THE UNIVERSITY OF TEXAS AT EL PASO

Geometric Conjunction Propensity Modeling in Sun-Synchronous Orbit and Evaluation of Orbital Slotting Mitigation Strategies

Yaneli Najera & Luis Cervantes

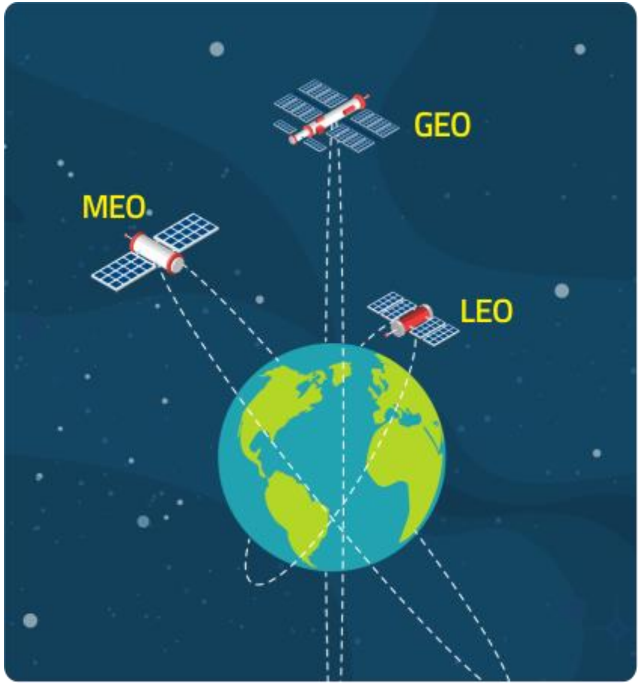
INTRODUCTION & BACKGROUND

Context

This project focuses on orbital congestion in Low Earth Orbit (LEO) and Sun-Synchronous Orbit (SSO). High satellite and debris density increases conjunction opportunities and collision risk.

Purpose

The goal of this project is to use the GCPI metric to identify critical congestion regions and evaluate mitigation strategies such as altitude slotting and RAAN separation.



PROBLEM DEFINITION

PROBLEM STATEMENT

The project addresses the increasing orbital congestion in Sun-Synchronous Orbit (SSO) caused by high satellite and debris density. The study analyzes congestion patterns, clustering behavior, and conjunction propensity using the GCPI metric while evaluating mitigation strategies such as altitude slotting and RAAN separation.

PROJECT OBJECTIVES

1

Quantify orbital congestion in Sun-Synchronous Orbit using the GCPI metric.

2

Analyze how density, inclination clustering, and RAAN overlap affect conjunction propensity.

3

Identify the most critical altitude regions with high congestion and debris concentration.

4

Evaluate mitigation strategies such as altitude slotting and RAAN separation using Monte Carlo simulation.

SCOPE & ASSUMPTIONS

- Analysis limited to objects in LEO below 2000 km altitude.
- SSO objects defined between 96°–100° inclination.
- Objects grouped into 50 km and 25 km altitude bins

.• GCPI measures geometric conjunction propensity, not collision probability.
- Monte Carlo simulations used 1000 runs per scenario.
- RAAN circular statistics simplifications were assumed.

METHODOLOGY & APPROACH

Statistical & Simulation-Based Orbital Congestion Analysis

STEP 1
Data Collection

Collected orbital data from Space-Track and filtered objects to LEO under 2000 km and SSO between 96°–100° inclination. Removed decayed objects and incomplete data.

STEP 2
Modeling and GCPI Development

Grouped objects into 50 km and 25 km altitude bins. Calculated density, inclination clustering (Ci), RAAN clustering (Cr), and GCPI values for each bin.

STEP 3
Statistical Analysis

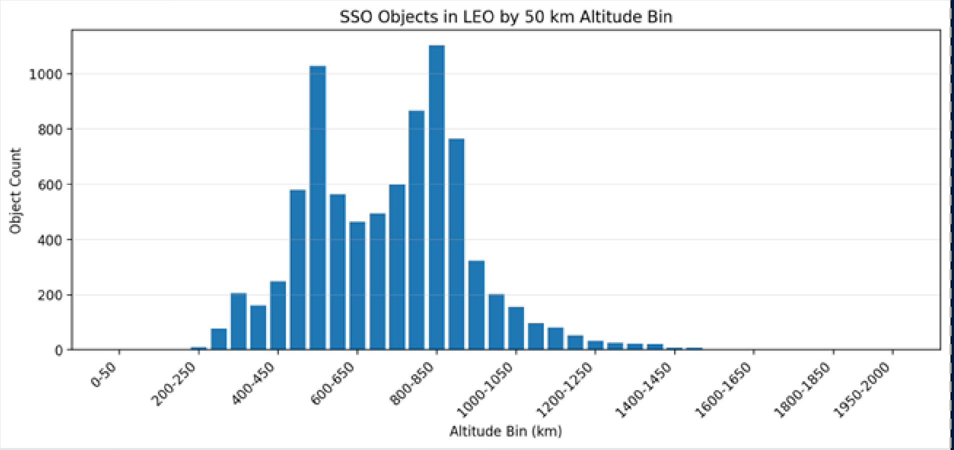
Performed Pearson correlation, Spearman correlation, and Chi-square analysis to study congestion, clustering behavior, and fragmentation contribution in high-risk regions.

STEP 4
Validation & Simulation

Used Monte Carlo simulation with 1000 runs to evaluate mitigation strategies such as altitude slotting and RAAN separation and compare GCPI reductions against the baseline scenario.

DATA & ANALYSIS

LEO/ SSO Density Distribution (50km)



KEY OBSERVATIONS

- Highest object concentration occurred between 500–900 km.
- The densest 50 km bin was 800–850 km with 1103 objects.
- Congestion peaks indicate critical orbital regions.
- Results show strong orbital stacking in SSO.

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DATA & ANALYSIS

Inclination & RAAN Clustering

$$C_i = \frac{1}{1+\sigma_i}$$

$$C_r = \frac{1}{1+\sigma_r}$$

Bin (50km)	σi	σr	Ci	Cr
100-150	0.1503	26.3588	0.8693	0.0366
150-200	0.1615	5.2566	0.8610	0.1598
200-250	0.5918	74.3162	0.6282	0.0133
250-300	0.3585	65.7028	0.7361	0.0150
300-350	0.2648	77.6372	0.7906	0.0127
350-400	0.4611	62.4591	0.6844	0.0158
400-450	0.4840	80.6136	0.6739	0.0123
450-500	0.4148	68.0183	0.7068	0.0145
500-550	0.3561	80.0962	0.7374	0.0123
550-600	0.4442	96.3124	0.6924	0.0103
600-650	0.4961	96.4377	0.6684	0.0103
650-700	0.4412	87.3542	0.6939	0.0113
700-750	0.4364	87.9744	0.6962	0.0112
750-800	0.3689	79.4952	0.7305	0.0124
800-850	0.3313	64.2137	0.7511	0.0153
850-900	0.3878	69.3155	0.7206	0.0142
900-950	0.5522	94.7341	0.6442	0.0104
950-1000	0.5541	135.4564	0.6435	0.0073
1000-1050	0.6875	117.4038	0.5926	0.0084
1050-1100	0.5274	94.4853	0.6547	0.0105
1100-1150	0.6151	111.8764	0.6192	0.0089
1150-1200	0.3466	124.1862	0.7426	0.0080
1200-1250	0.5804	98.2307	0.6328	0.0101
1250-1300	0.6143	129.6102	0.6195	0.0077
1300-1350	0.6962	90.4790	0.5896	0.0109
1350-1400	0.1630	73.8218	0.8598	0.0134
1400-1450	1.3579	103.0468	0.4241	0.0096
1450-1500	0.1505	55.0231	0.8692	0.0178
1500-1550	0.1243	8.7492	0.8894	0.1026

KEY OBSERVATIONS

- Inclination clustering showed weak correlation with density.
- RAAN clustering showed a small negative relationship.
- Density and clustering behave mostly independently.
- Congestion is influenced by multiple orbital factors.

Comparison	Pearson r	Spearman ρ
Density Dq vs Ci	0.038	-0.037
Density Dq vs Cr	-0.230	-0.144

Results

GCPI (50KM)

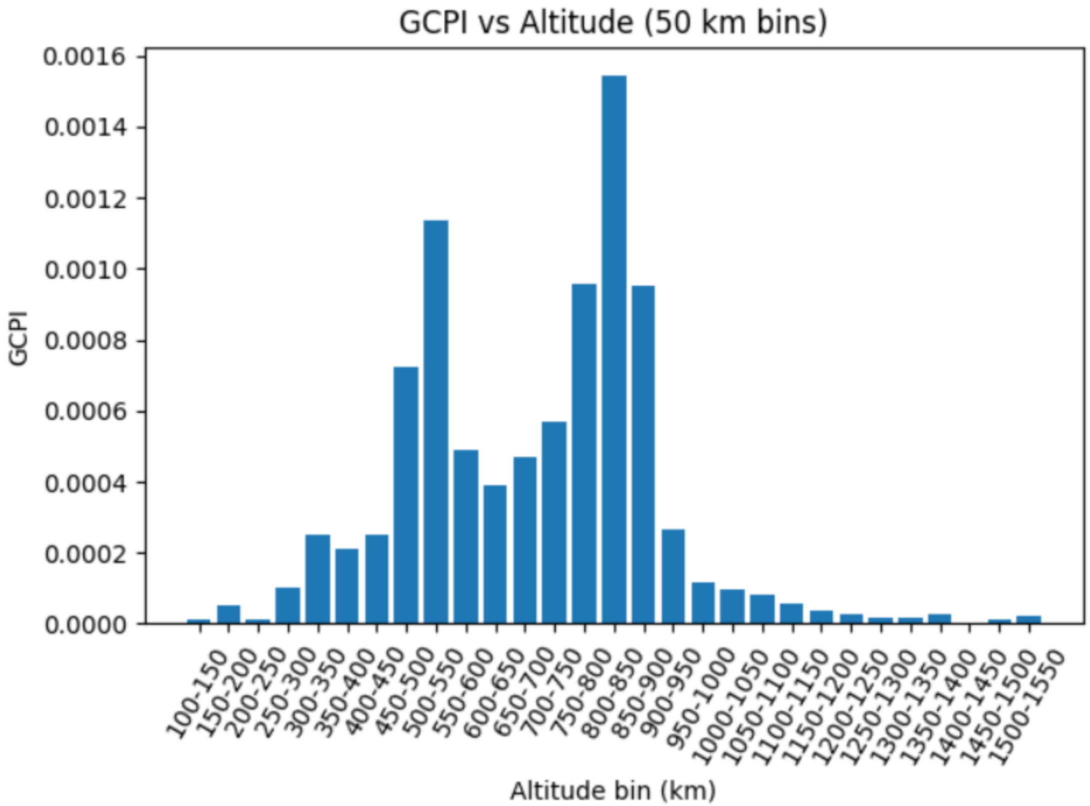
$$GCPI = D_a \times C_i \times C_r$$

Altitude Bin (50 Km)	σi	σr	Ci	Cr	N_bin	Density	GCPI
100-150	0.1503	26.3588	0.8693	0.0366	3	0.000366	0.000012
150-200	0.1615	5.2566	0.8610	0.1598	3	0.000366	0.000050
200-250	0.5918	74.3162	0.6282	0.0133	10	0.001219	0.000010
250-300	0.3585	65.7028	0.7361	0.0150	76	0.009263	0.000102
300-350	0.2648	77.6372	0.7906	0.0127	207	0.025229	0.000253
350-400	0.4611	62.4591	0.6844	0.0158	161	0.019622	0.000212
400-450	0.4840	80.6136	0.6739	0.0123	247	0.030104	0.000250
450-500	0.4148	68.0183	0.7068	0.0145	580	0.070689	0.000724
500-550	0.3561	80.0962	0.7374	0.0123	1029	0.125411	0.001137
550-600	0.4442	96.3124	0.6924	0.0103	564	0.068739	0.000490
600-650	0.4961	96.4377	0.6684	0.0103	464	0.056551	0.000389
650-700	0.4412	87.3542	0.6939	0.0113	494	0.060207	0.000472
700-750	0.4364	87.9744	0.6962	0.0112	598	0.072882	0.000568
750-800	0.3689	79.4952	0.7305	0.0124	867	0.105667	0.000957
800-850	0.3313	64.2137	0.7511	0.0153	1103	0.134430	0.001545
850-900	0.3878	69.3155	0.7206	0.0142	764	0.093114	0.000953
900-950	0.5522	94.7341	0.6442	0.0104	323	0.039366	0.000264
950-1000	0.5541	135.4564	0.6435	0.0073	203	0.024741	0.000116
1000-1050	0.6875	117.4038	0.5926	0.0084	156	0.019013	0.000095
1050-1100	0.5274	94.4853	0.6547	0.0105	97	0.011822	0.000081
1100-1150	0.6151	111.8764	0.6192	0.0089	82	0.009994	0.000055
1150-1200	0.3466	124.1862	0.7426	0.0080	53	0.006459	0.000038
1200-1250	0.5804	98.2307	0.6328	0.0101	33	0.004022	0.000026
1250-1300	0.6143	129.6102	0.6195	0.0077	26	0.003169	0.000015
1300-1350	0.6962	90.4790	0.5896	0.0109	24	0.002925	0.000019
1350-1400	0.1630	73.8218	0.8598	0.0134	21	0.002559	0.000029
1400-1450	1.3579	103.0468	0.4241	0.0096	8	0.000975	0.000004
1450-1500	0.1505	55.0231	0.8692	0.0178	7	0.000853	0.000013
1500-1550	0.1243	8.7492	0.8894	0.1026	2	0.000244	0.000022

KEY FINDINGS

- Highest GCPI occurred at 800–850 km (~0.001545).
- 500–550 km and 750–800 km also showed high GCPI.
- High density and clustering increased conjunction propensity.
- Critical congestion regions clearly emerged.

Results



GCPI vs Altitude (50 km bins)
GCPI
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
100-150
150-200
200-250
250-300
300-350
350-400
400-450
450-500
500-550
550-600
600-650
650-700
700-750
750-800
800-850
850-900
900-950
950-1000
1000-1050
1050-1100
1100-1150
1150-1200
1200-1250
1250-1300
1300-1350
1350-1400
1400-1450
1450-1500
1500-1550
Altitude bin (km)

RESULTS

Fragmentation

56.38% of total objects
were debris.

KEY FINDINGS

- 56.38% of total objects were debris.
- 800–900 km contained the highest debris percentages.
- Some bins exceeded 90% debris concentration.
- Fragmentation strongly contributes to congestion.

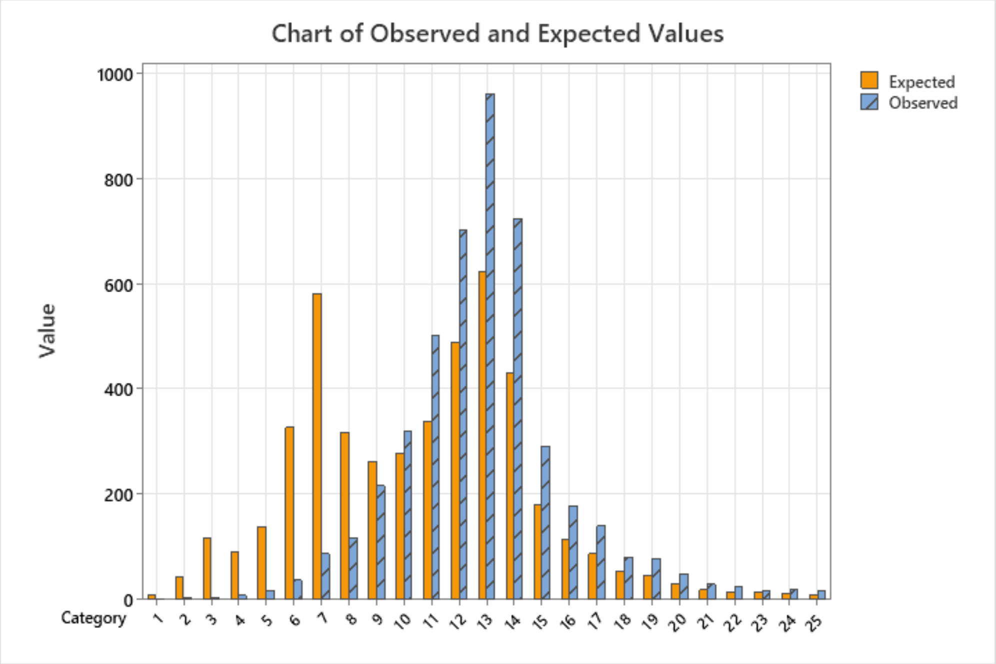
Top 5 GCPI Bins (50 km)

Rank	Bin Range (Km)	GCPI	Debris Count	Total Objects	% Debris
1	800–850	0.001545	960	1103	87.04%
2	500–550	0.001137	87	1029	8.45%
3	750–800	0.000957	702	867	80.97%
4	850–900	0.000953	724	765	94.64%
5	450–500	0.000724	37	580	6.38%

Chi-Square Validation

KEY FINDINGS

- Debris distribution was not proportional across bins.
- Chi-square test rejected the null hypothesis.
- Debris clustering is concentrated in specific orbital regions.
- Results validated fragmentation overrepresentation.



Mitigation Scenarios

Scenario 1: Baseline

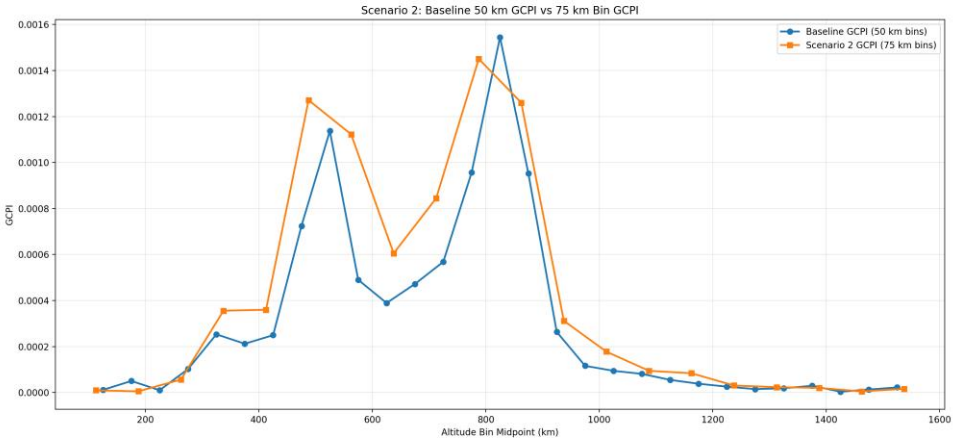
- The 50 km binning scenario represents the current orbital environment with no changes applied.
- Objects keep their original altitude, inclination, and RAAN values.
- This baseline scenario is used to compare the effectiveness of the mitigation strategies.

Mitigation Scenarios

Scenario 2: Altitude Slotting

KEY FINDINGS

- The 75 km altitude slotting reduced total GCPI from 0.008904 to 0.008107.
- This equals an 8.95% reduction compared to the baseline 50 km scenario.
- Some bins showed higher local GCPI due to object clustering, but overall congestion decreased.
- Monte Carlo simulations confirmed the mitigation strategy consistently lowered total GCPI.

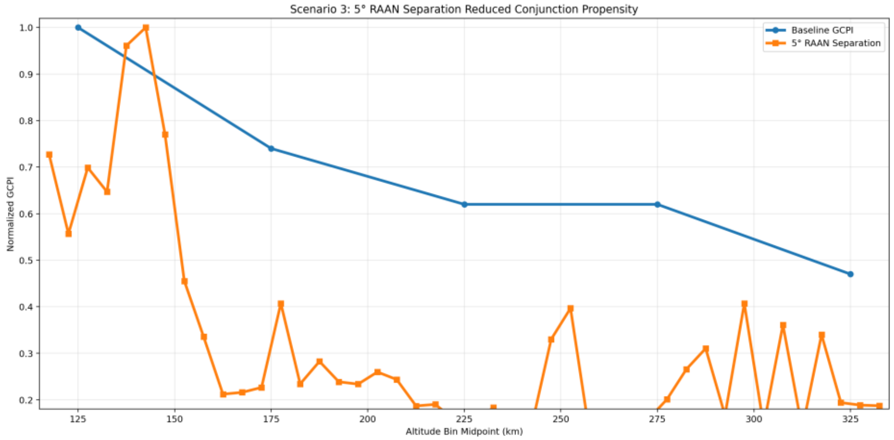


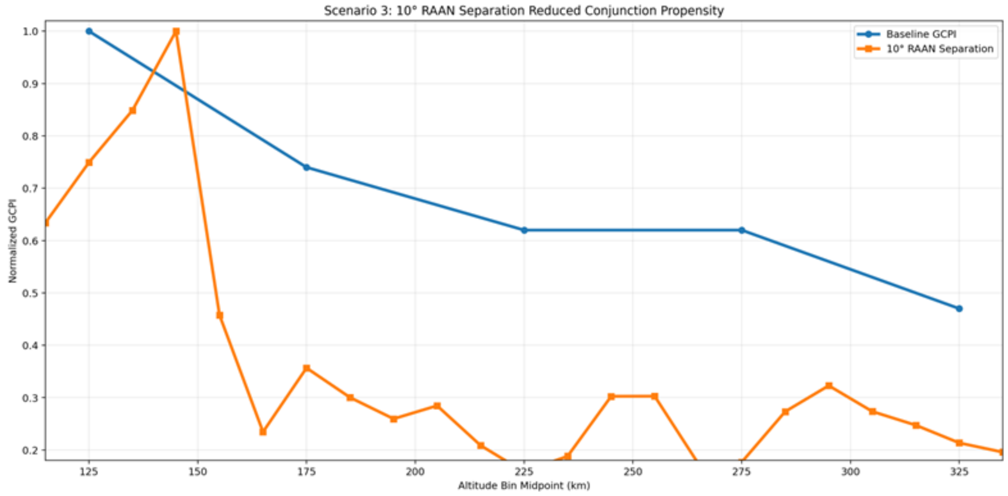
Mitigation Scenarios

Scenario 3: RAAN Separation

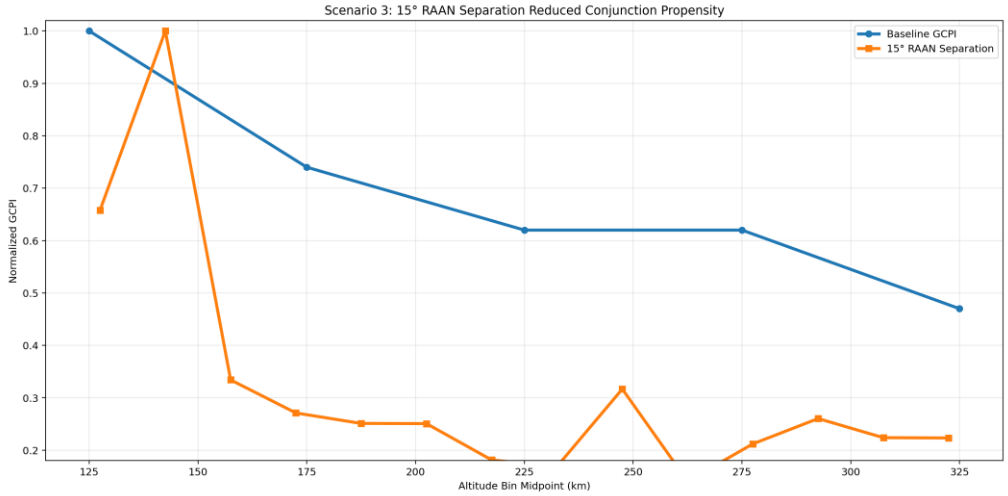
KEY FINDINGS

- Increasing RAAN separation reduced orbital overlap and lowered overall GCPI.
- Larger RAAN separation angles generally improved congestion reduction.
- Some local congestion spikes remained due to object redistribution.
- Monte Carlo simulations confirmed that increasing orbital spacing consistently reduced total GCPI.
- Overall, Scenario 3 showed RAAN separation is an effective congestion mitigation strategy.





Scenario 3: 10° RAAN Separation Reduced Conjunction Propensity
Baseline GCPI
10° RAAN Separation
Normalized GCPI
Altitude Bin Midpoint (km)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
125
150
175
200
225
250
275
300
325

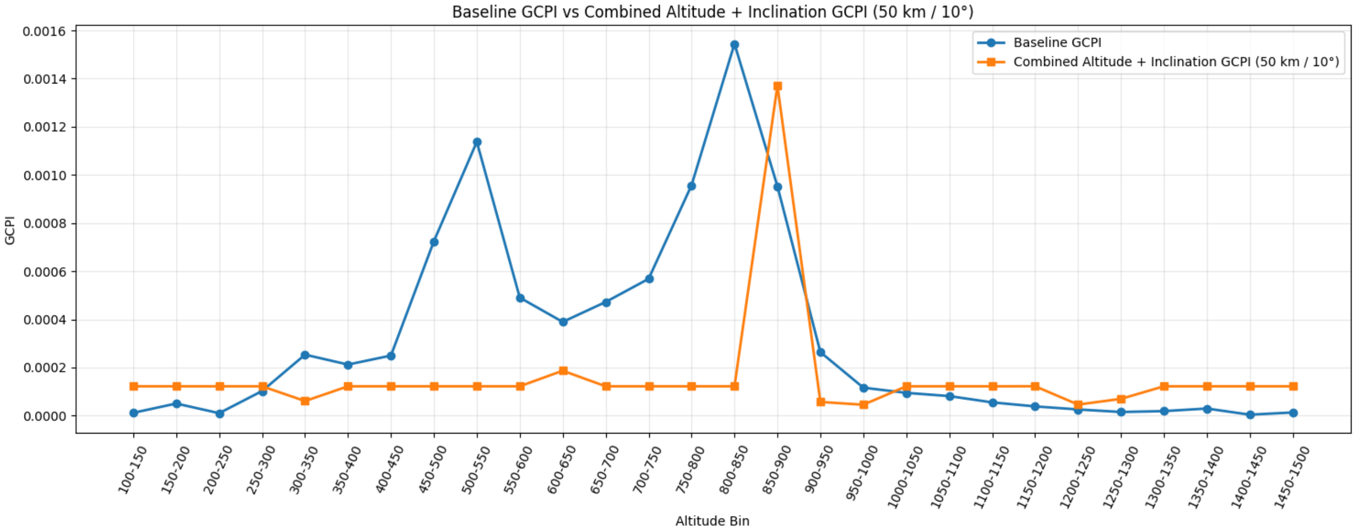


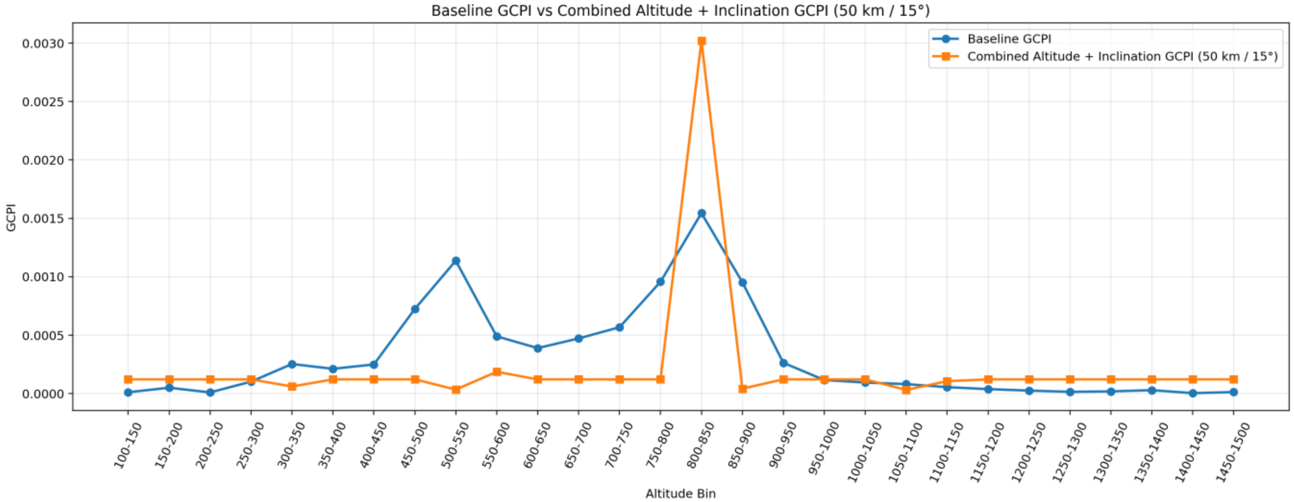
Scenario 3: 15° RAAN Separation Reduced Conjunction Propensity
Baseline GCPI
15° RAAN Separation
Normalized GCPI
Altitude Bin Midpoint (km)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
125
150
175
200
225
250
275
300
325

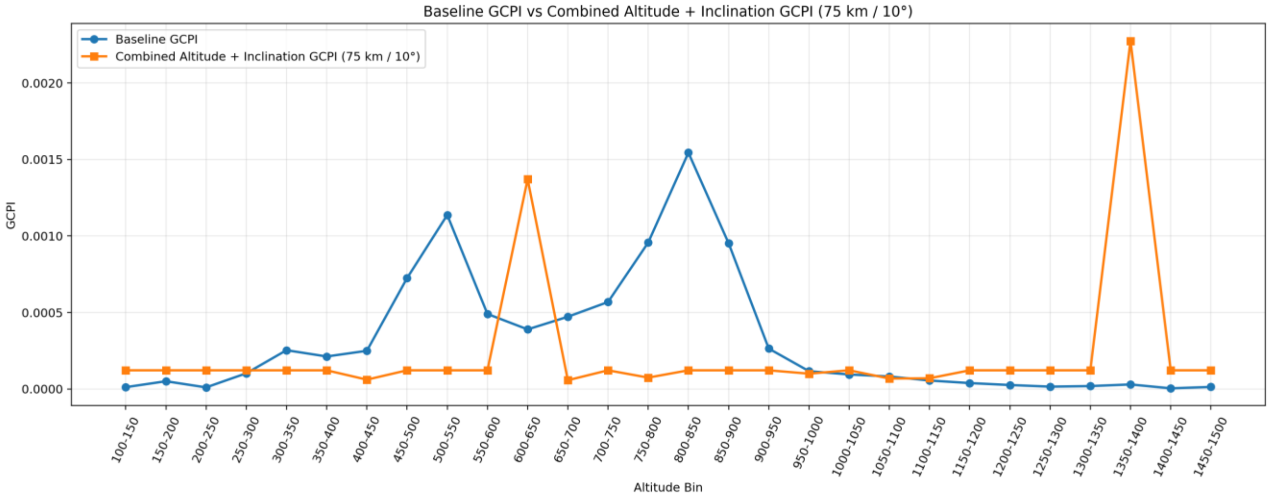
Mitigation Scenarios

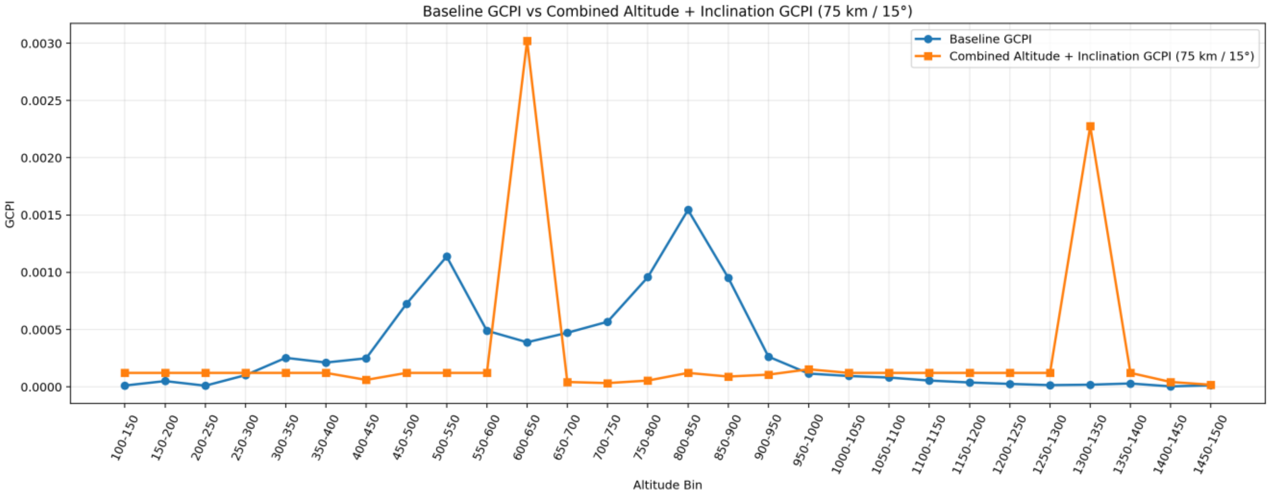
Scenario 4: Combined Strategy

- Combining altitude spacing with inclination/RAAN separation reduced GCPI more effectively than using a single mitigation method.
- The combined strategies improved orbital distribution and reduced orbital overlap.
- Several scenarios showed lower GCPI values compared to the baseline case.
- Some local congestion spikes remained due to redistribution effects.
- Monte Carlo simulations confirmed that combined mitigation strategies consistently reduced total GCPI.
- Overall, combined separation strategies provided the strongest and most stable congestion reduction.


Baseline GCPI vs Combined Altitude + Inclination GCPI (50 km / 10°)
Baseline GCPI
Combined Altitude + Inclination GCPI (50 km / 10°)
GCPI
Altitude Bin


Baseline GCPI vs Combined Altitude + Inclination GCPI (50 km / 15°)
Baseline GCPI
Combined Altitude + Inclination GCPI (50 km / 15°)
GCPI
Altitude Bin


Baseline GCPI vs Combined Altitude + Inclination GCPI (75 km / 10°)
Baseline GCPI
Combined Altitude + Inclination GCPI (75 km / 10°)
GCPI
0.0020
0.0015
0.0010
0.0005
0.0000
100-150
150-200
200-250
250-300
300-350
350-400
400-450
450-500
500-550
550-600
600-650
650-700
700-750
750-800
800-850
850-900
900-950
950-1000
1000-1050
1050-1100
1100-1150
1150-1200
1200-1250
1250-1300
1300-1350
1350-1400
1400-1450
1450-1500
Altitude Bin


Baseline GCPI vs Combined Altitude + Inclination GCPI (75 km / 15°)
Baseline GCPI
Combined Altitude + Inclination GCPI (75 km / 15°)
GCPI
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
100-150
150-200
200-250
250-300
300-350
350-400
400-450
450-500
500-550
550-600
600-650
650-700
700-750
750-800
800-850
850-900
900-950
950-1000
1000-1050
1050-1100
1100-1150
1150-1200
1200-1250
1250-1300
1300-1350
1350-1400
1400-1450
1450-1500
Altitude Bin

DISCUSSION & RECOMMENDATIONS

DISCUSSION

- Increasing altitude and RAAN separation reduced orbital congestion and GCPI.
- Combined mitigation strategies produced the best results.
- Monte Carlo simulations confirmed consistent GCPI reduction compared to the baseline.
- Some local congestion spikes remained due to uneven object redistribution.

RECOMMENDATIONS

- Increase altitude and RAAN separation in highly congested regions.
- Use combined mitigation strategies for better congestion reduction.
- Expand future research to include collision avoidance and dynamic traffic behavior.

CONCLUSIONS

KEY CONCLUSIONS

- The project objectives were successfully achieved by analyzing orbital congestion and evaluating multiple mitigation strategies using GCPI.
- Increasing altitude spacing and RAAN separation reduced conjunction propensity and improved orbital organization.
- Scenario 4 produced the strongest congestion reduction by combining vertical and horizontal orbital separation strategies.
- Monte Carlo simulation confirmed that the mitigation strategies consistently reduced total GCPI under many randomized orbital configurations.
- The project demonstrated that combined orbital spacing strategies can improve long-term space traffic management in LEO environments.

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THANK YOU

QUESTIONS?