Finding the Upper Threshold of LEO Activity That Makes Long-Term Space Operations Unsustainable

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Background

LEO Sustainability

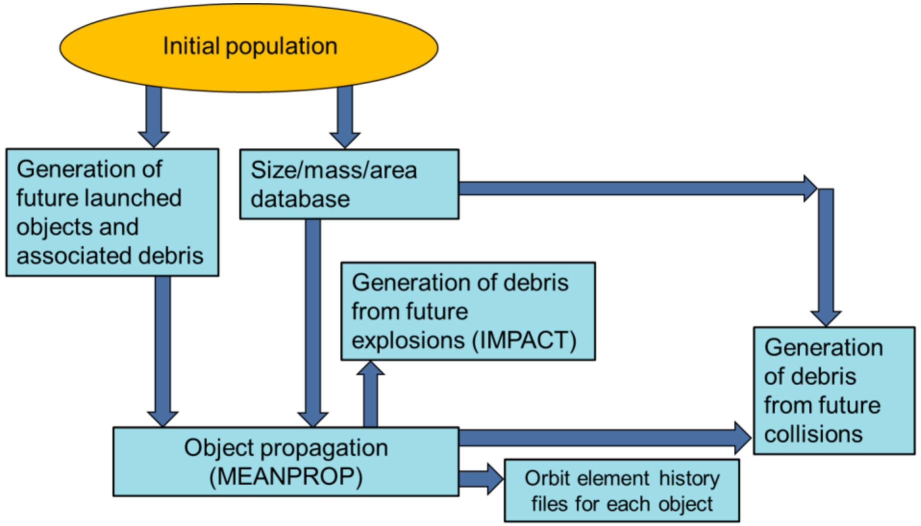
- Aerospace is performing a broad study of the environmental effects of varying future space activity levels
  - *Debris environment evolution modeled in Aerospace Debris Environment Projection Tool (ADEPT)*
  - *Representative Large LEO Constellations (LLC) included in Future Constellation Model (FCM)*

- **Motivation**:
  - *Several proposals for very large constellations indicate a significant increase in active satellites in LEO*
  - *Collisions, debris fragment counts, and collision avoidance (COLA) rates will also increase in the LEO environment*
  - *If left unchecked, high traffic levels combined with poor post-mission disposal (PMD) practices will render LEO unsustainable and make operating in LEO very difficult, if not impossible*
  - *Sustainability... What does that mean?*
    - *"The ability to maintain the conduct of space activities indefinitely…to meet the needs of the present generations while preserving the outer space environment for future generations."*
      - *United Nations Office for Outer Space Affairs (UNOOSA) Guidelines for the Long-term Sustainability of Outer Space Activities, 27 June 2018*

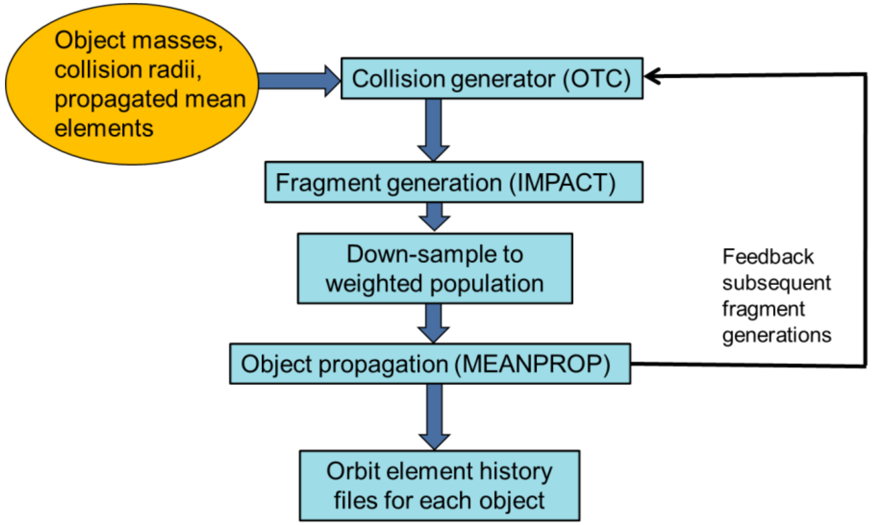
- **Goal**:
  - *Model different levels of future space activity with significant variations in traffic and PMD success rates*
  - *Relate activity levels and characteristics to the long-term effects on space operations to better determine when those effects may become unacceptable*
  - *Determine levels of activity that are either acceptable or unacceptable with respect to LEO sustainability*

Aerospace Debris Environment Projection Tool (ADEPT)

Population Generation Process



Generation of Debris from Future Collisions



- Projects evolution of the future on-orbit environment based on launch traffic, debris mitigation approaches and other options
- Used to determine how actions and events affect debris environment
- Included sources:
  - *New launch traffic (satellites and launch vehicles)*
  - *Debris from explosions*
  - *Debris from collisions between objects (feedback)*
- Included sinks
  - *Atmospheric drag*
  - *Active debris removal (recently added)*
- Results consistent with half-a-dozen+ international models over several studies

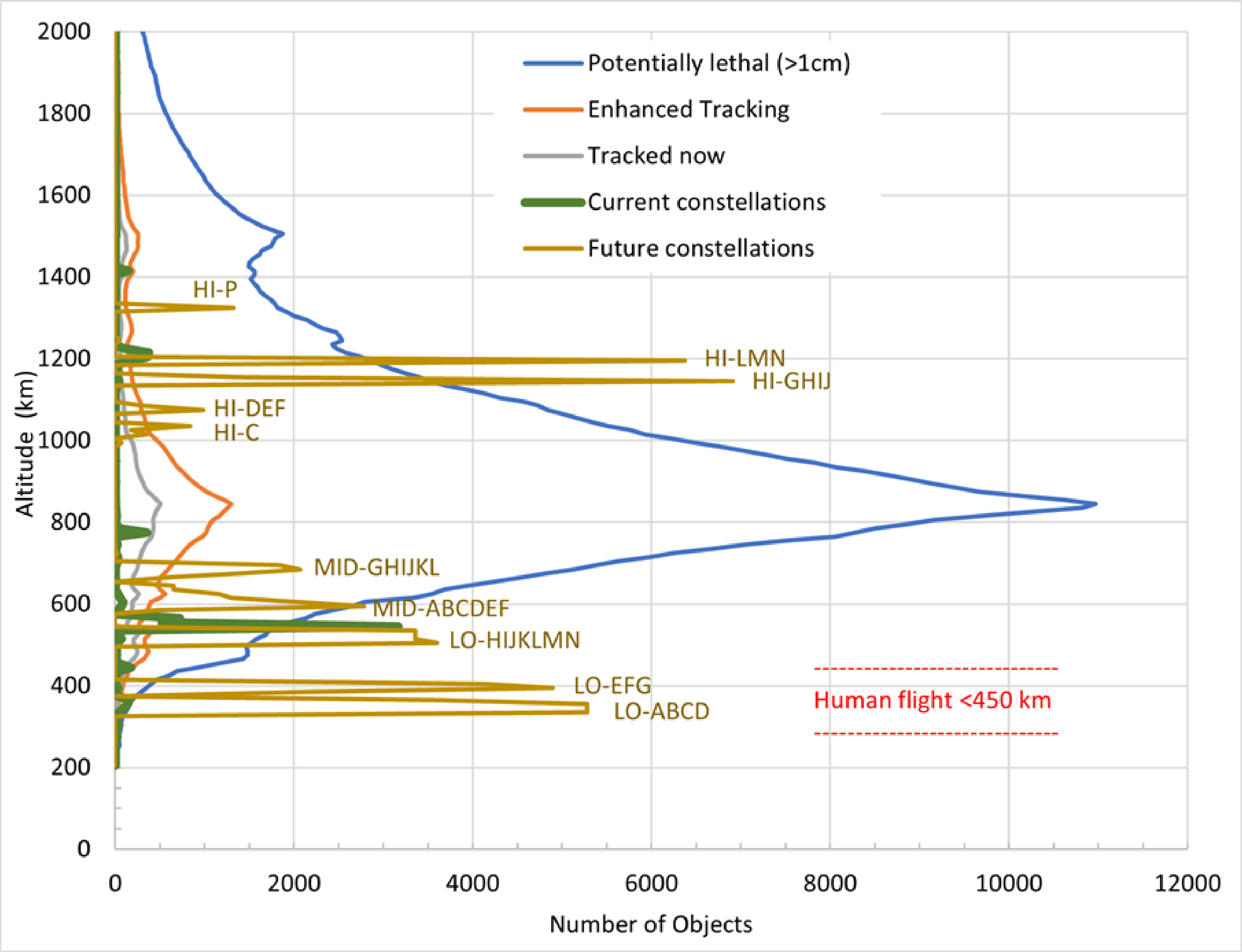
ADEPT Population Model

- Initial population model (IPM)
  - *Unclassified USSPACECOM catalog of resident space objects in LEO*
  - ***SUF** population in LEO*
    - **S**ub-trackable population (represents debris from most historical events)
    - An “**U**nknown” filler population (trackable)
    - **F**Y-1C and Iridium-Cosmos debris

- Future launch model (FLM)
  - *Continuously replenished constellations (CRCs)*
    - Hypothetical constellations representing existing Iridium, ORBCOMM, Globalstar, Starlink, and OneWeb
  - *Remaining non-CRC objects (NONCRCs)*
  - ***Large LEO Constellations (LLC)***
  - *FLM operational lifetimes vary by constellation shell from ~5-12 years*
    - PMD at End-of-Life places disposed satellites in ~5-year reentry trajectory

- “Background” = IPM + NONCRCs

Population Model Large LEO Constellations (LLC)



LLC Constellation Characteristics

LLC Name	Number	Alt (km)	Inc (deg)	Mass (kg)	Start Year
LO-A	5280	340	53	286	2025
LO-B	5280	345	46	286	2025
LO-C	5280	350	38	286	2025
LO-D	3600	360	96.9	286	2025
LO-E	2240	380	97	150	2026
LO-F	4896	390	30	150	2026
LO-G	4148	400	55	150	2026
LO-H	3600	508	55	350	2024
LO-I	3360	525	53	286	2025
LO-J	3360	530	43	286	2025
LO-K	3360	535	33	286	2025
LO-L	784	590	33	250	2023
LO-M	480	590	85	350	2024
LO-N	2000	600	50	350	2024
MID-A	144	604	148	286	2025
MID-B	1296	610	42	250	2023
MID-C	324	614	115.7	286	2025
MID-D	1156	630	51.9	250	2023
MID-E	652	640	72	250	2023
MID-F	650	650	80	250	2023
MID-G	600	670	82.9	800	2027
MID-H	1400	680	54.9	800	2027
MID-I	504	690	98	150	2026
MID-J	1564	690	37.9	800	2027
MID-K	40	700	0	150	2026
MID-L	1792	700	55	150	2026
MID-M	18	724	0	800	2026
HI-A	72	1000	99.5	700	2022
HI-B	351	1015	98.98	700	2022
HI-C	180	1023.5	50	800	2026
HI-D	840	1040	37.2	800	2027
HI-E	980	1070	48.8	800	2027
HI-F	286	1085	79.6	800	2027
HI-G	1728	1145	30	650	2024
HI-H	1728	1145	40	650	2024
HI-I	1728	1145	50	650	2024
HI-J	1728	1145	60	650	2024
HI-K	1440	1150	40	850	2026
HI-L	2304	1200	40	150	2025
HI-M	2304	1200	55	150	2025
HI-N	1764	1200	87.8	150	2025
HI-O	45	1248	37.4	700	2022
HI-P	1320	1325	50.88	700	2022

LLCs are representative of a wide range of proposed future constellations in high-traffic LEO orbit regimes

Scenarios

How to project the environment in LEO 270 times

- Scenario is defined by a combination of FCM traffic and PMD success rate
  - *27 traffic cases defined in table*
  - *10 PMD success rates each from 50% - 100%*

- Scenario list constructed to span full range of possible traffic, and explore varying configurations
  - *baseline scenario closely matches today's traffic level, replenished for the simulation duration*
  - *background excludes current LLCs, but includes all other traffic*
  - *no-llc is a future where LLCs do not replenish*
  - *fcm-all includes ALL possible LLCs*
  - *intermediate-X scenarios model even distribution between baseline and fcm-all*
  - *lo-leo and hi-leo scenarios explore effects of imbalance in LEO altitude distribution*
  - *fcm-llcX scenarios mimic real-world potential future LLCs*

- These scenarios represent a subset of cases that can be extracted from the study results

Scenario Name	LLCs Included	Total # FCM Sats	Low LEO (<600 km)	Mid LEO (600-800 km)	High LEO (>800 km)
background	baseline minus some current systems	0	0	0	0
no-llc	baseline – with no replenishment	0	0	0	0
baseline	LO-I + HI-N	5124	3360	0	1764
intermediate-0	baseline + 2 LO	11844	10080	0	1764
intermediate-1	baseline + 4 LO, 2 MID, 3 HI	19135	12800	3060	3275
intermediate-2	baseline + 4 LO, 1 HI	23172	18960	144	4068
intermediate-3	baseline + 6 LO, 5 MID, 4 HI	31211	20772	5000	5439
intermediate-4	baseline + 6 LO, 6 MID, 5 HI	31995	19840	5820	6335
intermediate-5	baseline + 5 LO, 4 MID, 6 HI	32083	20068	5852	6163
intermediate-6	baseline + 6 LO, 1 MID, 2 HI	36360	29520	468	6372
intermediate-7	baseline + 8 LO, 7 MID, 7 HI	44163	28720	5964	9479
intermediate-8	baseline + 9 LO, 6 MID, 7 HI	50206	34384	6222	9600
intermediate-9	baseline + 10 LO, 8 MID, 10 HI	55415	35492	7416	12507
intermediate-10	baseline + 9 LO, 8 MID, 10 HI	62760	40804	6386	15570
intermediate-11	baseline + 10 LO, 13 MID, 14 HI	69038	39828	12140	17070
fcm-all	all proposed LLCs	76606	45668	12140	18798
lo-leo	baseline + all LO and MID LLCs	59572	45668	12140	1764
lo-leo-half	baseline + ½ of all LO & MID LLCs	36392	27812	6816	1764
hi-leo	baseline + all HI LLCs	28878	10080	0	18798
hi-leo-half	baseline + ½ of all HI LLCs	20672	10080	0	10592
fcm-llc1	baseline + LO-ABCDJK + MID-AC	31752	29520	468	1764
fcm-llc2	baseline + HI-LM	9732	3360	0	6372
fcm-llc3	baseline + LO-L + MID-BDEF	9662	4144	3754	1764
fcm-llc4	baseline + LO-EFG + MID-KL	18744	14644	2336	1764
fcm-llc5	baseline + HI-ABQR	6912	3360	0	3552
fcm-llc6	baseline + MID-GHJ + HI-DEF	10794	3360	3564	3870
fcm-llc7	baseline + LO-HMN + HI-GHIJ	18116	9440	0	8676

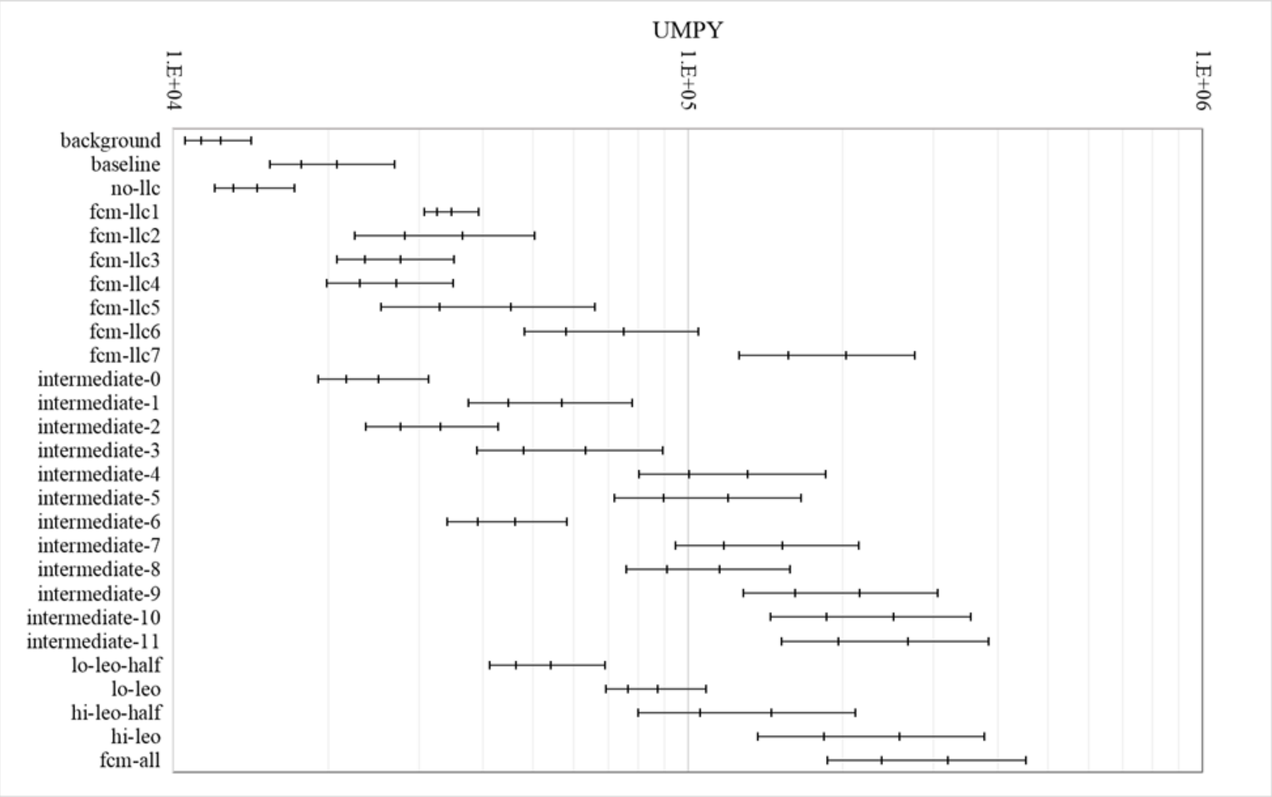
Undisposed Mass Per Year (UMPY)

Parameterizing Constellation Level of Activity

- Wide range of "Level of Activity" is modeled by numerous combinations of FCM scenarios
- Single parameter to characterize effect of constellation activity
- Considered various parameters such as sat count, altitude, size, mass, area, etc.
- Define Undisposed Mass Per Year (UMPY):

$$\boldsymbol{UMPY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{sats}} m_i \frac{life_i}{t_{sim}}}$$

$t_{sim} = 100$ *years*
$n_{sats} =$ *# sats left on orbit*
$m_i =$ *satellites mass [kg]*
$life_i =$ *satellite lifetime [years]*

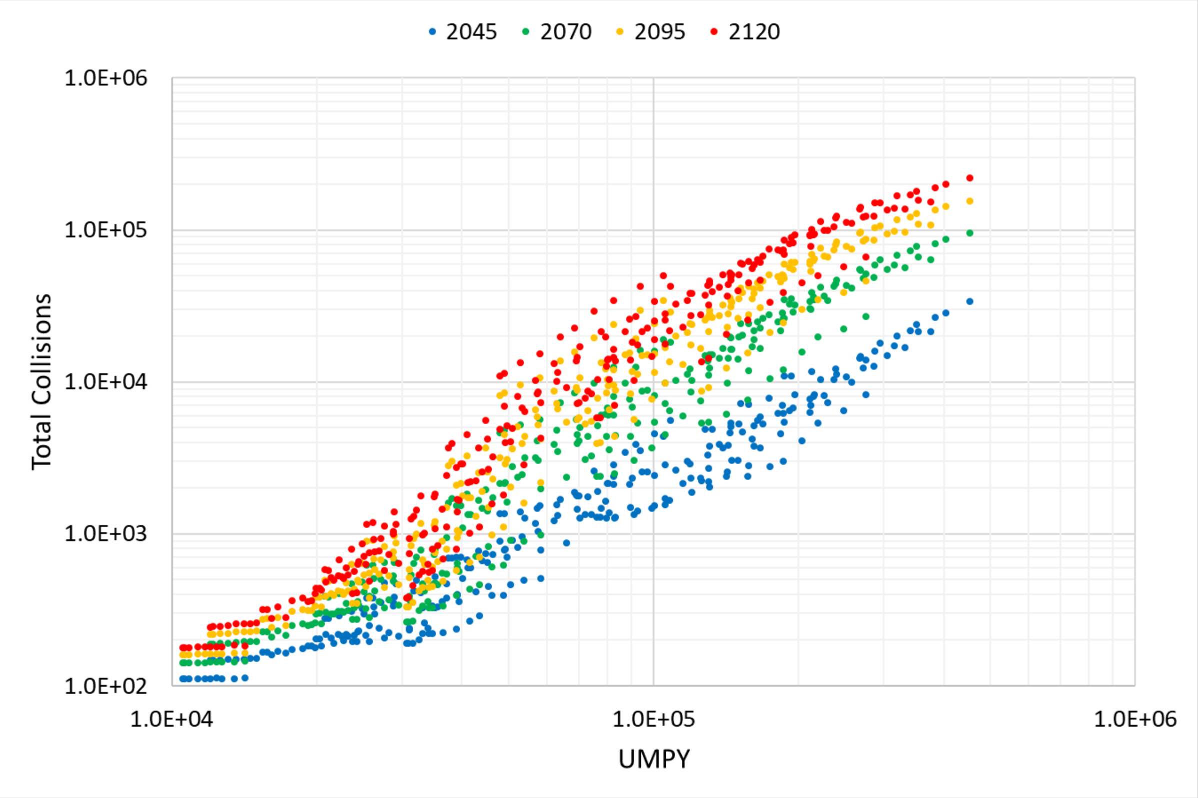


- Figure shows UMPY ranges for scenarios
  - *Compare all "apples-to-apples" with UMPY*
  - *Range hashes are PMD% = 100, 90, 75, and 50*
  - *UMPY values fall with range of ~10,000 – 500,000 kg/yr*

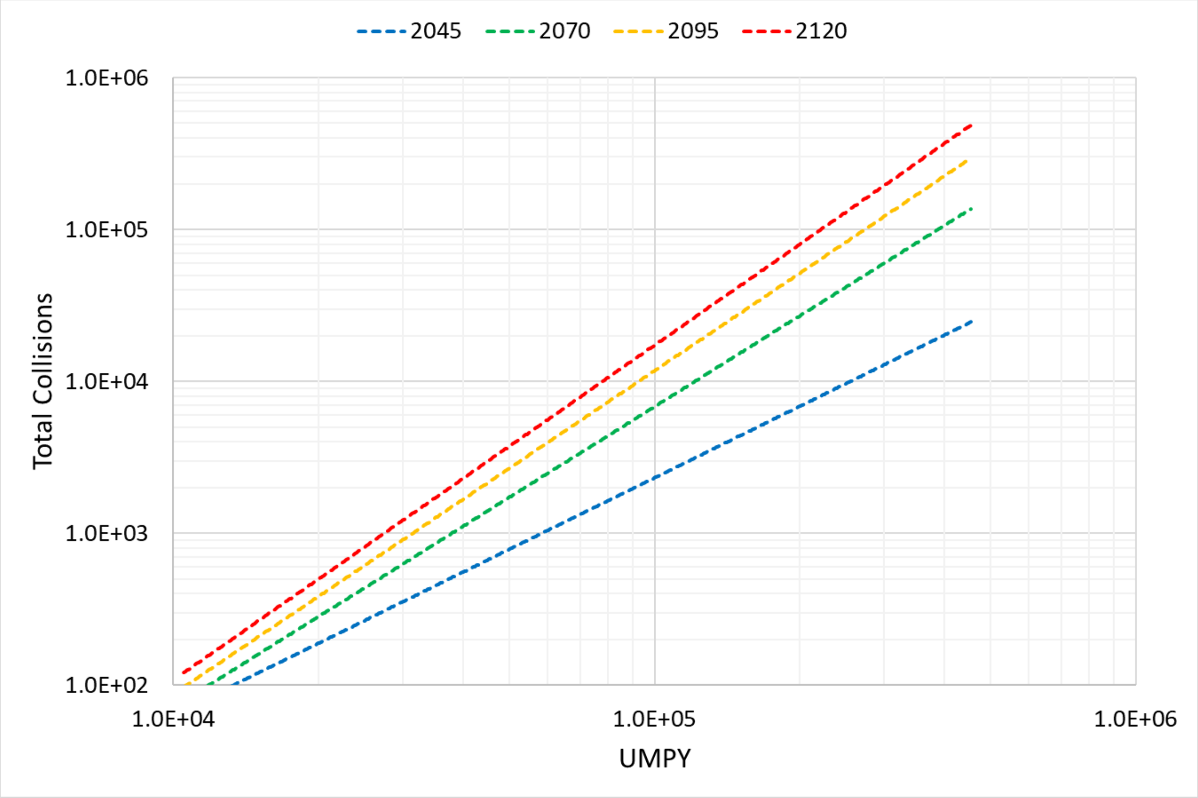
Collision Risk

All-Scenario Comparison vs. UMPY

- Cumulative collisions at 25-, 50-, 75-, and 100-year snapshots shown for all 270 scenarios vs. UMPY
- Data plotted on log-log scale shows power law fit approximates relationship between UMPY and collisions
- High traffic scenarios (high UMPY) exhibit at least ~100 times more collisions than low traffic scenarios
- Increasing slope also indicates compounding long-term effect on collision rate



All Collisions vs. UMPY

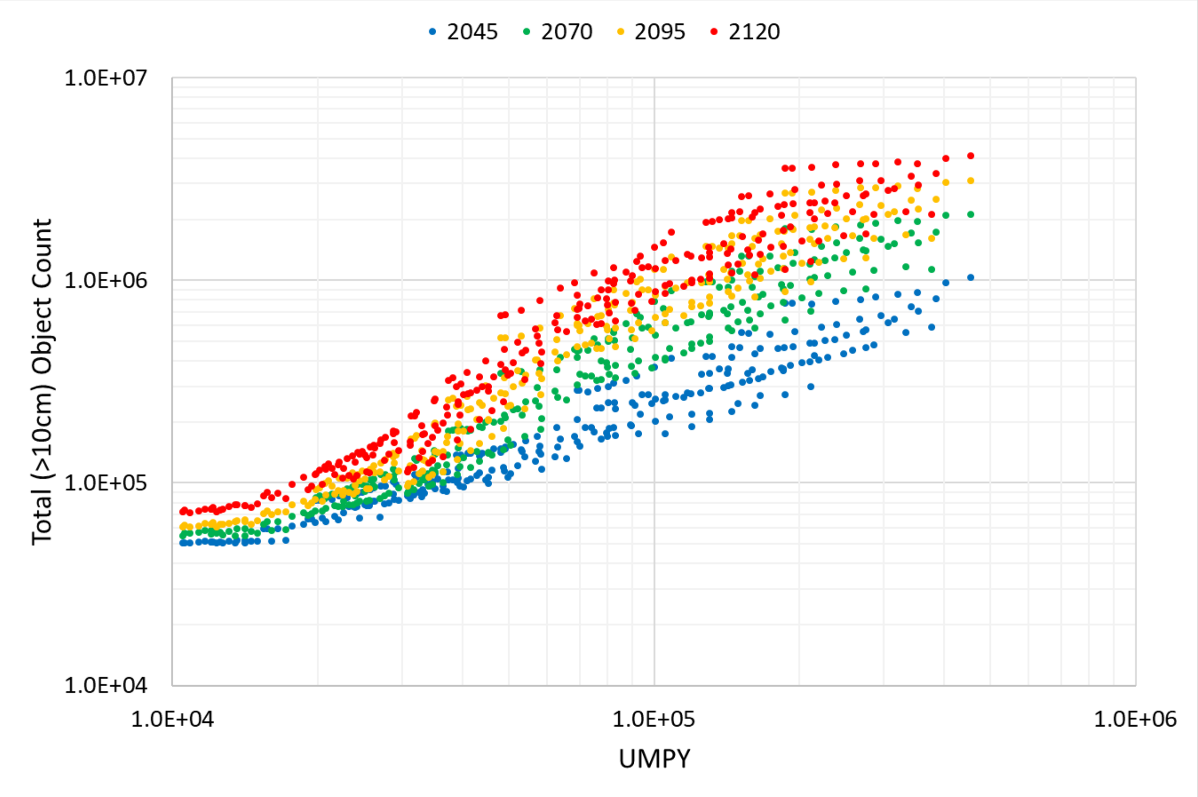


Power Law Curve Fit of All Collisions vs. UMPY

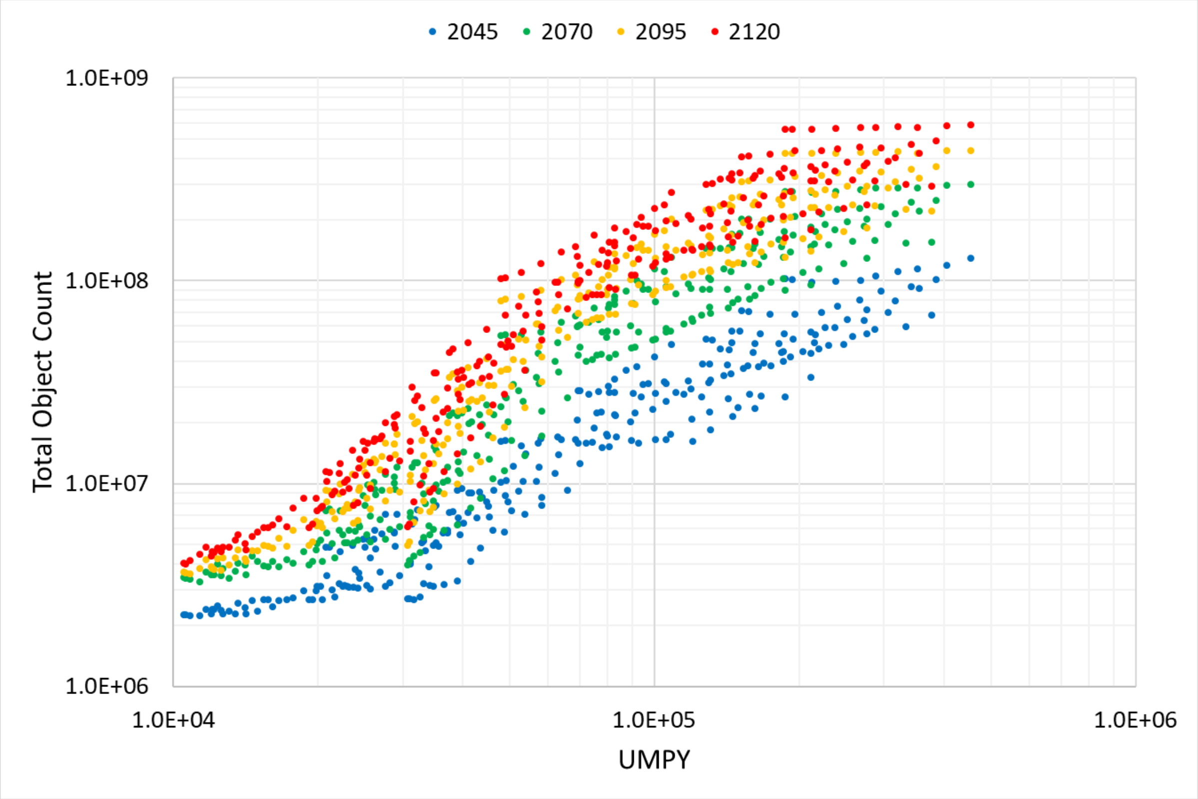
Environment Growth

All-Scenario Comparison vs. UMPY

- Similar figure to collision vs UMPY at same future snapshots for trackable and all object counts
- Trackable object counts remain low at low UMPY, but begin increasing noticeably around UMPY ≈ 40,000
- "Roll-off" at higher UMPY likely indicative of lack of more than the 2 generations of fragmentation debris modeled



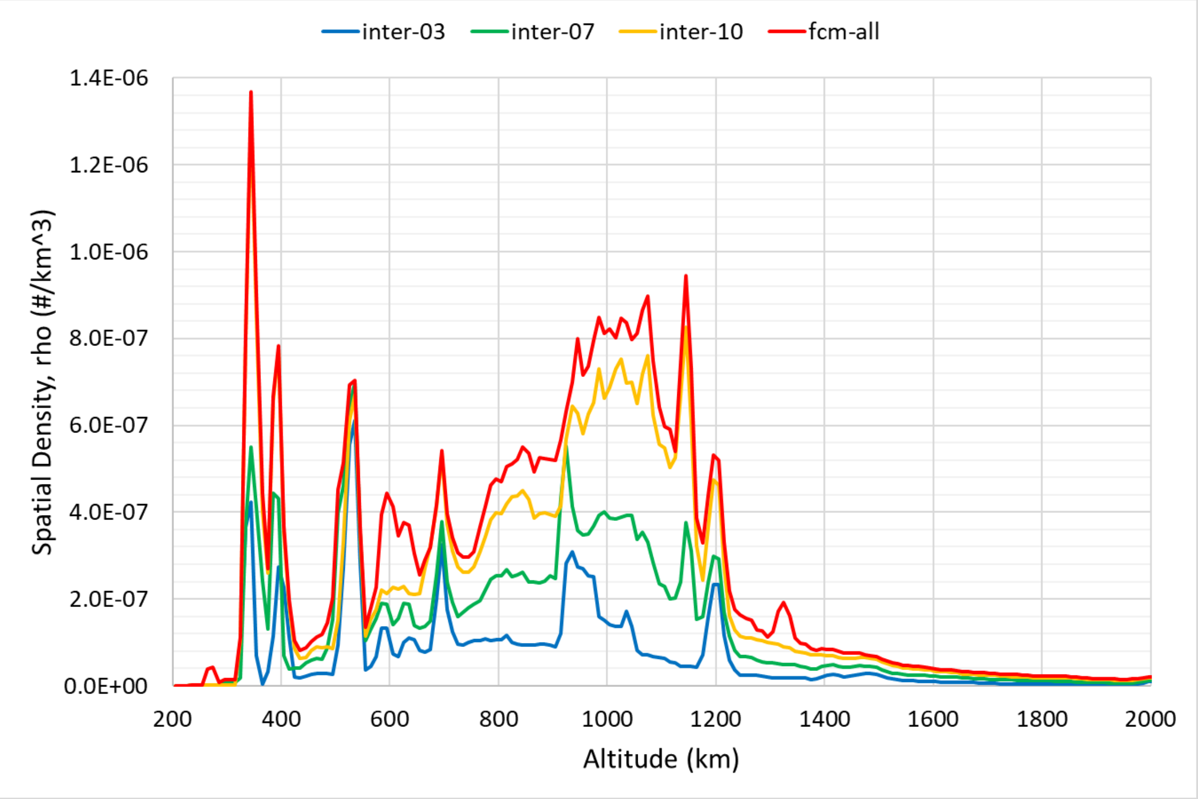
Trackable (>10cm) Object Count vs. UMPY



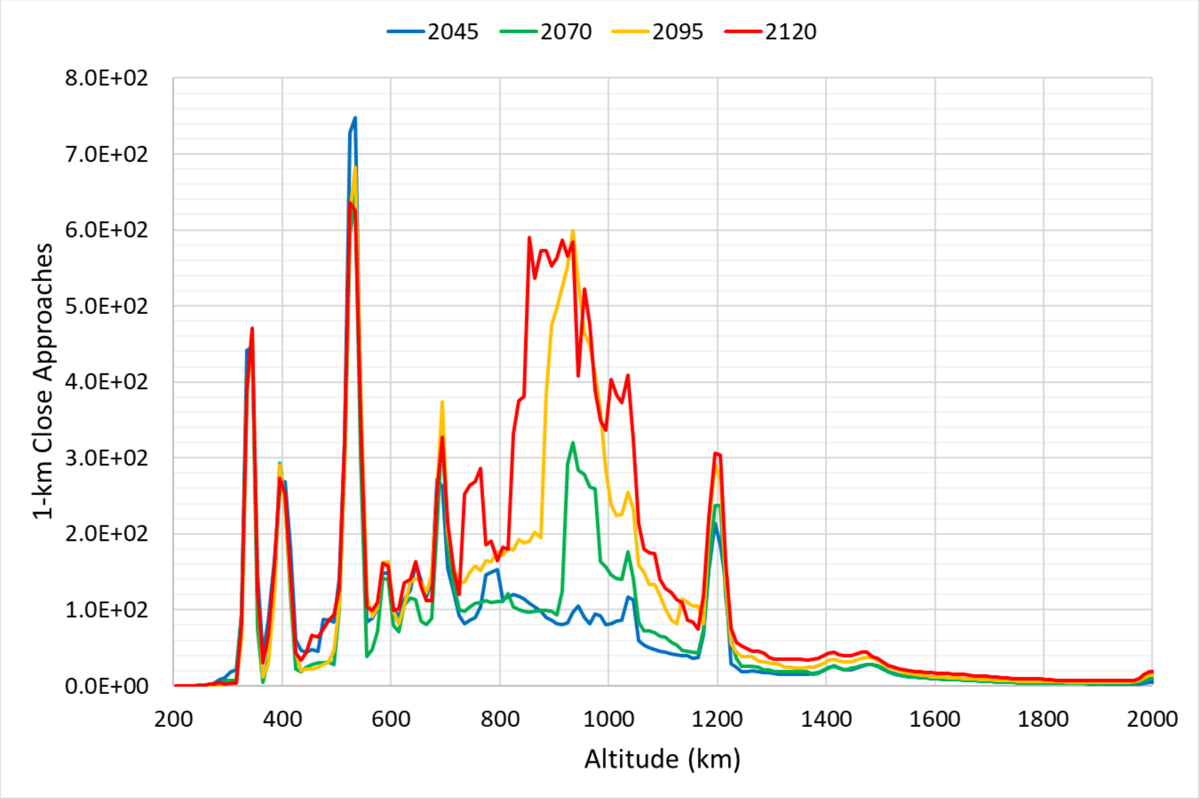
All (>1cm) Object Count vs. UMPY

Close Approaches

- COLA analyzed by proxy using 1-km close approaches between operational satellites and trackable objects
- Spatial density by altitude bin computed based on yearly snapshot of objects in simulation
- Close approach count computed for each altitude bin based on # operational satellites and spatial density
- Examples below for spatial density across various scenarios and for close approach counts in snapshot years

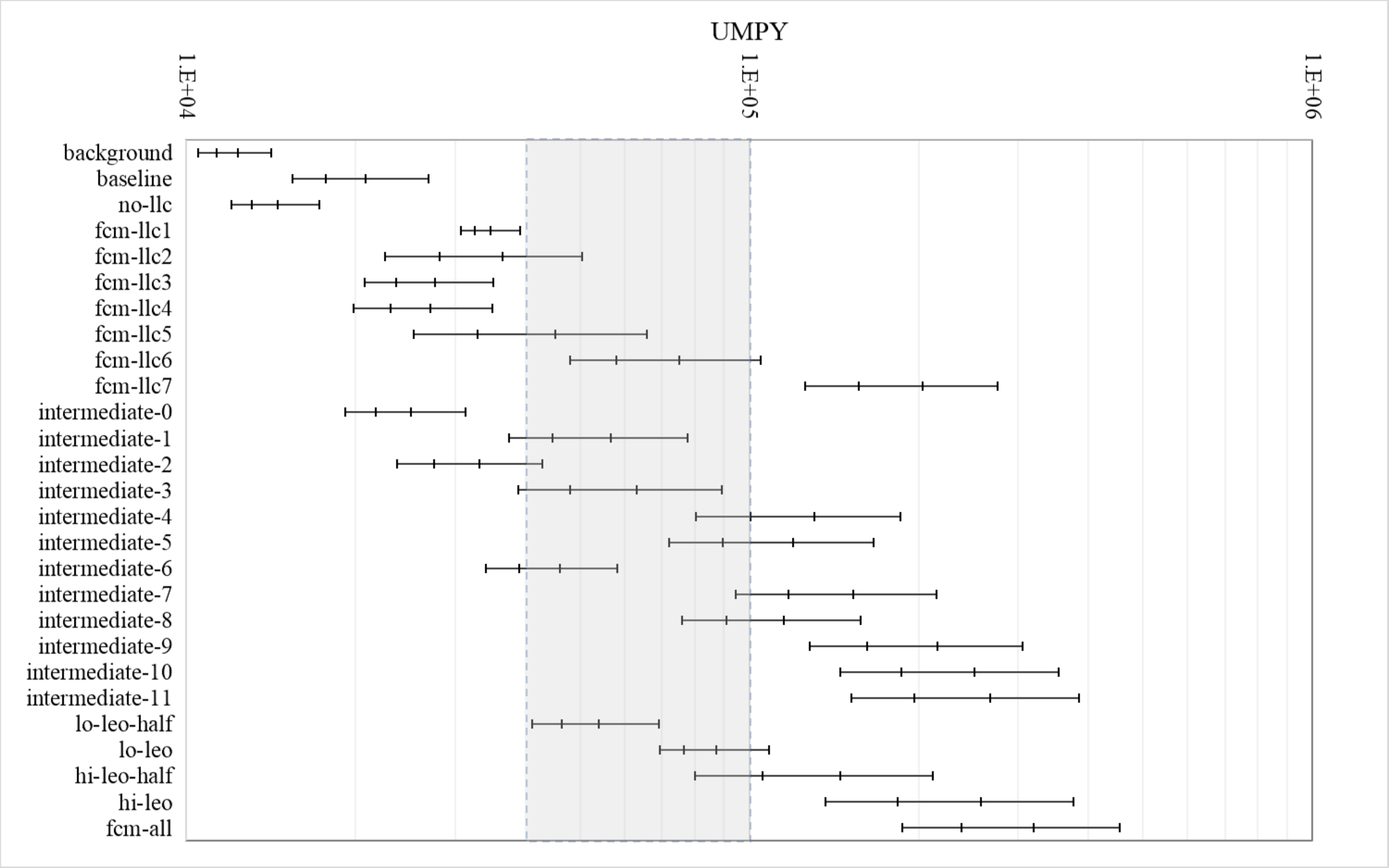


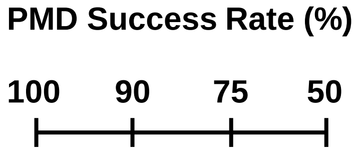
Trackable Object Spatial Density in vs. Altitude in 2070
Varying Scenarios, PMD = 75%



Close Approach Count vs. Altitude
intermediate-3 Scenarios, PMD = 75%

UMPY Sustainability Threshold Range





UMPY region from ~40,000 and ~100,000 kg/yr in gray corresponds where operational effects transition

Conclusions

- The Aerospace-developed ADEPT model provides efficient methods to evaluate the short-term and long-term impact on the space environment for a large number and range of possible future scenarios

- A wide range of scenarios was developed based on proposed future LLC traffic with varying satellite traffic levels, distributions and application of debris mitigation; a subset of results considering a variety of parameters that can affect LEO “usability,” and identify environmental capacity were presented
  - *This range is wide enough to include thresholds of acceptable operational consequences, such as collision rates and environmental growth, and the satellite traffic and corresponding debris mitigation measures needed to remain under those thresholds.*

- Undisposed Mass Per Year (UMPY) used to quantify the level of satellite activity and debris mitigation for all scenarios, and showed good correlation to most operational effect parameters considered

- Results suggest a common region in the tens of thousands of UMPY to maintain a reasonable operating environment by limiting collision counts, population growth, and conjunction frequency over 100 years
  - *Even at 100% PMD, high traffic scenarios that include proposed LLCs would create a difficult operating environment*
  - *The wide range of scenarios provides decisionmakers information needed to determine “acceptable” thresholds*

- The large quantity of data from this analysis enables examination of other factors that can contribute to the state of the future environment, such as active debris removal, or that can affect operations, such as launch collision avoidance window closures. These topics will be addressed in future studies.

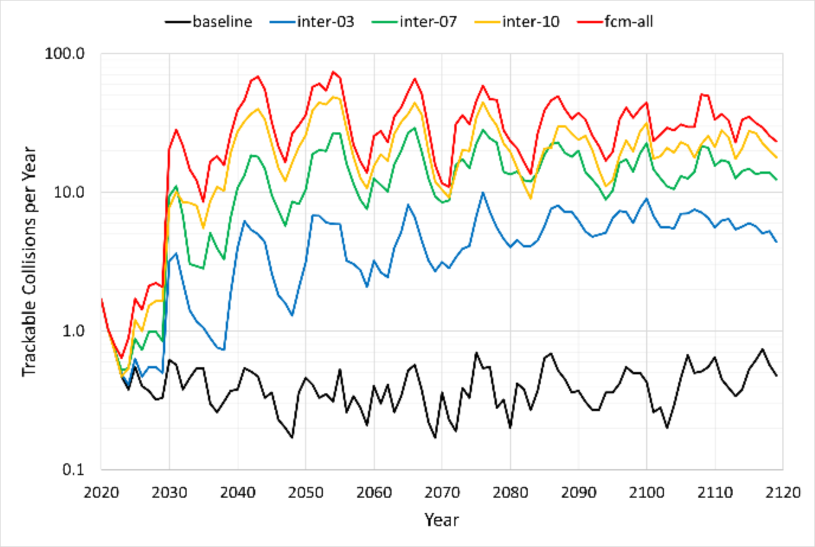
Questions?

The views expressed are those of the authors and do not reflect the official guidance or position of the United States Government, the Department of Defense, United States Air Force, or the United States Space Force.

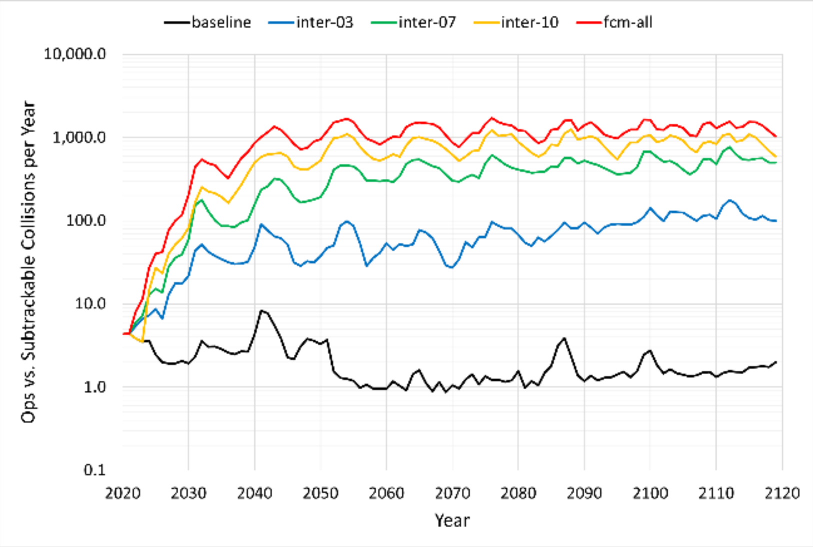
Collision Risk

- Collision categories analyzed
  - ***Trackable vs. Trackable*** *– Two inactive objects, both >10 cm in diameter – Generate most debris*
  - ***Trackable vs. Subtrackable*** *– Two inactive objects, one object <10 cm – Most common collisions, smaller contribution to debris*
  - ***Operational vs. Trackable*** *– Operational satellite vs. inactive object >10 cm – Assume avoided via COLA*
  - ***Operational vs. Subtrackable*** *– Operational satellites vs. inactive object <10 cm – Unavoidable, potentially lethal to operational sat*

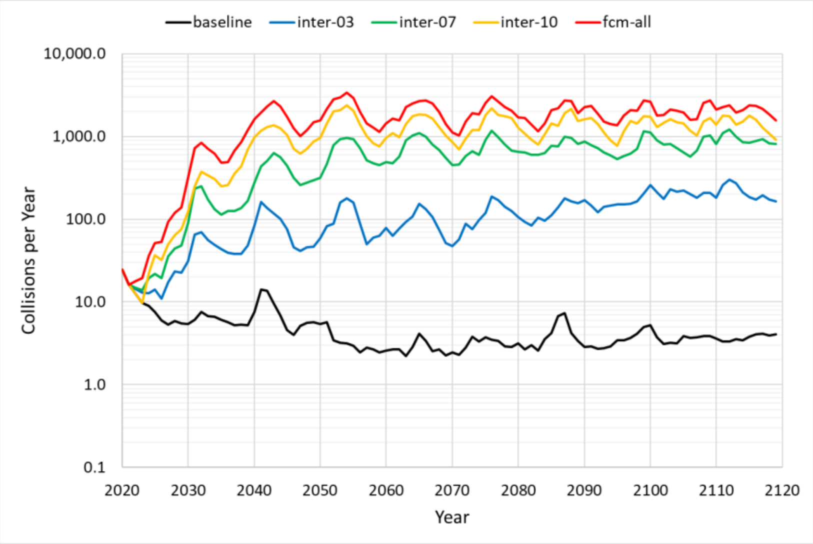
- Average yearly collision counts for various scenarios at PMD = 75% shown below
  - *Baseline scenario collision rate shows steady state of <1 collision per year between trackable objects, consistent with recent history*
  - *Collision rate rapidly increases with increasing traffic, by multiple orders of magnitude in the highest traffic scenarios*
  - *Ops vs. Subtrackable make up significant portion of all collisions in every scenario**



Trackable vs. Trackable Collisions



Operational vs. Sub-Trackable Collisions*

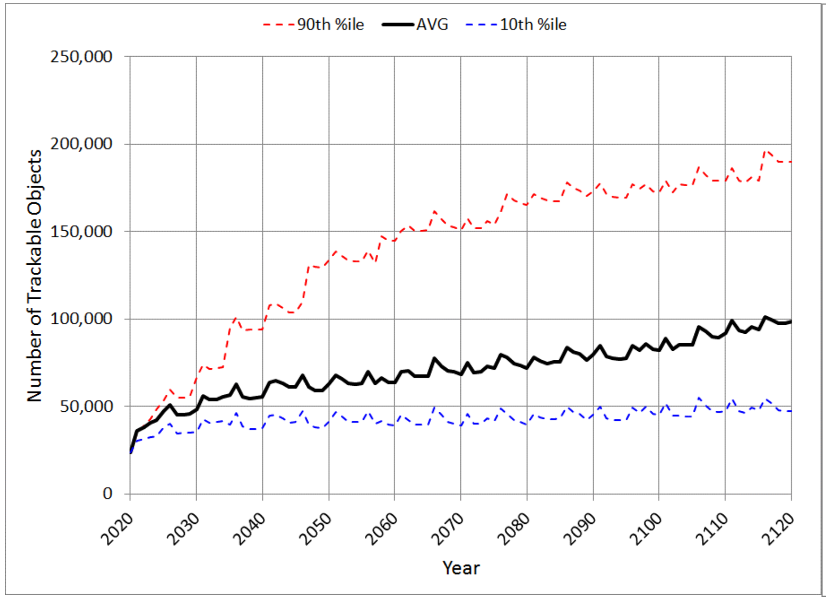


All Collisions

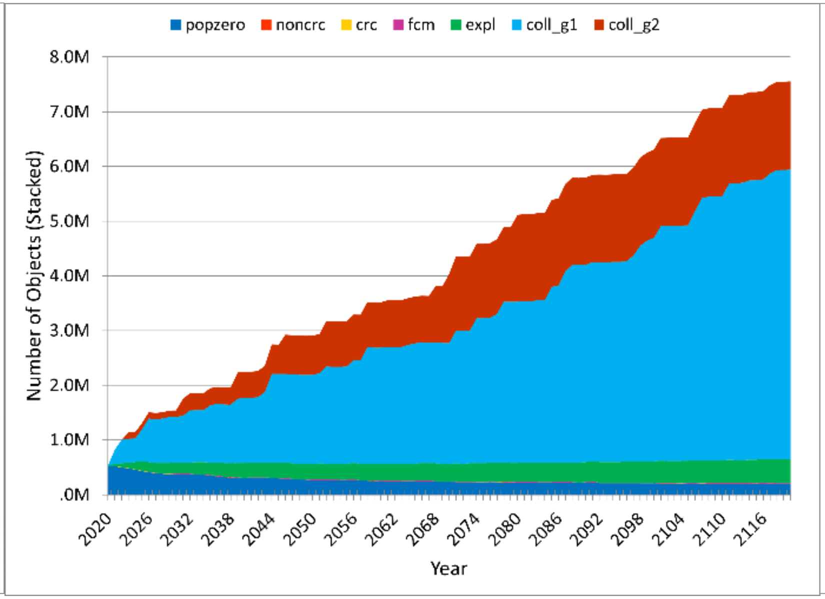
*Rate of modeled collisions with subtrackable objects is higher than reality

Environment Growth

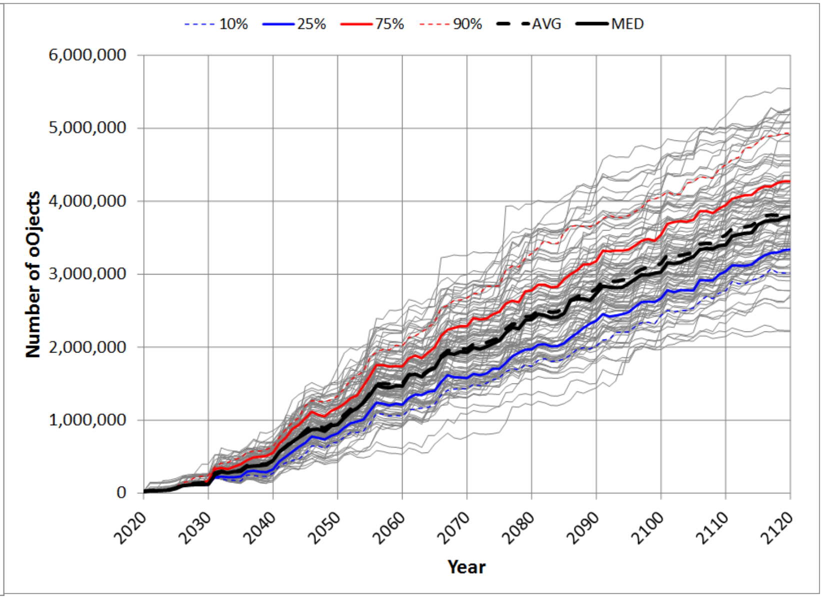
- Increasing collision rates lead to growth in LEO environment object count
- Left shows slow but steady growth in trackable objects in the Baseline scenario at PMD = 90%
- Center shows stack chart of all simulated object (>1cm) for same scenario with 2 generations of collisions
  - *Multiple generations of collision fragments help show effect of “feedback loop” of fragments causing more collisions*
- Right shows other end of the traffic extreme, with all FCM LLCs modeled, and worse PMD
  - *All 100 Monte Carlo runs displayed in gray and statistical bounds in red and blue, to indicate statistical uncertainty*
  - *Slow, steady growth is replaced by unrelenting, significant growth over the simulation duration*



Baseline PMD 90% Trackable Objects



Baseline PMD 90% All Objects

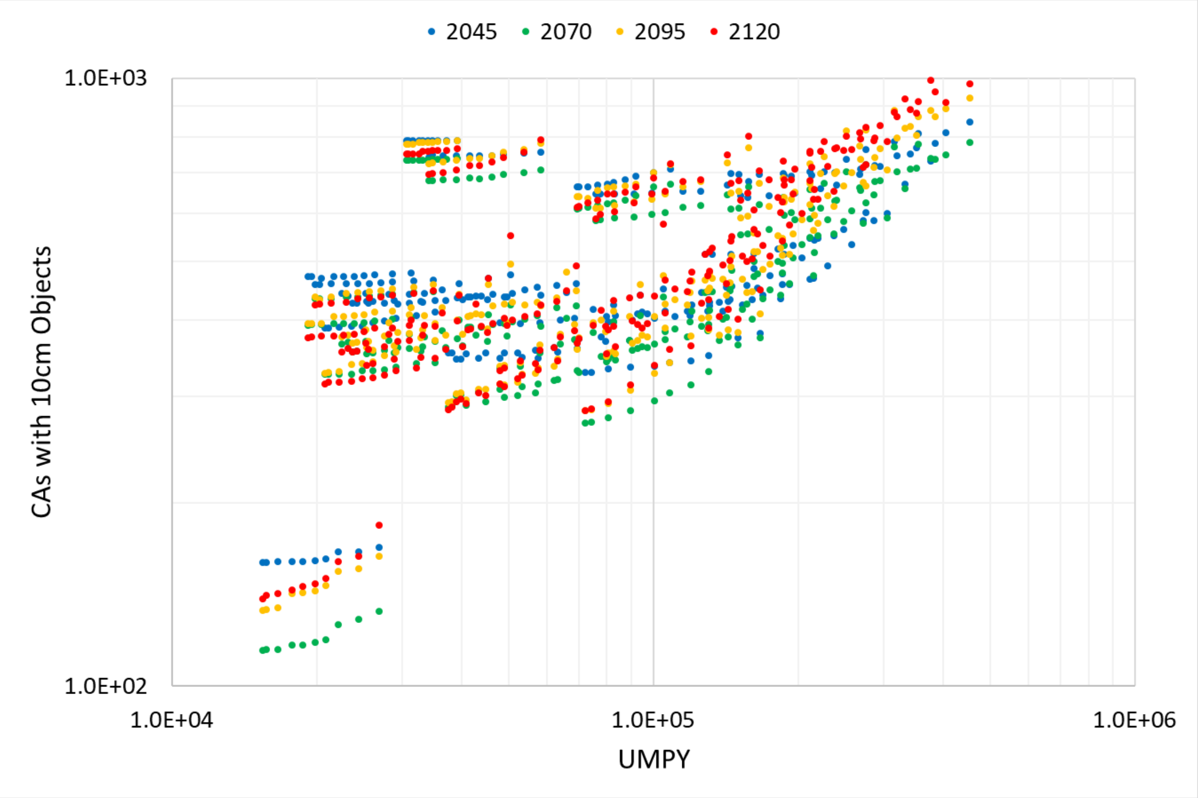


FCM-ALL PMD 75% Trackable Objects

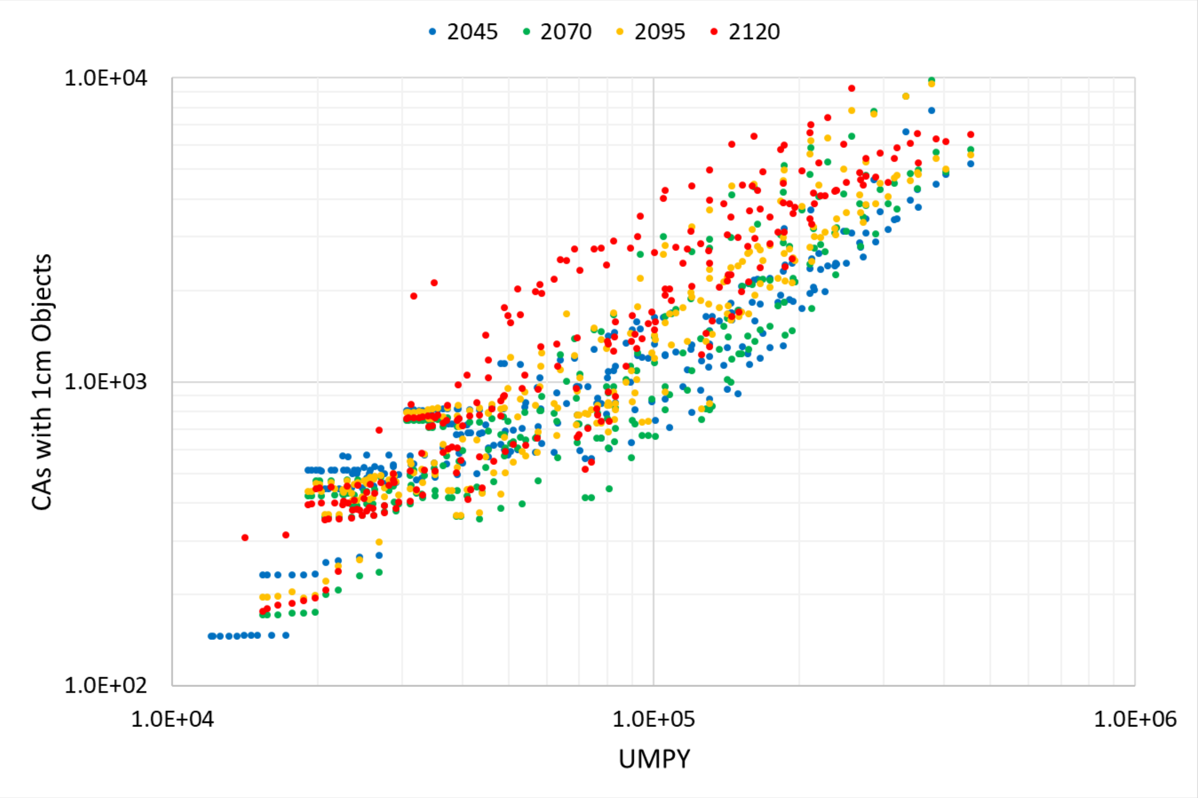
Close Approaches

All-Scenario Comparison vs. UMPY

- Close approach count vs. UMPY correlation is not as good as other metrics, likely due to LLC colocation
  - *Most relevant for trackable objects (>10 cm), which is dominated by other operational and disposed satellites*
- Improved tracking capabilities would mean close approaches with >1 cm objects would also translate to COLA actions
  - *Correlation to UMPY is better here, likely because small objects now dominate the count and are typically spread more across LEO*



Trackable (>10cm) Close Approach Count vs. UMPY



All Object (>1cm) Close Approach Count vs. UMPY