QUANTIFYING PROPAGATION-MODEL DIVERGENCE AS AN EARLY-WARNING METRIC FOR SATELLITE CONJUNCTION ASSESSMENT

1st Jits Doomen
The Hague, Netherlands Jits.doomen@gmail.com

Abstract—**The increasing amount of artificial objects in Low Earth Orbit (LEO) has resulted in a growing number of predicted conjunction events, placing increasing demands on Space Situational Awareness (SSA) and conjunction assessment systems. As the number of tracked objects continues to increase, processing every potential conjunction using computationally expensive, high-fidelity methods becomes increasingly impractical. This paper investigates whether the divergence between orbital propagation models of different fidelities can be used as an early-warning metric for identifying conjunctions that require more detailed analysis. The proposed approach compares the predicted relative states, time of closest approach and miss distances produced by progressively higher- fidelity propagation models. Conjunctions exhibiting significant disagreement between models are classified as candidates for escalation to more computationally intensive analysis. The objective is to determine whether propagation-model divergence correlates with errors in conjunction predictions can be used to reduce computational requirements while maintaining an acceptable level of conjunction-assessment reliability. A series of simulated conjunction scenarios will be evaluated across different orbital regimes, encounter geometries, propagation uncertainties and time-to-closest-approach intervals. The results will be used to evaluate the feasibility of incorporating an adaptive propagation-fidelity mechanism into large-scale conjunction assessment systems. Such a mechanism could allow computational resources to be concentrated on conjunctions for which propagation uncertainty or model disagreement indicates a greater need for high-fidelity analysis.**

Index Terms—**Space Situational Awareness, SSA, conjunction analysis, propagation, conjunction assessment**

I. INTRODUCTION

As of July 2026, there are reported to be approximately 54,000 artificial objects larger than 10 centimeters in Low Earth Orbit (LEO) [1]. With the rapid deployment of mega-constellations, this number is projected to exceed 100,000 active satellites and trackable debris fragments by 2030 [2]. Consequently, the demand for timely and accurate conjunction assessment (CA) is increasing at an unprecedented rate. Currently, Space Situational Awareness (SSA) entities rely on a tiered filtering approach to manage the immense volume of potential collision pairs. Initial all-vs-all screenings typically employ computationally inexpensive analytical propagators, such as Simplified General Perturbations-4 (SGP4), to eliminate definitively safe pairings. The remaining subset of close approaches is then escalated to high-fidelity Special Perturbation (SP) numerical propagators. These advanced models incorporate complex perturbations, including atmospheric drag, non-spherical Earth gravity harmonics, and third-body effects. However, as the space catalog grows exponentially, the number of pairings that survive initial filtering is bottlenecking computational resources. The accuracy of any orbital propagation relies heavily on the environment and the chosen force models. In certain orbital regimes—particularly in lower altitudes where atmospheric density fluctuates unpredictably due to solar weather—low-fidelity models rapidly accumulate along-track errors. If a conjunction involves objects subject to these highly dynamic perturbations, the predicted trajectory from a simple analytical model will quickly deviate from that of a complex numerical model. This paper proposes leveraging this exact phenomenon—propagation-model divergence—as an active, early-warning metric. Rather than relying solely on traditional triggers, such as arbitrary miss-distance thresholds or fixed time-to-closest-approach (TCA) windows, we hypothesize that the *rate of divergence* between low- and high-fidelity models can serve as a proxy for orbital uncertainty. A high divergence rate may indicate increased sensitivity of the predicted trajectory to differences in modeled dynamics, and is therefore hypothesized to provide a useful trigger for computational escalation, thereby flagging the conjunction as a priority for immediate computational escalation. Conversely, conjunctions demonstrating low divergence across models may be monitored with lower-fidelity methods for longer periods. By quantifying this divergence, SSA operators could dynamically allocate computational resources, focusing high-fidelity processing power only on the conjunctions that truly require it. The remainder of this paper is organized as follows. Section II reviews existing conjunction assessment frameworks and standard orbital propagation methods. Section III details the mathematical formulation for quantifying model divergence. Section IV describes the simulation environment and the scenarios tested across various LEO regimes. Section V presents and analyzes the results of the model comparisons. Finally, Section VI concludes the paper and discusses future avenues for operational implementation.

II. Methods

A. Standard Orbital Propagation Methods

1) SGP4 (Simplified General Perturbations-4): The SGP4 algorithm is an analytical method used to calculate the orbital state vectors of space objects relative to the Earth-centered inertial coordinate system. Operating in conjunction with Two-Line Element (TLE) sets, SGP4 models the secular and periodic effects of Earth's oblateness, atmospheric drag, and solar-lunar gravitational perturbations. Because it is an analytical model, SGP4 is computationally highly efficient, making it the widely used operational model for initial, large-scale catalog screenings and baseline conjunction filtering [3].

2) Numerical Integration: Unlike analytical approximations, numerical integration propagates orbital states by directly solving the ordinary differential equations (ODEs) of motion that govern a satellite's trajectory. These Special Perturbation (SP) methods employ stepwise numerical techniques, such as explicit or implicit Runge-Kutta schemes or Cowell's formulation, to evaluate high-fidelity force models at discrete time intervals along the orbit. By iteratively calculating the precise forces acting on a spacecraft, numerical integration can account for highly dynamic and complex environmental perturbations. These typically include detailed spherical harmonic representations of Earth's non-uniform gravity field, atmospheric drag parameterized by fluctuating solar weather data, solar radiation pressure, and third-body gravitational effects from the Sun and the Moon. While numerical integration yields the highest level of predictive accuracy required for definitive conjunction assessment, the continuous evaluation of these comprehensive force models makes it computationally expensive. This immense computational burden restricts its use in all-vs-all catalog screenings, necessitating intelligent filtering and escalation metrics, such as the propagation divergence approach proposed in this study. [4].

3) Uncertainty Propagation: Accurate conjunction assessment requires not only predicting nominal spacecraft trajectories but also mapping the spatial evolution of state uncertainties over time. Initial orbit determination (OD) uncertainties—originating from tracking sensor noise, baseline measurement errors, and force model inaccuracies—are typically parameterized as multi-variate Gaussian state vectors and covariance matrices at a given epoch. Uncertainty propagation projects these statistical distributions forward to define the dynamic error volumes at the Time of Closest Approach (TCA), serving as the foundational input for computing probability of collision (P_c) metrics. Linear uncertainty propagation relies on the State Transition Matrix (STM) to map initial covariance matrices through linearized orbital dynamics. While computationally lightweight and well-suited for short-term predictions, linear methods assume that the Gaussian structure of the error distribution remains intact. Over extended propagation arcs or in environments dominated by strong non-linear perturbations—such as atmospheric drag fluctuations and high-degree geopotential variations—the physical state space distorts, leading to non-Gaussian covariance stretching. To preserve spatial accuracy in these regimes, higher-order non-linear propagation techniques, including the Unscented Transform (UT), Gaussian Mixture Models (GMMs), and Monte Carlo sampling, are utilized to map accurate probability density functions at the expense of higher computational complexity. [5].

4) Coordinate Systems and Local Orbital Frames: Evaluating model divergence requires consistent reference frames and representations. While analytical models such as SGP4 natively output states in the True Equator Mean Equinox (TEME) frame, numerical propagators typically operate in Geocentric Celestial Reference Frame (GCRF) or J2000 coordinates. Comparing state vectors across propagators requires transformation to a unified inertial frame. Furthermore, to physically characterize divergence mechanisms (such as along-track drag error vs. radial altitude drift), differential state vectors $\mathbf{\Delta r} = \mathbf{r}_{\text{high}} - \mathbf{r}_{\text{low}}$ are mapped into the local Radial, In-track, Cross-track (RIC) orbital frame centered on the primary object:

$$\hat{\mathbf{R}} = \frac{\mathbf{r}}{|\mathbf{r}|}, \quad \hat{\mathbf{C}} = \frac{\mathbf{r} \times \mathbf{v}}{|\mathbf{r} \times \mathbf{v}|}, \quad \hat{\mathbf{I}} = \hat{\mathbf{C}} \times \hat{\mathbf{R}} \tag{1}$$

This decomposition isolates force-model discrepancies along specific orbital vectors, providing the structural basis for the divergence metric formulated in Section III [7].

III. Propagation-Model Divergence Metric

A. Definition of Propagation-Model Divergence

The proposed method uses the disagreement between orbital propagation models as an indicator of when a conjunction assessment may require escalation to a higher-fidelity propagation model. Let the state vector of an object propagated using a low-fidelity model be defined as

$$\mathbf{x}_L(t) = \left[\mathbf{r}_L(t)\ \mathbf{v}_L(t)\right]. \tag{2}$$

Here, $\mathbf{r}_L(t)$ and $\mathbf{v}_L(t)$ represent the propagated position and velocity. Similarly, the state produced by a higher-fidelity model is

$$\mathbf{x}_H(t) = \left[\mathbf{r}_H(t)\ \mathbf{v}_H(t)\right]. \tag{3}$$

The instantaneous state divergence between the two propagation models is defined as

$$\Delta\mathbf{x}(t) = \mathbf{x}_H(t) - \mathbf{x}_L(t). \tag{4}$$

The position and velocity components of this difference are evaluated independently:

$$\Delta\mathbf{r}(t) = \mathbf{r}_H(t) - \mathbf{r}_L(t). \tag{5}$$

$$\Delta\mathbf{v}(t) = \mathbf{v}_H(t) - \mathbf{v}_L(t). \tag{6}$$

The magnitude of the position divergence is then

$$D_r(t) = |\Delta\mathbf{r}(t)|. \tag{7}$$

The corresponding velocity divergence is

$$D_v(t) = |\Delta\mathbf{v}(t)|. \tag{8}$$

These quantities provide direct measures of the disagreement between the two propagated trajectories. Because propagation errors can accumulate with increasing prediction time, $D_r(t)$ and $D_v(t)$ are evaluated throughout the propagation interval rather than only at the final prediction epoch.

B. Radial, In-Track, and Cross-Track Divergence

The Cartesian position difference does not directly indicate the orbital direction in which propagation models diverge. Therefore, the relative position difference is transformed into the Radial, In-track, Cross-track (RIC) frame defined in Section II. For the reference spacecraft, the RIC unit vectors are

$$\hat{\mathbf{R}} = \frac{\mathbf{r}}{|\mathbf{r}|}, \tag{9}$$

$$\hat{\mathbf{C}} = \frac{\mathbf{r} \times \mathbf{v}}{|\mathbf{r} \times \mathbf{v}|}, \tag{10}$$

$$\hat{\mathbf{I}} = \hat{\mathbf{C}} \times \hat{\mathbf{R}}. \tag{11}$$

The Cartesian propagation difference can consequently be decomposed into

$$D_R = \Delta\mathbf{r} \cdot \hat{\mathbf{R}}, \tag{12}$$

$$D_I = \Delta\mathbf{r} \cdot \hat{\mathbf{I}}, \tag{13}$$

and

$$D_C = \Delta\mathbf{r} \cdot \hat{\mathbf{C}}. \tag{14}$$

This decomposition allows the direction of propagation-model disagreement to be examined independently. In particular, the in-track component may be significant for conjunction prediction because small differences in orbital period or mean motion can accumulate into substantial along-track separation over time.

C. Temporal Divergence

In addition to the magnitude of model disagreement, the rate at which the disagreement develops is considered. Given a position-divergence measure $D_r(t)$, its temporal rate of change can be approximated numerically as

$$G_r(t) \approx \frac{D_r(t + \Delta t) - D_r(t)}{\Delta t}. \tag{15}$$

The resulting quantity represents the growth rate of propagation disagreement. A rapidly increasing divergence may indicate that the low-fidelity model is becoming increasingly inconsistent with the higher-fidelity trajectory. The divergence rate is evaluated over multiple propagation intervals to determine whether it provides useful predictive information beyond the absolute magnitude of the state difference.

D. Conjunction-Level Divergence

For conjunction assessment, the divergence between models is evaluated using the predicted relative state of the two objects. Let the relative position predicted by each model be

$$\mathbf{r}_{rel,L}(t) = \mathbf{r}_{1,L}(t) - \mathbf{r}_{2,L}(t). \tag{16}$$

Similarly,

$$\mathbf{r}_{rel,H}(t) = \mathbf{r}_{1,H}(t) - \mathbf{r}_{2,H}(t). \tag{17}$$

The resulting relative-state divergence is

$$\Delta\mathbf{r}_{rel}(t) = \mathbf{r}_{rel,H}(t) - \mathbf{r}_{rel,L}(t). \tag{18}$$

The corresponding scalar divergence is

$$D_{rel}(t) = |\Delta\mathbf{r}_{rel}(t)|. \tag{19}$$

This quantity is particularly relevant to conjunction assessment because the objective is not simply to predict the absolute trajectory of each spacecraft, but to accurately predict their relative geometry.

E. TCA and Miss-Distance Divergence

The effect of propagation-model disagreement on the conjunction itself is evaluated through the predicted Time of Closest Approach (TCA) and miss distance. Let the TCA predicted by the low- and high-fidelity models be $t_{TCA,L}$ and $t_{TCA,H}$, respectively. The TCA disagreement is defined as

$$\Delta t_{TCA} = |t_{TCA,H} - t_{TCA,L}|. \tag{20}$$

Similarly, if $d_{TCA,L}$ and $d_{TCA,H}$ denote the predicted miss distances,

$$\Delta d_{TCA} = |d_{TCA,H} - d_{TCA,L}|. \tag{21}$$

These quantities provide conjunction-specific measures of the practical consequences of propagation-model divergence. A large state divergence does not necessarily imply a significant change in the predicted conjunction geometry. Conversely, a comparatively small trajectory difference may result in a substantial change in the predicted miss distance for a close encounter.

F. Candidate Divergence Metric

The individual divergence quantities described above have different physical units and therefore cannot be directly summed. To permit comparison and combination, each quantity is normalized relative to an appropriate reference scale. For a general divergence quantity X, its normalized form is defined as

$$\tilde{X} = \frac{X}{X_{ref}}, \tag{22}$$

where X_{ref} represents a reference scale determined during the experimental phase of the study. A candidate composite divergence metric may then be expressed as

$$D(t) = w_r\tilde{D}_R + w_i\tilde{D}_I + w_c\tilde{D}_C + w_v\tilde{D}_v + w_t\widetilde{\Delta t}_{TCA} + w_d\widetilde{\Delta d}_{TCA}. \tag{23}$$

Here, w_r, w_i, w_c, w_v, w_t, and w_d represent weighting coefficients. This formulation is considered a candidate metric rather than a predetermined operational criterion. The appropriate normalization factors and weighting coefficients will be determined empirically through the simulation experiments described in Section IV. The experiments will investigate whether individual divergence components correlate with changes in conjunction predictions and whether a composite metric provides predictive value beyond conventional distance- and time-based screening criteria.

G. Escalation Criterion

The ultimate purpose of the divergence metric is to determine whether a conjunction should be propagated using a higher-fidelity model. A threshold-based escalation mechanism can therefore be defined as

$$D(t) > D_{crit} \quad \Rightarrow \quad \text{high-fidelity propagation.} \tag{24}$$

Conversely,

$$D(t) \leq D_{crit} \quad \Rightarrow \quad \text{continue low-fidelity monitoring.} \tag{25}$$

The critical value D_{crit} should not be selected arbitrarily. It will instead be evaluated using simulated conjunction scenarios and selected according to the relationship between divergence, propagation error, and conjunction-assessment performance. The experiments will therefore investigate whether propagation-model divergence can identify cases in which low-fidelity propagation produces materially different conjunction predictions from higher-fidelity propagation. If such a relationship is demonstrated, the metric may provide a basis for adaptive propagation fidelity in large-scale conjunction assessment systems.

IV. Simulation Methodology and Experimental Design

A. Methodology

Placeholder

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