Redefining Performance in Space Traffic Management

How SAFE sets a new benchmark

ecosmic

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ABOUT US/

Ecosmic is building the operating system for satellite security. With **Space Domain Awareness** now a top priority for safely navigating the orbital environment, we provide operators with the intelligence needed to act with confidence. By aggregating data across a fragmented value chain and processing it through advanced algorithms, Ecosmic will create a unified intelligence layer that enhances **awareness, prediction, and coordination in orbit.**

Truly data agnostic, our platform maximises the value of available infrastructure by orchestrating information from a global network of partners including radars, telescopes, radio frequency antennas and space-based sensors to build a comprehensive, real-time view of the orbital environment.

Powered by our advanced algorithms, these **insights are accurate, timely, and actionable**, empowering operators and decision-makers to safeguard missions, anticipate risks, and ensure resilient satellite operations at scale.

Our first product, **SAFE**, designed for **precise space traffic management**, is already operational and beats Space-Track 100 to 0, detecting every false positive and false negative the system misses. This is just the first piece of the puzzle, proving that our algorithms are setting a new standard in Space Domain Awareness.

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EXECUTIVE SUMMARY

CONTEXT/

As space becomes exponentially more complex, congested, and contested, resilient Space Domain Awareness is essential to safeguard critical infrastructure

Around 11,000 active satellites now operate in orbit, surrounded by nearly 100 million pieces of debris [1]. The situation will become even more challenging, with over 60,000 additional satellites projected to operate in orbit by 2030 [2].

As mega-constellations expand and satellite missions become increasingly complex and technologically advanced, maintaining accurate awareness of the orbital environment is essential to safeguard the continuity, safety, and resilience of the systems that underpin our connected world, from stock exchanges to GPS. At orbital speeds, operators have less than a tenth of a second to react, highlighting how fragile current space operations can be. This tiny window for action underscores the urgent need for advanced tools and reliable intelligence.

As satellites become essential to life on Earth, and new technologies capable of damaging this infrastructure emerge every day, space has become a contested domain. NATO recognised this in 2019, designating space as an operational environment. Today, both nation-states and private companies compete for valuable orbital regions, making strategic coordination and operational control more critical than ever.

Understanding what is happening in a timely and accurate manner will be essential to prevent the escalation of geopolitical tensions. Space is no longer a detached environment; it is a direct continuum of Earth.

SPACE TRAFFIC MANAGEMENT/

Space Traffic Management involves tracking and coordinating satellites to prevent collisions, ensure safe access to orbit, and maintain the continuity of space operation

SPACE-TRACK/

Currently, most operators rely on Space-Track as their primary source of collision alerts, known in space jargon as Conjunction Data Messages. Managed by the US Department of Defense, Space-Track has been operational since the 1950s. It leverages telescopes and radars around the world to track objects in orbit, predict their trajectories, and calculate collision probabilities among tens of thousands of objects.

While still valuable, Space-Track's algorithms are struggling to keep up with the growing number of space objects. Operators are overwhelmed by false collision alerts every day, which can disrupt operations and consume valuable time.

SAFE/

SAFE is our in-house solution for Space Traffic Management, designed to detect and eliminate the false collision alerts that overwhelm operators using Space-Track. At its core, SAFE's strength lies in its algorithms: when processing Conjunction Data Messages, it produces zero false positives and zero false negatives. This translates into hours of saved work, eliminates unnecessary manoeuvre planning, and provides complete visibility of potential collisions.

SAFE also maintains a flawless track record of service availability and allows operators to request conjunction analysis on demand, anytime. In contrast, Space-Track provides updates only every eight hours, limiting responsiveness and situational awareness

RESULTS/

Thanks to comparison with Monte Carlo simulations, this White Paper proves that SAFE outperforms Space-Track with no false positives or negatives, giving satellite operators accurate and timely conjunction alerts. SAFE provides extra lead time for proactive decision-making and reduces operational stress. Designed for high-volume LEO operations, SAFE enables efficient, continuous satellite operations.

ABOUT THIS WHITE PAPER/

The *Introduction* chapter explains the importance of conjunction assessment and its impact on satellite operations. If you don't have a technical background or are short on time, you can skip to the *Conclusions* chapter, where SAFE's operational performance is summarised.

Information on our patented algorithm for estimating the probability of collision can be found in *The algorithm* chapter. The *Analysis method and setup* chapter details the methodology and configuration used to benchmark SAFE's performance against Space-Track. The *Results* chapter presents all the technical results.

This White Paper offers a new approach: a safe and transparent way to trust software with the critical task of protecting satellites. Such a delicate responsibility demands radical transparency. Our goal is to provide satellite operators with the tools they need to make informed, critical decisions.

TRY SAFE FOR FREE/

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acronyms/

BC	Ballistic Coefficient
COLA	Collision Avoidance
ECEF	Earth Centred Earth Fixed
ECI	Earth Centred Inertial
GEO	Geostationary Orbit
HBR	Hard Body Radius
IERS	International Earth Rotation Service
LEO	Low Earth Orbit
MD	Miss Distance
OD	Orbit Determination
ODE	Ordinary Differential Equation
PC	Probability of Collision
RF	Radiofrequency
RTN	Radial, Transversal, Normal
SRP	Solar Radiation Pressure
SSA	Space Situational Awareness
STM	Space Traffic Management
TCA	Time of Closest Approach
UTC	Coordinated Universal Time

/meaning

INTRODUCTION

HOW SPACE TRAFFIC IS MANAGED TODAY/

Satellite operators rely on public and private tools to monitor collision risks, but orbital uncertainty makes alerts inherently imprecise

Satellite operators currently have access to a variety of tools to analyse collision risks. These solutions may be public and free, like Space-Track and EU SST, or offered by private providers.

Collision alert services typically provide metrics such as the probability of collision, miss distance, and time of closest approach. However, these alerts are inherently **probabilistic**, as there is no absolute certainty that a collision will occur. Positional uncertainty for objects in orbit can be substantial, sometimes spanning several kilometres. Updates on orbital positions are often **infrequent**: active satellites are usually tracked only when passing over a ground station, while inactive objects are observed via telescopes or radar only under favourable conditions. As time passes between observations, uncertainty grows. Handling this **orbital uncertainty** effectively is critical to producing accurate collision risk predictions; failure to do so floods operators with unrealistic alerts.

CONSEQUENCES OF THIS APPROACH/

Poorly calculated alerts keep operators busy for hours every day, draining time and resources

In 2025, MIT researchers estimated that “the maximum acceptable conjunction rate per satellite was set at 10 conjunctions per month, beyond which the maneuver burden or collision risk becomes too high to justify continued operations” [3].

Today, a typical satellite in Low Earth Orbit performs between 2 and 14 collision avoidance manoeuvres per year [4][5], meaning that it faces hundreds of conjunctions. With the exponential rise in launches and space objects, space traffic management has already become a significant **operational burden**, consuming hours each day to address poorly calculated alerts and superfluous manoeuvres

WHAT WE DID/

SAFE is built to eliminate false alerts, providing accurate and actionable insights into collision risk

When building SAFE, we focused on developing a **robust algorithm** capable of delivering accurate and timely results even under high initial uncertainty.

This White Paper evaluates SAFE’s performance, comparing it against Space-Track and other systems that rely on similar algorithms and models. Because collision-risk prediction is inherently probabilistic, performance evaluation is essential to determine which algorithms most accurately approximate reality. For this purpose, we used **Monte Carlo simulations**, a computationally intensive yet effective approach for empirically assessing probabilistic algorithms by estimating their performance distributions.

THE ALGORITHM

WHY SAFE IS DIFFERENT/

SAFE estimates collision probability using a fully non-linear, non-Gaussian algorithm, providing a more accurate representation of reality

SAFE estimates the probability of collision between two satellites using an algorithm that **reduces the amount of assumptions** about the encounter. Unlike conventional approaches, SAFE does not rely on Gaussian distributions, it doesn't ignore the velocity covariance, and fully accounts for all elements of the dynamics model.

The overall algorithm, based on [6], consists of three main patented components:

- → A novel dynamical model and integration schema
- → A non-Gaussian uncertainty model
- → The computation and integration of the PC rate

The first two components form the model for uncertainty propagation, while the third computes the probability of collision using the outputs of this model.

Most widely used methods for uncertainty propagation in space trajectories rely on linear approximations and uncertainties in states and measurements are assumed to be Gaussian. Examples include the minimum variance estimator or the Kalman filter [7].

SAFE removes the need for linear and Gaussian approximations, offering a fully **non-linear**, non-Gaussian alternative that guarantees more accurate and reliable collision risk estimates.

REFERENCE FRAMES AND TIMEKEEPING/

- → Earth Centred Reference Frames. SAFE is currently designed for Earth orbiting satellites, and two types of frames are used: Earth Centred Earth Fixed (ECEF) and Earth Centred Inertial (ECI). The International Earth Rotation Service (IERS) conventions define both inertial and earth fixed frames (Earth centred and others), as well as the methods to convert between one and the other.

- → Time Scales. The Coordinated Universal Time (UTC) time scale progresses at the same rate as the international atomic time, TAI, kept by atomic clocks, except that UTC also occasionally has leap seconds added to it to keep it close to UT1. Most data sources for the orbital states of satellites use UTC.

DYNAMICAL MODEL/

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, t) = (\boldsymbol{v}, \boldsymbol{a}(\boldsymbol{r}, \boldsymbol{v}))$$
$$\boldsymbol{x}(t_0) = \boldsymbol{x}_0$$

The propagation of the state of a spacecraft in orbit can be represented by a 6D vector $\mathbf{x} = (\mathbf{r}, \mathbf{v})$ with its position $\mathbf{r}$ and velocity $\mathbf{v}$ in the Geocentric Celestial Reference Frame (GCRF).

$$\frac{d\phi(x_0, t_0, t)}{dt} = f(x, t)$$
$$\phi(x_0, t_0, t_0) = x_0$$

It is determined by solving an ordinary differential equation (ODE) as an initial value problem, where $\mathbf{a}$ is the acceleration given as described in the next section, and $\mathbf{x}_0$ and t_0 are the initial state and time. The solution is a state transition function $\phi(x_0, t_0, t_f)$

This function can be computed using numerical methods for solving ODEs, provided a model is available to calculate the acceleration.

ACCELERATION MODEL/

The acceleration is a sum of the point-mass acceleration from the Earth and the following perturbations:

- → Earth's spherical harmonics, with degree and order up to 70
- → Drag, with a constant ballistic coefficient B_C and the NRLMSISE-00 atmospheric model
- → Solar Radiation Pressure (SRP) with coefficient C_{SRP}
- → Third-body perturbations from the Sun and Moon

The third body perturbations are defined as the point-mass gravitational acceleration exerted by a third body, in this case the Sun and the Moon, relative to the gravitational acceleration acting on the central body.

NUMERICAL ODE SOLVER/

To solve the ODE shown above, an implementation of RK7(8) is used. The step size was adjusted to keep the integration error below 10^{-12}.

This type of ODE solver is designed to propagate one state at the time and give an output that is a single state at a different time. However, using SAFE's algorithm, a run of the ODE solver returns instead a representation of the function of the final state with respect to the initial state. This representation is particularly useful for uncertainty propagation.

ANALYSIS METHOD AND SETUP

GENERAL APPROACH/

SAFE and Space-Track performances are compared, using Monte Carlo as benchmark

This analysis compares SAFE's risk estimates with Space-Track, using Monte Carlo simulations as a benchmark. The evaluation focuses solely on Probability of Collision (PC) to maintain clarity, leaving other metrics like Miss Distance or RTN components outside the scope.

CONFIGURATION ALIGNMENT/

To reduce potential biases, the same force model and space objects characteristics were used across the two algorithms and Monte Carlo whenever possible. In order to do that, the following keys were sourced from each individual Space-Track CDM and set accordingly within SAFE and Monte Carlo:

1. **GRAVITY_MODEL**
   to set the gravitational order and degree
2. **SOLAR_RAD_PRESSURE**
   to turn on/off SRP modelling
3. **N_BODY_PERTURBATIONS**
   to know which third body perturbations to model
4. **COMMENT Exclusion Volume Radius**
   to be used as HBR
5. **CD_AREA_OVER_MASS**
   to obtain the BC for drag modelling
6. **CR_AREA_OVER_MASS**
   to obtain the SRP coefficient for SRP modelling

CONFIGURATION LIMITATIONS AND IMPACT ASSESSMENT/

A different atmospheric model and different gravitational harmonics coefficients were used within SAFE and Space-Track, and Earth tides were not considered by SAFE. Since the PC estimates from both Space-Track and SAFE are based on the states and covariances at TCA provided by Space-Track, the propagation time is in the order of seconds, so these differences in the dynamic modelling yield a negligible impact on the results.
All Space-Track CDMs use the Foster-1992 method for PC computation, assuming **linear trajectories** for objects propagation and neglecting orbital dynamics during PC calculations.

MONTE CARLO SIMULATIONS SETUP/

As explained in detail in a previous publication [8], for each CDM, we performed N independent Monte Carlo runs. In each run, the initial states at TCA were sampled from the nominal solution using the covariance matrices to represent uncertainty, and then propagated backward and forward in time to determine that sample's closest-approach time. If, during propagation, the objects came within the sum of their hard-body radii, the event was counted as a collision. The Monte Carlo probability of collision was computed as the number of counted collisions divided by N.

The PC of Space-Tracks' CDMs was used to determine the number N of samples to be used for each Monte Carlo simulation

1. **If CDM PC > 1e-4, then N = 1e6**
2. **If 1e-7 < CDM PC < 1e-4, then N = 1e7**
3. **If CDM PC < 1e-7, then N = 1e6**

While this approach may initially seem counterintuitive, it balances **estimation accuracy** with **computational load.** With more than 1,000 CDMs to analyze, setting N > 1e6 for all runs would be computationally unsustainable.

Considering that European Space Agency guidelines recommend a PC actionability threshold of 1e-4, the number of samples was chosen to ensure a standard deviation below 10% at least up to PC = 1e-5. Additionally, many operators, particularly those managing large fleets, adopt lower actionability thresholds in the range 1e-5 to 1e-7.

To provide greater precision in this critical region, the number of samples was increased to 1e7 for PC estimates between 1e-4 and 1e-7. For PC estimates below 1e-7, N was returned to 1e6, as further increasing samples yields diminishing returns, with negligible practical impact.

It is also worth noting that for 17 CDMs, a second Monte Carlo run was performed with an ad-hoc number of samples between 1e7 and 1e8. These additional runs were triggered only when initial PC estimates were close to the actionability thresholds, ensuring a more accurate assessment of whether the conjunction should be considered concerning.

SAFE SETUP/

When setting up a SAFE run, two main parameters can be tuned depending on the use case at hand: time window and time step

TIME WINDOW/

To ensure robustness, the time window should be chosen such that it reliably covers **any plausible encounter scenario**. Once the time window is sufficiently large to encompass the entire conjunction event, increasing it further only results in an increase in execution time. Currently, an initial guess of the time window is provided based on the orbital regime, spanning between 100 and 1500 seconds. However, SAFE has been updated so that the integration of the probability density rate now terminates once it falls below a predefined threshold.

TIME STEP/

The PC rate integration step size is the parameter that has the greatest direct effect on the **integration accuracy**, and it also affects the run time significantly. An extensive sensitivity analysis was performed to determine the best default value for this parameter based on the orbital regime, currently spanning between 0.01s and 0.1412s.

DATA SELECTION/

For this analysis, **1,030 CDMs** associated with 513 different conjunction events were examined. These CDMs are operational files generated by the 19th SDS and published on Space-Track between 2024-12-21 and 2025-07-02. The 33 primary objects involved are all LEO satellites managed by operators who participated in the SAFE beta-testing phase.

All CDMs are based on high accuracy catalog (HAC) vs HAC screening, with no data taken from operator-provided ephemerides. This ensures a fair comparison between Space-Track predictions and SAFE results, demonstrating that SAFE delivers improved performance when the two alorithms employ the same input data. Normally, Ecosmic's operational services integrate data and ephemerides provided directly by the operators.

CDMs were considered actionable when the Probability of Collision exceeded 1e-4, representing a concerning conjunction that requires mitigation by the operator. While some operators may adopt more conservative thresholds, 1e-4 aligns with **ESA Space Debris Mitigation Requirements** and remains the most commonly used value in the industry.

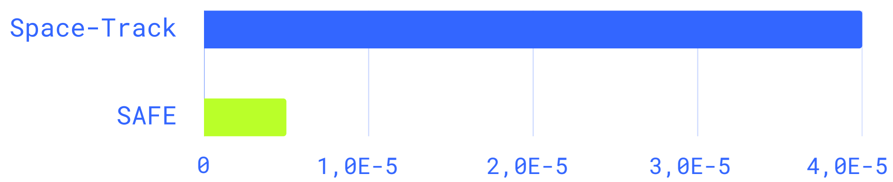
RESULTS

ABSOLUTE AND RELATIVE DEVIATION FROM MONTE CARLO ESTIMATES/

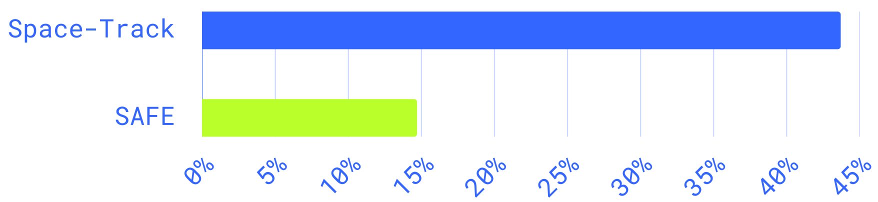
SAFE outperforms Space-Track, closely matching Monte Carlo results

Estimation accuracy is evaluated using absolute and relative deviations from the benchmark. SAFE substantially outperforms Space-Track on both metrics, consistently producing results that closely match the Monte Carlo estimates.

Average Absolute Error



Average Relative Error



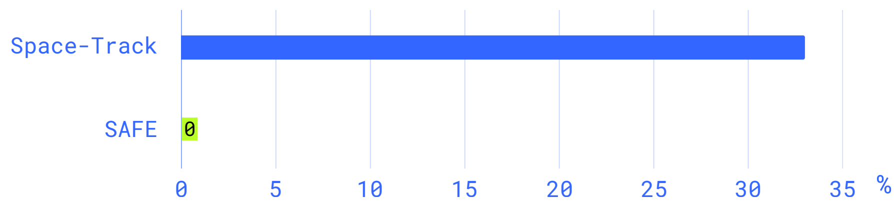
Metric	SAFE	SPACE-TRACK
Absolute error wrt Monte Carlo	**4.7E-6**	3.9E-5
Relative error wrt Monte Carlo	**14.7%**	43.7%

PERFORMANCE WITHIN STATISTICAL BOUNDS/

SAFE always falls within Monte Carlo bounds; Space-Track is outside 1/3 of the time

Another key metric is how often PC estimates fall outside the Monte Carlo 3-sigma bounds. SAFE estimates never exceed these bounds, while Space-Track estimates fall outside the bounds for one third of the analyzed CDMs.

Estimations outside Monte Carlo bounds

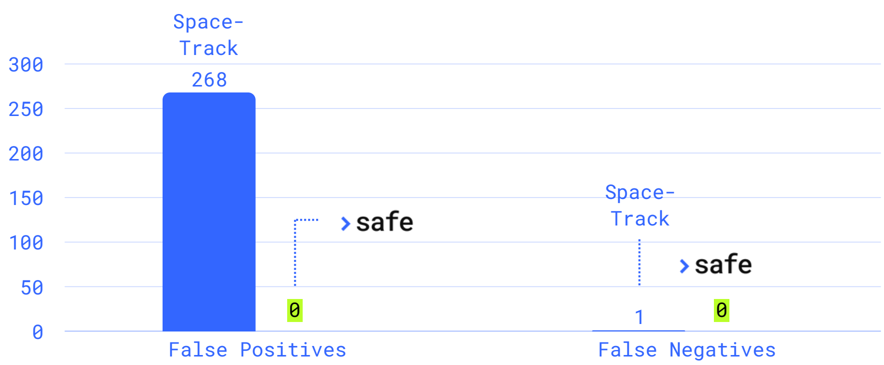


FALSE ALERTS DETECTION AND CLASSIFICATION/

SAFE catches all false positives and false negatives missed by Space-Track

- False positives occur when a conjunction is flagged as actionable even though the actual collision probability is below the actionability threshold. They lead operators to plan unnecessary collision avoidance manoeuvres, increasing workload, operational pressure, and fuel consumption.
- False negatives occur when a conjunction is not flagged as actionable but the actual collision probability exceeds the threshold. This represents a missed threat, potentially exposing the satellite to a collision, with financial consequences and possible regulatory or public scrutiny.

SAFE eliminates false Collision Alerts



SAFE outperforms Space-Track in this case as well, showing a complete absence of false positives and false negatives and demonstrating its reliability for confident, timely, and effective decision-making.

It is worth noting that, for this analysis, the HBR value in SAFE and Monte Carlo was set to match Space-Track to avoid potential bias. In operational use, when the HBR is sourced from operator-provided information, Space-Track can underestimate the object's true HBR, leading to underestimation of the PC and more false negatives, which Ecosmic has observed when running SAFE in real scenarios.

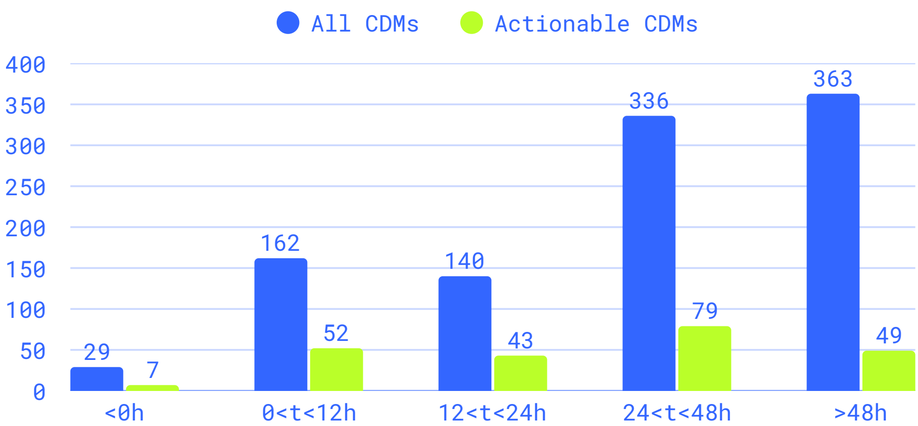
ALERT LEAD TIME

Timely conjunction alerts enable better operational readiness and minimize disruption

The timing of conjunction warnings is critical for effective operational response. Late-notice alerts can be stressful and disruptive, so this chapter provides a data-driven analysis of typical alert lead times by Space-Track.

The figure below reports the alerts lead time, i.e. the time between a CDM creation epoch and the TCA, for all the analysed CDMs.

Alert Lead Time



The histogram reports the lead time of all analysed CDMs, measured as the time between CDM creation and TCA. Intervals of 0, 12, 24, and 48 hours highlight the operational implications, from continuous 24/7 coverage to standard working-hours response. Actionable CDMs are shown separately, revealing that a significant portion is often received on short notice.

Notably, one third of all CDMs were created within 24 hours of TCA, emphasizing the need for operators to assess and **act** on potential threats **quickly**.

RUN TIME/

SAFE delivers collision alerts in minutes, not hours

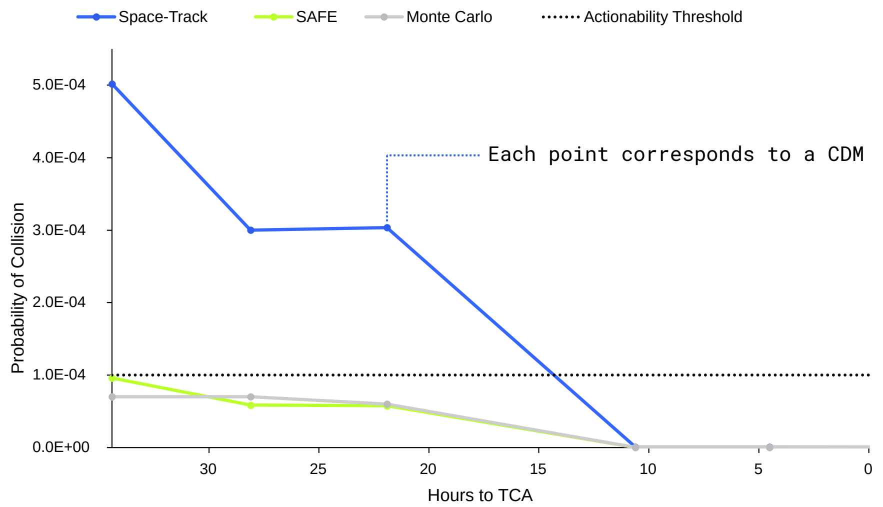
Given that a significant number of conjunction warnings, including critical ones, are issued within 24 hours of TCA, fast run times are essential for timely and effective operational responses.

SAFE has an average runtime of under a few minutes. By comparison, Monte Carlo simulations take over ten times longer, and Space-Track's standard screening cycle is 8 hours, highlighting the advantage of rapid processing for timely operational responses.

NOTABLE CASES/

This chapter presents three events, each comprising multiple CDMs, where SAFE's competitive advantage over Space-Track is clear, demonstrating its accuracy and decision-making support in high-stakes scenarios.

Case 1: early Identification of False Alarms

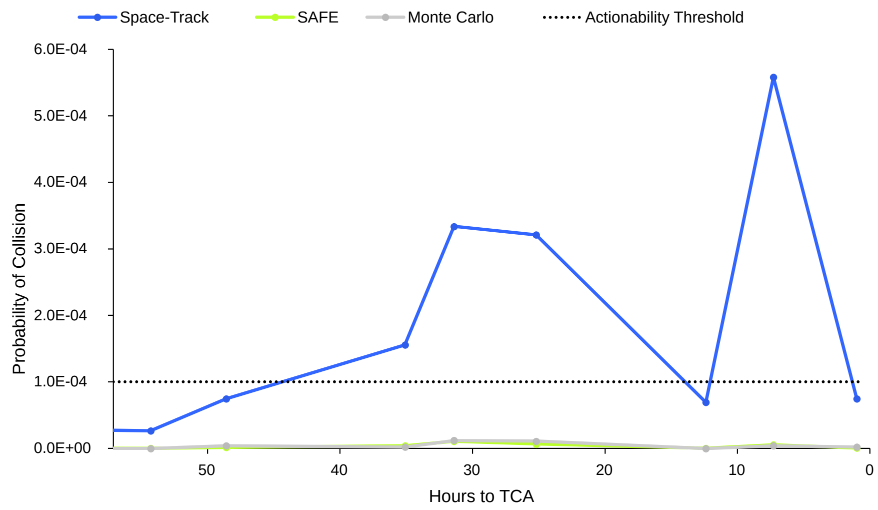


Space-Track initially flagged this conjunction as highly concerning, with the PC estimation well above the actionability threshold. It took four CDM updates over 24 hours for Space-Track's estimate to align with the Monte Carlo benchmark.

SAFE, in contrast, matched the Monte Carlo estimation from the start and correctly identified the conjunction as non-concerning.

Using SAFE, operators could have known **24 hours earlier** that this event did not require action, avoiding unnecessary collision avoidance manoeuvres, operational workload, fuel waste, and disruption of payload availability.

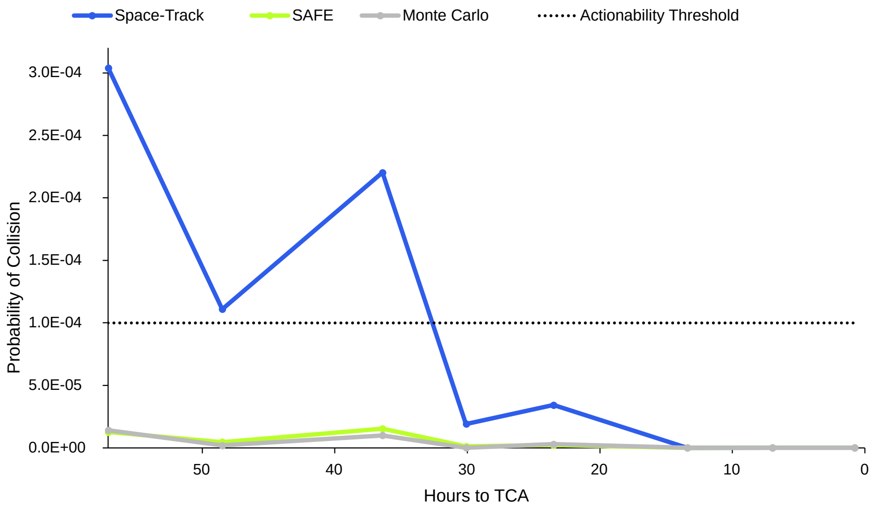
Case 2: Avoiding Ambiguity in Conjunction Assessment



The trend for this event shows repeated inconsistencies in Space-Track's evaluation, with the PC oscillating above and below the actionability threshold. Between CDM #3 and CDM #9—a span of 48 hours—operators faced uncertainty about whether action was required.

SAFE, in contrast, clearly indicated from the beginning that the conjunction was non-concerning. Using SAFE, operators could have known 48 hours in advance, reducing stress, preserving satellite resources, and optimising payload availability.

Case 3: Disregarding False Alarms with Confidence



Event 3 again demonstrates inconsistencies in Space-Track's evaluation of the Probability of Collision. SAFE would have informed operators 24 hours in advance that this conjunction was non-concerning.

Notably, this event involved an active secondary satellite, so early knowledge that the conjunction could be disregarded would have greatly facilitated coordination between operators.

FAILED MONTE CARLO RUNS/

Out of the 1030 CDMs analyzed, 20 Monte Carlo runs failed to complete. In these cases, all samples failed to reach a conjunction due to unrealistically large uncertainties. For either the primary or secondary object, the standard deviation in all three position axes was equal to 10 times the Earth's radius, and the standard deviation in all three velocity axes was equal to 10 times the circular orbit velocity at the TCA.

Given these extreme values, the uncertainties were considered unrealistic, and no attempt was made to correct them. These 20 CDMs were therefore excluded from this analysis.

CONCLUSIONS

OPERATIONAL IMPACT/

SAFE demonstrates a measurable impact on satellite operations teams. Over 1030 CDMs, SAFE **recorded no false positives**, whereas Space-Track generated more than one false positive every four alerts, meaning over 25% of alerts from Space-Track represented unnecessary distractions and wasted effort.

Equally important, SAFE recorded **no false negatives**, ensuring that no critical conjunction went unnoticed. Space-Track, on the other hand, missed at least one critical case, which could have led to a collision or a last-minute, highly disruptive collision avoidance manoeuvre.

LEAD TIME FOR ALERTS/

SAFE gives operators **up to 24 extra hours to react** to a concerning conjunction, reducing operational stress and improving decision-making quality.

In one example, SAFE correctly identified a conjunction involving an active satellite as non-concerning 24 hours before Space-Track did, facilitating **better coordination** between operators in different time zones with varying collision avoidance protocols.

SCALABILITY AND RELIABILITY/

With LEO satellites often receiving thousands of alerts per year, having a reliable conjunction analysis service is crucial. SAFE enables operators to **scale efficiently**, save time, act confidently, and ensure uninterrupted operations for global connectivity, navigation, and communication.

SAFE has a spotless track record in terms service availability, which can be checked in real-time and publicly at status.ecosmic.space.

LOOKING AHEAD/

Ecosmic is launching a screening service for operators to upload OEM files and receive collision alerts with SAFE's proven accuracy. In the coming months, additional features, including **Orbit Determination** and **Collision Avoidance Manoeuvre Optimisation** will be made available.

TRY SAFE FOR FREE/

Experience SAFE first-hand by contacting us at hello@ecosmic.space

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