International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

AstroShield: A Physics-Verified Learning Framework for Explainable Spacecraft Collision Avoidance

Mugdha Bhavsar[1], Bhumika Salvi[1], Dr. Arundhati Niwatkar[2]

[1]Department of Information Technology, Usha Mittal Institute of Technology, SNDT Women's University, Mumbai, India 400049

[2]Assistant Professor and Project Guide, Department of Data Science, Usha Mittal Institute of Technology, SNDT Women's University, Mumbai, India

ABSTRACT

As satellite constellations expand and the catalogue of tracked debris grows, operators need efficient ways to identify close approaches and evaluate possible avoidance actions. This paper presents AstroShield, a software prototype that combines orbital-element acquisition, local data caching, SGP4 propagation, conjunction screening, machine-learning-based maneuver proposal, numerical verification, persistent history, and a three-dimensional web interface. A Random Forest proposes maneuver parameters from encounter features; an independent physics stage then propagates the modified trajectory and checks whether the resulting closest approach satisfies a configured separation threshold. The model therefore nominates options but does not determine safety by itself. The implementation includes candidate burn directions, discrete velocity-change magnitudes and execution lead times, with a fallback search when the initial proposal is not verified. A representative software demonstration begins with a critical conjunction displayed at approximately 7.57 km. The interface proposes a 1.00 m/s prograde maneuver 60 minutes before closest approach; the numerical check reports approximately 324.4 km post-maneuver separation against a configured minimum of 25 km. These values describe one demonstration session and are not statistical evidence of operational collision-avoidance performance. The paper describes the architecture, implementation, decision logic, evaluation plan, and limitations. AstroShield is intended as human-supervised decision support and is not a certified flight-safety system.

Keywords—Space situational awareness, conjunction assessment, spacecraft collision avoidance, space debris, SGP4, Random Forest, physics-based verification.

1. INTRODUCTION

Earth orbit contains operational spacecraft, inactive satellites, spent rocket bodies, and fragments from past breakups. As the number of tracked objects increases, identifying potentially hazardous close approaches and evaluating possible responses become important tasks for space situational awareness. A conjunction warning indicates predicted proximity; it does not, by itself, establish that a collision will occur or that a maneuver is necessary.

Collision avoidance involves two related challenges. First, orbital data must be propagated to identify close approaches. Second, when an event warrants further analysis, a maneuver must be selected with suitable timing and velocity change while respecting mission constraints and propellant limitations. Exhaustively evaluating every candidate may be computationally expensive when many events must be processed.

AstroShield explores a hybrid decision-support approach. A Random Forest nominates a candidate maneuver from encounter features, while a separate numerical stage checks the post-maneuver trajectory. This separation is deliberate: the learned model generates a proposal, and the configured physics-based safety condition determines whether the proposal can be presented as verified.

1.1 Problem Definition

Given a protected spacecraft and one or more tracked objects, the prototype aims to (i) screen propagated trajectories for close approaches, (ii) propose a candidate maneuver for a critical event, (iii) independently evaluate the modified trajectory against a configured minimum-separation threshold, and (iv) present the result in a form that a human operator can inspect.

1.2 Main Contributions

The main contributions are an integrated software workflow spanning data acquisition to visualization; a learning-guided maneuver proposal stage coupled to independent numerical verification; a candidate-search fallback that favours a feasible maneuver with a small velocity change; and persistent analysis records that support traceability and repeatable demonstrations. These contributions concern the software architecture and prototype implementation, not a claim of certified safety or demonstrated superiority over operational systems.

2. LITERATURE SURVEY

Conjunction assessment relies on orbital-state information and trajectory propagation. The foundational SpaceTrack Report No. 3 describes the models associated with general perturbations, while later work by Vallado and colleagues revisited the

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

implementation of these methods. CelesTrak provides general-perturbation data in formats used by current orbital-analysis workflows. In AstroShield, TLE/GP data and SGP4 form the initial screening layer.

Operational conjunction assessment is more involved than comparing nominal positions. It can require state uncertainty, encounter geometry, object size, and collision-probability analysis. NASA's Conjunction Assessment Risk Analysis programme documents operational processes for assessing conjunctions. Monte Carlo methods and other numerical techniques have also been studied for investigating how uncertainty in initial conditions affects predicted close approaches.

Maneuver-design research includes analytical, semi-analytical, and numerical approaches, with different trade-offs in computational cost, propellant use, and treatment of uncertainty. Random Forests combine multiple decision trees and can model nonlinear relationships in tabular data, making them a plausible candidate generator for encounter descriptors. However, a data-driven output is not a physical guarantee. AstroShield therefore places machine learning before a separate trajectory-verification stage rather than allowing the learned model to make the final safety decision.

Compared with a stand-alone learned recommender, the proposed architecture explicitly tests each proposed post-burn trajectory. Compared with an exhaustive candidate sweep, the learned proposal may guide the initial search, while the fallback search checks other candidates if the first proposal fails. Whether this arrangement reduces runtime or search effort requires controlled evaluation and is not assumed in this paper.

3. SYSTEM ARCHITECTURE AND METHODOLOGY

AstroShield is implemented as a modular web-based prototype. The backend provides data acquisition, screening, and maneuver-analysis services, while the browser interface presents the orbital scene and analysis results. The system checks a local SQLite cache before requesting orbital data from the remote source. Cached snapshots allow repeated propagation and maneuver trials to use the same input data.

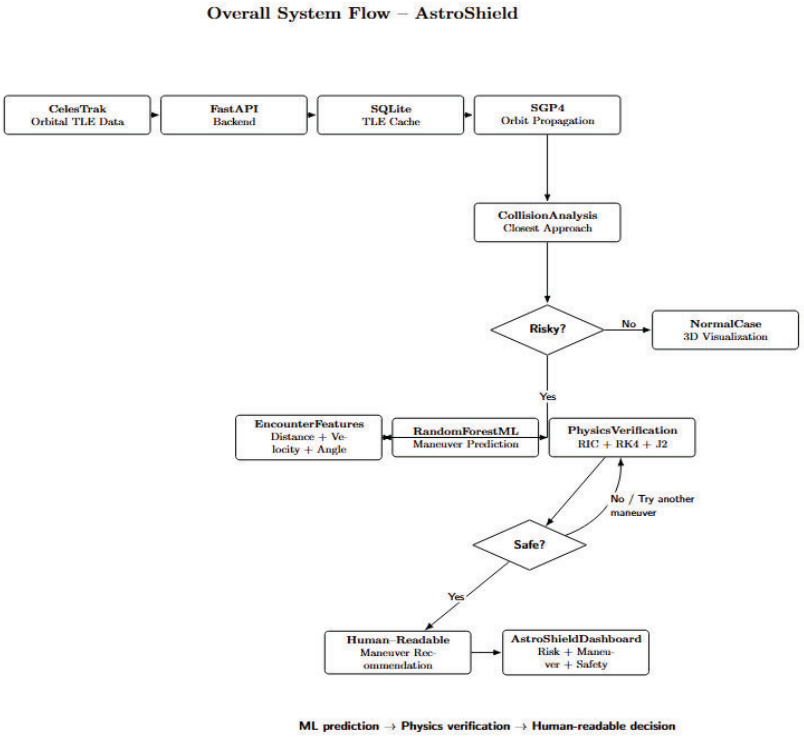


Fig. 1. AstroShield processing pipeline from orbital-data acquisition and caching through propagation, screening, maneuver recommendation, verification, history, and visualization.

3.1 Orbital Data Acquisition and Propagation

Orbital data are obtained as TLE/general-perturbation records from CelesTrak and stored in a local SQLite cache with group identifiers, serialized entries, retrieval timestamps, and expiry metadata. SGP4 propagates the orbital elements to position and velocity samples over the prediction window. The quality and age of the input elements constrain the reliability of the resulting predictions.

For two objects with position vectors $r_1(t)$ and $r_2(t)$, their instantaneous separation is $d(t) = \|r_1(t) - r_2(t)\|$. The time of closest approach over a prediction interval T is the time at which d(t) is minimized, and the corresponding miss distance is the

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

minimum separation. The prototype's screening layer is a preliminary filter and should not be confused with a full operational conjunction-risk calculation.

3.2 Risk Classification

For interface presentation, AstroShield uses project-specific distance bands: Critical for separation below 10 km; Moderate for separation from 10 km to less than 100 km; and Low for separation of at least 100 km. These thresholds organize the prototype's warnings and deeper analysis. They are not universal operational limits and are not collision probabilities.

3.3 Maneuver Proposal and Verification

When a critical conjunction is selected, encounter descriptors such as miss distance, relative-motion information, and time remaining until closest approach are supplied to the Random Forest component. The model proposes a maneuver direction and related parameters. The candidate space includes prograde, retrograde, normal, and anti-normal directions, a discrete set of velocity-change magnitudes, and several lead times before closest approach.

The proposed velocity change is applied to the spacecraft state. The modified trajectory is then numerically propagated, and the minimum separation over the evaluation window is calculated independently of the machine-learning prediction. A candidate is accepted only if the computed minimum separation meets the configured safety threshold. If the initial proposal fails, the fallback search evaluates other candidates and selects the feasible candidate with the smallest velocity-change magnitude. If no candidate passes, the system should report that no verified maneuver was found rather than presenting an unsafe candidate as successful.



Fig. 2. Physics-gated maneuver recommendation: the learned proposal is propagated and checked; an unsuccessful proposal triggers a fallback search.

4. IMPLEMENTATION

4.1 Software Components

Component	Purpose
TLE/GP acquisition	Retrieves orbital elements for selected satellite and debris groups.
SQLite cache	Stores orbital data, retrieval time, and expiry metadata for reuse.
Orbit propagation	Produces position and velocity samples for screening and

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

	maneuver analysis.
Conjunction engine	Identifies close approaches and assigns interface risk bands.
Random Forest	Nominates maneuver direction and associated burn parameters.
Physics verifier	Propagates candidate post-burn states and checks minimum separation.
History database	Stores analysis sessions, thresholds, object groups, and warning summaries.
Web interface	Displays the orbital scene, warning list, maneuver details, and verification status.

4.2 Persistent Records

The SQLite database supports both caching and traceability. The cache stores object-group data and expiry information. The collision-history table records analysis sessions, selected object groups, screening threshold, prediction window, warning details, and warning counts. This makes it possible to revisit the input context associated with a displayed result, although the records alone do not establish that a prediction is operationally accurate.

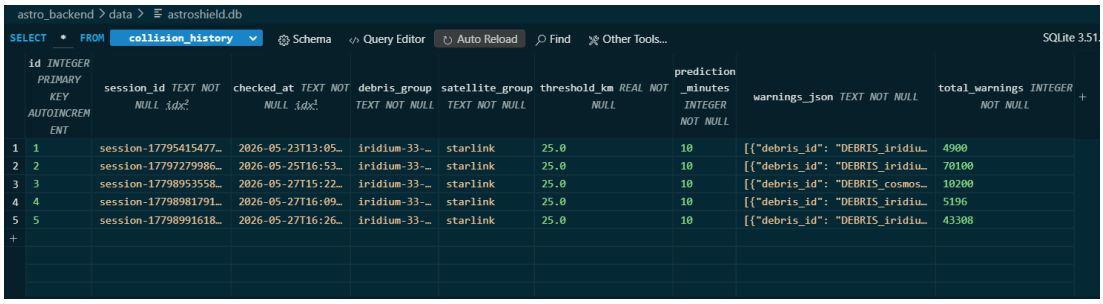


Fig. 3. Database evidence showing the orbital-data cache and stored collision-analysis history.

4.3 Web-Based Decision Support

The dashboard combines a three-dimensional orbital view with a warning panel. Tracked objects are represented using different visual categories, and the warning panel lists detected conjunctions with their risk labels. For a critical event, the user can request maneuver analysis and inspect the proposed direction, velocity change, lead time, predicted separation, configured minimum separation, and physics-verification status.

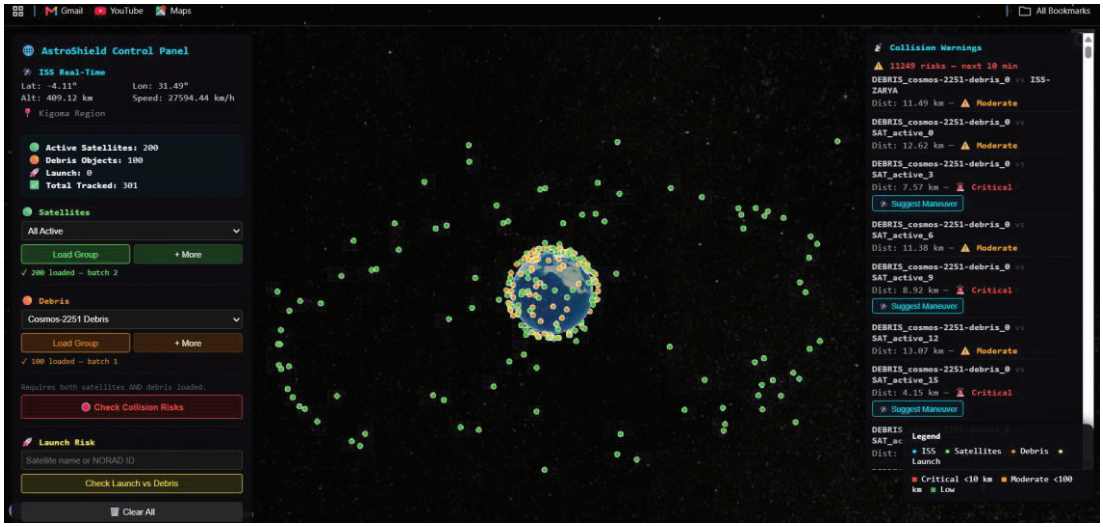


Fig. 4. AstroShield dashboard showing tracked orbital objects, risk classifications, collision warnings, and access to maneuver analysis.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

5. RESULTS AND DISCUSSION

5.1 Representative Demonstration

In the demonstrated session, the interface lists a critical conjunction at approximately 7.57 km. The system proposes a prograde velocity change of 1.00 m/s, scheduled 60 minutes before closest approach. After evaluating 64 candidate maneuvers, the displayed numerical verification reports a post-maneuver separation of approximately 324.4 km, compared with a configured minimum separation of 25.0 km. The interface marks the result as "Physics verified."

This example illustrates the intended interaction between learning, propagation, and the safety check. A prograde burn changes the spacecraft's orbital energy and along-track timing, which can alter where the spacecraft is located relative to the other object at the encounter. The actual result depends on the state data, propagation model, maneuver assumptions, and search interval; therefore, the demonstration should not be interpreted as a guarantee of safety.

Fig. 7 Behaviour of the AstroShield maneuver recommender

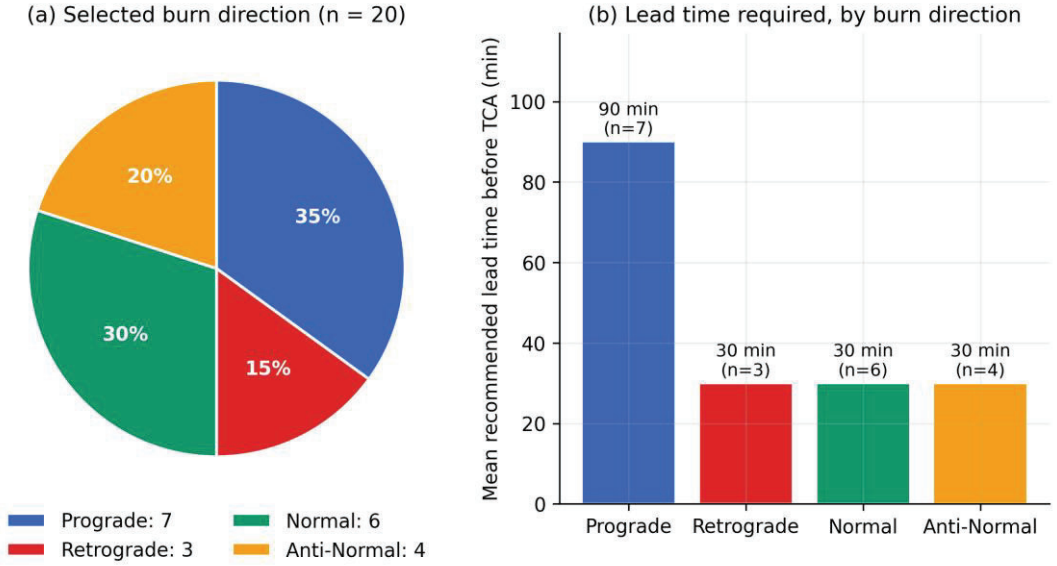


Fig. 5. Summary of the 20 maneuver-recommender cases represented in the supplied manuscript; these descriptive values are not a general performance evaluation.

5.2 Evaluation Metrics

A rigorous evaluation should use a documented set of conjunction scenarios separated into training, validation, and test partitions. Synthetic encounters used to train the model must not be reused for final testing. Results should be compared against a physics-only candidate search and, where meaningful, a learned-only proposal without the verification gate.

Evaluation level	Metrics to report
Screening	Detection rate, false-alarm rate, and computation time.
Maneuver quality	Minimum post-maneuver separation, velocity-change magnitude, lead time, and runtime.
ML–physics interaction	Fraction of proposals accepted and fraction requiring fallback search.
Robustness	Safe-separation rate and separation distribution under perturbed initial states and execution parameters.
Reproducibility	Fixed train/validation/test split, cached input snapshots, and stored session metadata.

The current paper reports the prototype's demonstrated workflow and a representative software example, rather than a completed statistical benchmark. The 20 cases shown in the supplied manuscript provide descriptive counts and mean lead times only; without a defined sampling protocol and larger independent test set, they cannot establish general model accuracy or maneuver superiority.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

5.3 Limitations

First, TLE/GP accuracy varies with element age, object characteristics, and prediction horizon. Second, the interface's distance bands are project-specific screening thresholds and do not replace covariance-based collision-probability analysis. Third, a trained model may encounter inputs outside its training distribution. The verification stage can reject an infeasible proposal, but it cannot correct inaccurate orbital data or omitted physical effects. Finally, the prototype is intended for human-supervised decision support. Operational use would require stronger uncertainty modelling, extensive validation, mission-specific constraints, fault handling, command authorization, and integration with established conjunction-assessment procedures.

6. CONCLUSION AND FUTURE WORK

AstroShield integrates orbital-data retrieval, local caching, SGP4 propagation, conjunction screening, Random Forest maneuver nomination, numerical verification, persistent history, and an interactive display. Its central design principle is that machine learning proposes an action while a separate physics-based stage checks whether the resulting trajectory meets a configured separation requirement. A representative session demonstrates how a close-approach warning can be converted into a readable maneuver recommendation with timing, velocity change, predicted separation, and verification status.

The next step is a controlled evaluation using a larger independently generated encounter dataset, a physics-only baseline, repeated timing measurements, and robustness trials. The study should report maneuver feasibility, velocity-change cost, fallback frequency, computation time, and safe-separation outcomes under perturbations. Until such validation is completed, AstroShield should be treated as a proof-of-concept decision-support prototype rather than an autonomous or certified collision-avoidance system.

ACKNOWLEDGMENT

The authors thank their project guide and collaborators for their guidance and support during the development and testing of the AstroShield prototype.

REFERENCES

[1] D. A. Vallado, P. Crawford, R. Hujsak, and T. S. Kelso, "Revisiting Spacetrack Report #3," in Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, Keystone, CO, USA, 2006, Paper AIAA 2006-6753.

[2] T. S. Kelso, "A new way to obtain GP data (aka TLEs)," CelesTrak. Available: https://celestrak.org/NORAD/documentation/gp-data-formats.php. Accessed: Sep. 26, 2026.

[3] NASA, "Conjunction Assessment Risk Analysis (CARA)." Available: https://www.nasa.gov/cara/. Accessed: Sep. 26, 2026.

[4] L. Breiman, "Random forests," Machine Learning, vol. 45, no. 1, pp. 5–32, 2001, doi: 10.1023/A:1010933404324.

[5] Z. Pavanello, L. De Maria, A. De Vittori, M. Maestrini, P. Di Lizia, and R. Armellin, "CAMmary: A review of spacecraft collision avoidance manoeuvre design methods," Acta Astronautica, vol. 236, pp. 770–789, 2025, doi: 10.1016/j.actaastro.2025.07.027.

[6] A. Morselli, R. Armellin, P. Di Lizia, and F. Bernelli Zazzera, "A high order method for orbital conjunctions analysis: Monte Carlo collision probability computation," Advances in Space Research, vol. 55, no. 1, pp. 311–333, 2015, doi: 10.1016/j.asr.2014.09.003.

[7] D. J. Kessler and B. G. Cour-Palais, "Collision frequency of artificial satellites: The creation of a debris belt," Journal of Geophysical Research, vol. 83, no. A6, pp. 2637–2646, 1978.

[8] F. R. Hoots and R. L. Roehrich, "Models for propagation of NORAD element sets," Spacetrack Report No. 3, Aerospace Defense Command, U.S. Air Force, 1980.

[9] F. K. Chan, Spacecraft Collision Probability. El Segundo, CA, USA: Aerospace Press, 2008.

[10] K. T. Alfriend, M. R. Akella, J. Frisbee, J. L. Foster, D.-J. Lee, and M. Wilkins, "Probability of collision error analysis," Space Debris, vol. 1, no. 1, pp. 21–35, 1999.

[11] F. J. Krage, "NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook," NASA/SP-20230002470, Feb. 2023. Available: https://ntrs.nasa.gov/citations/20230002470.

[12] T. Flohrer, H. Krag, and H. Klinkrad, "ESA's process for the identification and assessment of high-risk conjunction events," Advances in Space Research, vol. 44, no. 3, pp. 355–363, 2009, doi: 10.1016/j.asr.2009.04.012.

[13] M. R. Akella and K. T. Alfriend, "The probability of collision between space objects," Journal of Guidance, Control, and Dynamics, vol. 23, no. 5, pp. 769–772, 2000.

[14] M. S. Balch, R. Martin, and S. Ferson, "Satellite conjunction assessment and the false confidence theorem," Proceedings of the Royal Society A, vol. 475, no. 2227, 2019, doi: 10.1098/rspa.2018.0565.

[15] "Enhanced conjunction assessment in LEO: A hybrid Monte Carlo and spline-based method using TLE data," Aerospace, vol. 12, no. 8, Art. no. 674, 2025, doi: 10.3390/aerospace12080674.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)