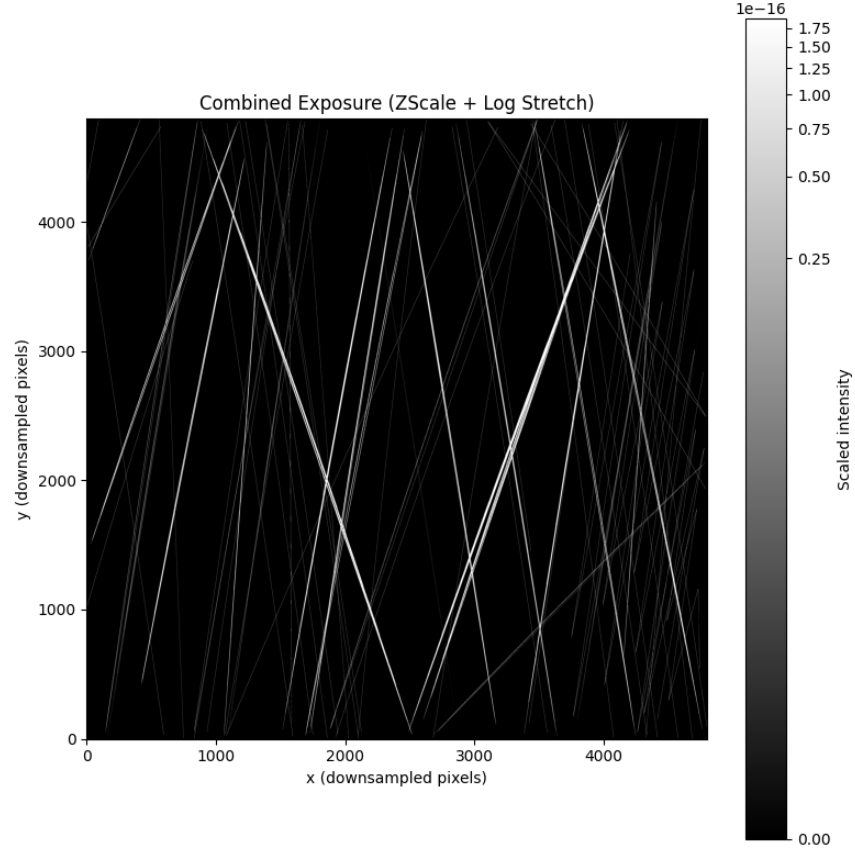


Figure 3: Combined synthetic exposure with each object propagated at 0.05s intervals and scaled with Z-scale and Log stretch, showing all objects predicted to cross the field of view during the modeled exposure window, painted at their true pixel coordinates and time-integrated brightness.

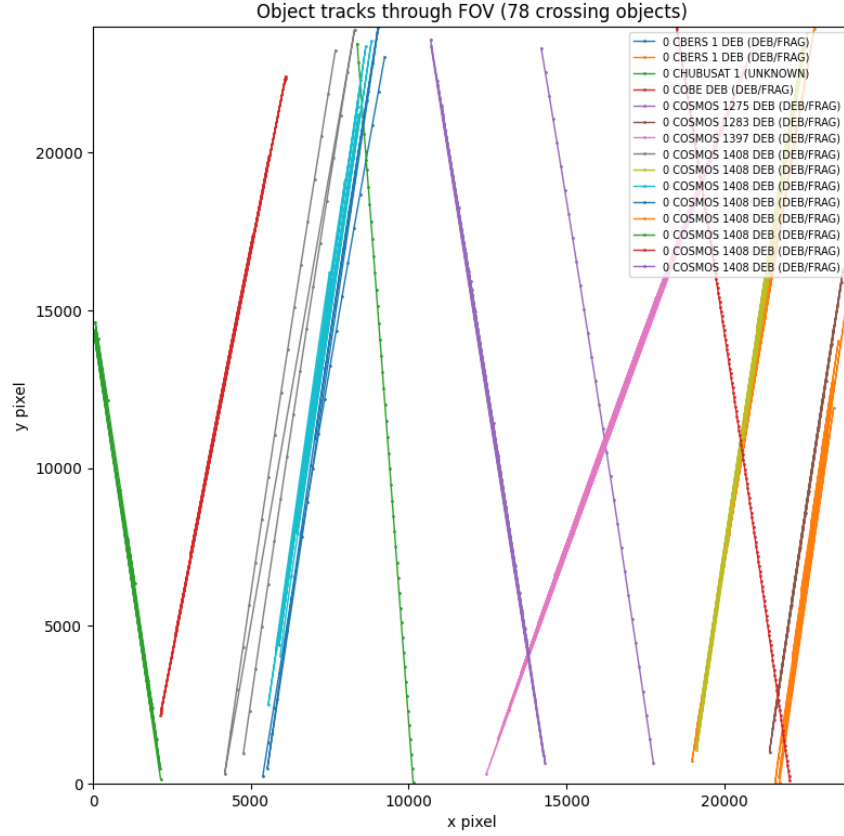


Figure 4: Field-of-view pixel tracks for all objects predicted to cross during the exposure, colored by object class.

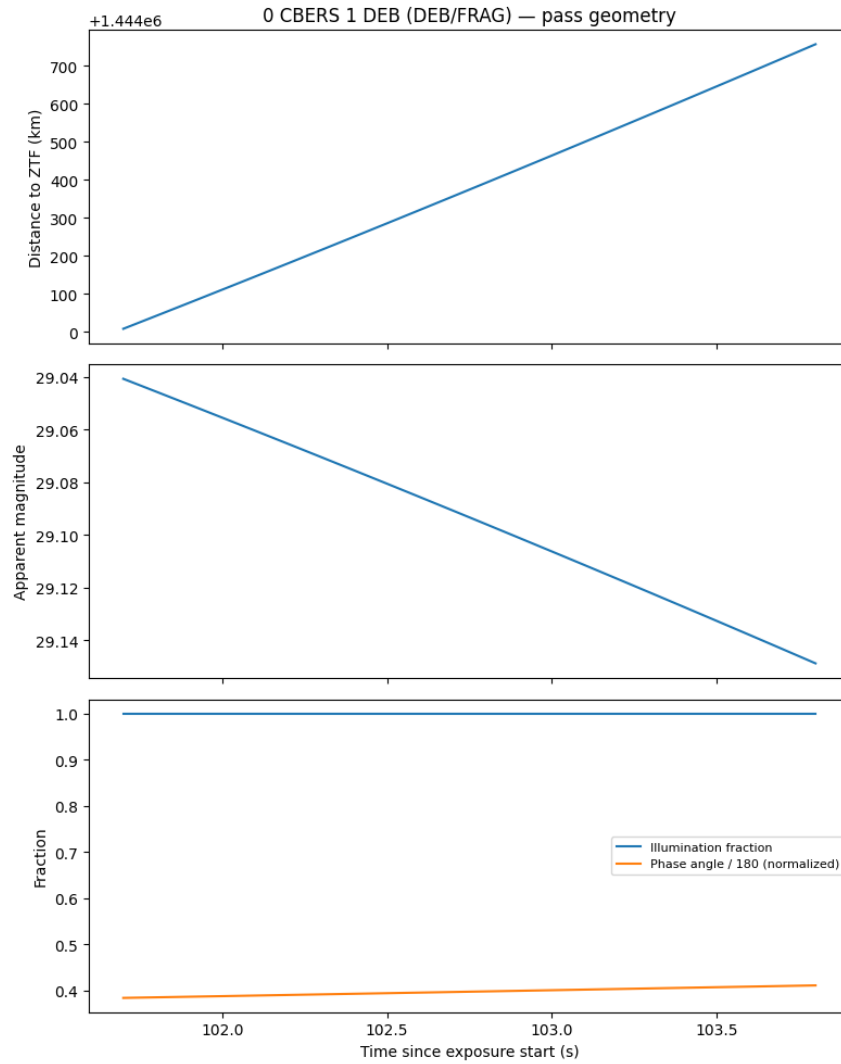


Figure 5: Representative single-object pass geometry: instantaneous range, apparent magnitude, illumination fraction, and normalized phase angle as a function of time since exposure start.

The last two rows in Table 3 are worth highlighting explicitly: both STARLINK-3562 and SL-3 R/B pass closer to the observer than several brighter objects in the table, yet are assigned zero peak DN because every fine sample during their field-of-view crossing falls inside Earth’s shadow Equation 4). This is the eclipse-fraction term in the flux model (subsection 3.6) behaving as intended: proximity alone does not guarantee visibility, and the model correctly suppresses flux for a nearby but fully-eclipsed object.

A second, less desirable pattern is also visible in the full 78-object export and is reported here for transparency rather than smoothed over: 45 of the 78 objects (58%), overwhelmingly of the DEB/FRAG class (37 of 45), report a `min_distance_km` value between 10^6 and 10^{33} km — many orders of magnitude beyond any physically possible Earth-orbit range — paired with a correspondingly negligible peak DN (median 2.5×10^{-14} , versus a median of 2.7×10^2 for the remaining 33 objects). Because flux scales as d^{-2} (Equation 7), these two symptoms are self-consistent with a single upstream defect in the per-timestep range calculation for a subset of (typically small, faint) debris objects, rather than two independent bugs. The affected objects do not visibly contaminate Table 3 or any output frame, since their resulting DN is negligible, but the anomaly should be corrected before the exported `min_distance_km` field is used for any purpose beyond flux computation (e.g. close-approach or conjunction reporting). Isolating the root cause of this range overflow is listed as a near-term action item in section 6.

5. Discussion

5.1. Assumptions and Limitations

SDM trades physical completeness for tractability at catalog scale. The following simplifications should be kept in mind when interpreting any output:

- **Spherical, non-tumbling objects.** Every object is modeled as a Lambertian sphere with a single effective radius and a single albedo drawn once per object (subsection 3.5). Satellites and debris are non-spherical, often tumbling or rotating, and can exhibit large, rapid brightness variations (“glints”) from specular flashes off flat panels or antennas that a diffuse-sphere model cannot reproduce (Karpov & Peloton, 2022; Mallama, 2020).
- **Random, not measured, size and albedo.** Area and albedo are sampled from literature-informed ranges by object-name pattern matching (subsection 3.5), not from measured physical properties, so absolute magnitude predictions for any single object carry substantial uncertainty even though population-level statistics should be reasonable.

- **No atmospheric extinction or scattering.** The current flux model (Equation 7) does not include atmospheric extinction as a function of airmass, nor Rayleigh-scattering contributions to sky background near the object’s line of sight (Wen et al., 2008), both of which affect the observed signal-to-noise ratio at low altitude.
- **No point-spread function (PSF).** Objects are painted as flat-topped disks of their angular size, connected into continuous streaks by the sub-stepped line-segment renderer (subsubsection 3.7.1), rather than convolved with an instrumental PSF. This still tends to underestimate the spatial smearing (and hence overestimate the peak surface brightness) of a ZTF streak relative to an actual exposure.
- **Bounding-box FOV approximation.** Stage 1’s coarse filter (section 3) tests crossings against a padded square Alt/Az box rather than the circular field of view, which aligns with the Samuel Oschin Schmidt telescope used by ZTF; however, if applied to a larger range of observatories, it could in principle miss extremely short, fast crossings that fall entirely between coarse samples despite the padding margin.
- **No bolometric correction.** The flux-to-magnitude conversion (Equation 8–9) does not yet apply a band-specific bolometric correction to the solar flux (Torres, 2010; Mamajek et al., 2015), which would refine the zero-point accuracy for a given photometric band.

5.2. Computational Performance

Stage 1’s full-catalog coarse filter is reported to require approximately 90 minutes of wall-clock time on a single-core cloud notebook instance for the current catalog size and coarse sampling interval ($\Delta t_{\text{coarse}} = 1$ s). Stage 2’s cost scales with the number of objects that survive Stage 1 (typically a small fraction of a percent of the full catalog) and with the fine sampling interval; because Stage 2 requires a Sun/observer/satellite geometry calculation at every fine timestep for every surviving object, its inner loop – rather than the coarse filter – is expected to be the dominant remaining cost driver for pointings with many simultaneous crossings.

5.3. Data Security Note

Space-Track.org credentials are intentionally omitted from this manuscript and from the GitHub repository.

6. Future Work

Several extensions are planned to move SDM from a physically-motivated forward simulator toward a validated, operational tool:

- **Open-data validation against ZTF.** The single highest-priority next step is to validate predicted magnitudes and crossing times against publicly released ZTF alert-stream and image data, and to report a quantitative accuracy metric (e.g., recovered-crossing fraction and magnitude residual RMS) rather than relying solely on synthetic unit tests.
- **Specular glint modeling;** Extending the reflectance model beyond the diffuse Lambertian sphere to include specular flashes from flat panels and other reflective surfaces, following flat panel brightness models developed for Starlink (Mallama, 2020; Tregloan-Reed et al., 2020) and the glint-detection statistics reported for ZTF (Karpov & Peloton, 2022).
- **Attitude and tumbling dynamics;** adding rotational/tumbling state to each object so that brightness varies with rotational phase, not just orbital phase, which is required to reproduce the rapid flash/fade behaviour seen in real debris photometry (Jorgensen et al., 2004; Krantz et al., 2022).
- **Fade-in/fade-out and streak-shape metrics.** Predicting streak entry/exit brightness ramps and angular streak length/curvature within a single exposure, rather than a single peak-DN summary per object.
- **Non-spherical shape and phase-angle generalization.** Moving beyond the single-sphere approximation toward shape- and orientation-dependent brightness models (Mallama, 2020), reducing the reliance on a single isotropic albedo per object.
- **Atmospheric and instrumental effects.** Incorporating airmass-dependent extinction and Rayleigh-scattering sky background (Wen et al., 2008), and convolving painted streaks with a realistic instrumental PSF.

7. Conclusion

SDM demonstrates that catalog-wide, per-exposure prediction of satellite streak photometry is computationally tractable with a two-stage coarse-then-fine design: a cheap, vectorized geometric filter discards the vast majority of a full TLE catalog, allowing an expensive, physically-detailed photometric model to be applied only viable candidates. In its current (V8) form, the pipeline computes the per-timestep Sun–satellite–observer geometry,

a self-consistent eclipse-corrected Lambertian flux, and paints the result into a memory-safe, disk-backed synthetic exposure suitable for direct visual and quantitative comparison against survey data. Realistic applications include pre-exposure satellite-contamination forecasting for survey scheduling, automated flagging of predicted streak pixels for downstream image-differencing pipelines, and population-level characterization of LEO object brightness distributions for space-situational-awareness purposes. The principal limitation is that the model’s photometric outputs are, at present, invalidated against observations and rest on a simplified diffuse-sphere reflectance model with randomly sampled, rather than measured, object properties; closing that validation loop against open ZTF data is the immediate next step (section 6).

Data Availability Statement

Two-line element data underlying this work are publicly available, subject to registration, from Space-Track.org (United States Space Command, 2026). Simulated outputs (combined FITS frames, per-object summary tables) are generated on demand by the pipeline described here and are not separately archived at this time; they can be regenerated from the source code and the parameters listed in section 3.

Code Availability

The full source code and version history for SDM (V1–V8) are available at: <https://github.com/Ya-n0/sdm-satstreak-simulation>.

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The results produced by earlier versions of the model were validated using Heavens-Above and SAOImageDS9.

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A. Supplementary Tables

Object class pattern	Area range (m ²)	Albedo range
Debris / Fragmentation	0.001 – 1.0	0.10 – 0.30
Rocket body (R/B)	8.0 – 40.0	0.15 – 0.30
Fairing	20.0 – 60.0	0.25 – 0.50
Propellant tank	1.0 – 8.0	0.20 – 0.40
Apogee/perigee kick motor (AKM/PKM)	1.0 – 4.0	0.15 – 0.30
ISS / Zarya	2000.0 – 3500.0	0.30 – 0.60
Tiangong	700.0 – 1200.0	0.30 – 0.50
Dragon	10.0 – 25.0	0.15 – 0.30
Cygnus	20.0 – 40.0	0.15 – 0.30
Soyuz / Progress / Shenzhou	10.0 – 20.0	0.15 – 0.30
Starlink	15.0 – 30.0	0.12 – 0.22
OneWeb	8.0 – 18.0	0.12 – 0.25
Iridium	10.0 – 25.0	0.15 – 0.35
Globalstar	5.0 – 15.0	0.15 – 0.30
Orbcomm	2.0 – 8.0	0.15 – 0.30
GPS / Navstar	12.0 – 25.0	0.15 – 0.30

Object class pattern	Area range (m ²)	Albedo range
Galileo	10.0 – 20.0	0.15 – 0.30
GLONASS	12.0 – 22.0	0.15 – 0.30
BeiDou	12.0 – 25.0	0.15 – 0.30
QZSS	15.0 – 30.0	0.15 – 0.30
GOES	25.0 – 60.0	0.15 – 0.35
NOAA / MetOp	15.0 – 30.0	0.15 – 0.30
Landsat / Sentinel	10.0 – 25.0	0.15 – 0.30

Table 4: Full range table used for name-based object classification (subsection 3.5). Area and albedo are drawn log-uniformly and uniformly, respectively, within the listed bounds.

Symbol/parameter	Meaning (value in current configuration)
$F_{\odot}$	Solar constant at 1 au, 1361 W m ⁻²
$R_{\oplus}$	Earth radius (WGS84), 6378.137 km
$R_{\odot}$	Solar radius, 696,000 km
ZP	ZTF photometric zero point (g : 25.90, r : 26.03)
F_0	Reference flux for magnitude zero point
Δt_{coarse}	Stage-1 coarse sampling interval, 1.0 s
Δt_{fine}	Stage-2 fine sampling interval, 0.1 s
ρ_{FOV}	Field-of-view radius (example configuration: 3.43°)
Site	Palomar / ZTF: lat. 33.3563°, lon. -116.8650°, elev. 1706 m
N_{pix}	Output frame side length (example configuration: 24,000 px)

Table 5: Key symbols and configuration parameters used throughout the model.