ADEPT as an Analysis Framework for Space Environment Sustainability Indices

Greg Henning
The Aerospace Corporation

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Introduction

Motivation

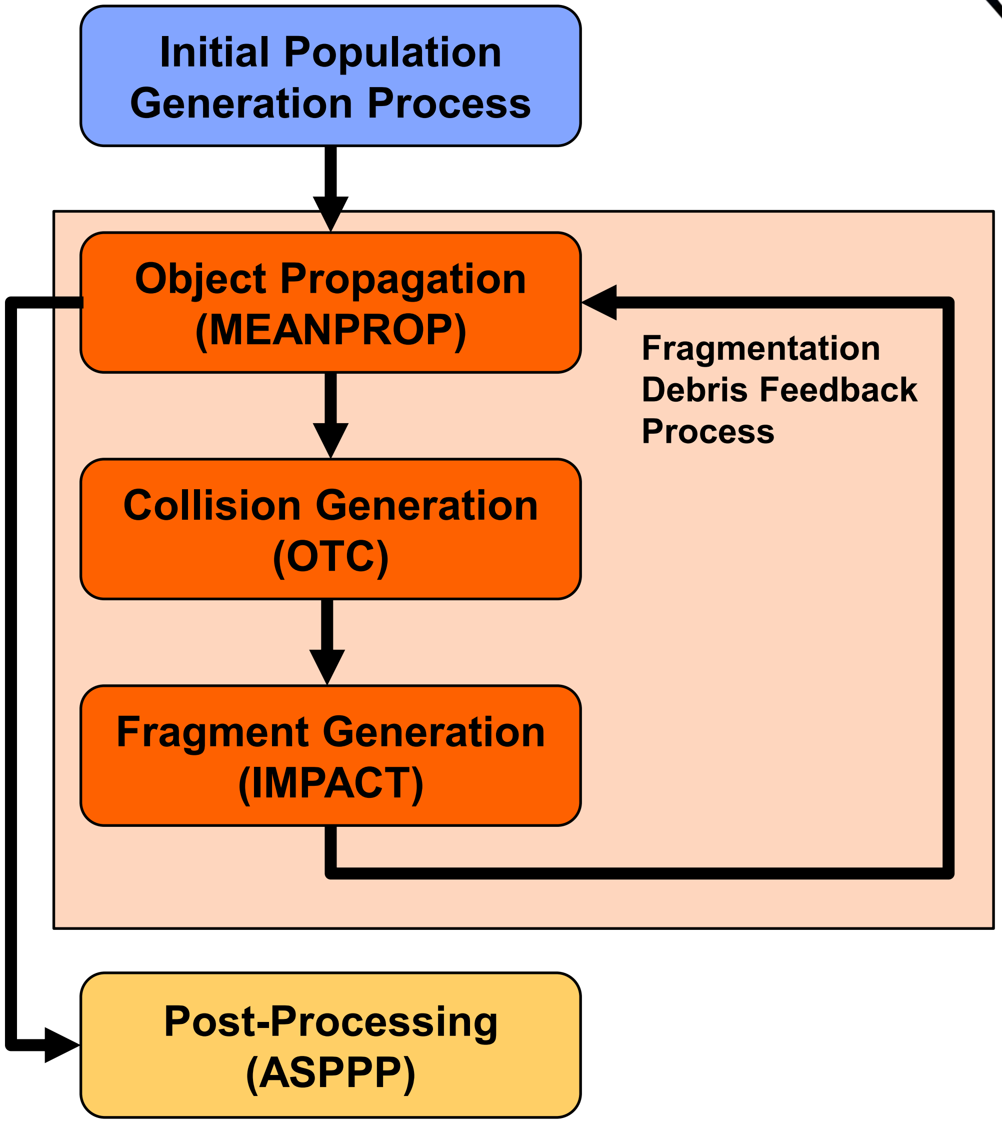
- Multiple formulations exist to quantify the environmental impact of future space systems
- Uncontrolled Mass per Year (UMPY) developed to characterize and compare the results of future environment simulations
  - Strongly correlated to population growth, collision rates, conjunction frequencies

Purpose

- Walk through the process of developing an environmental index using UMPY
- Examine other indices using insights from the design process

Aerospace Debris Environment Projection Tool (ADEPT)

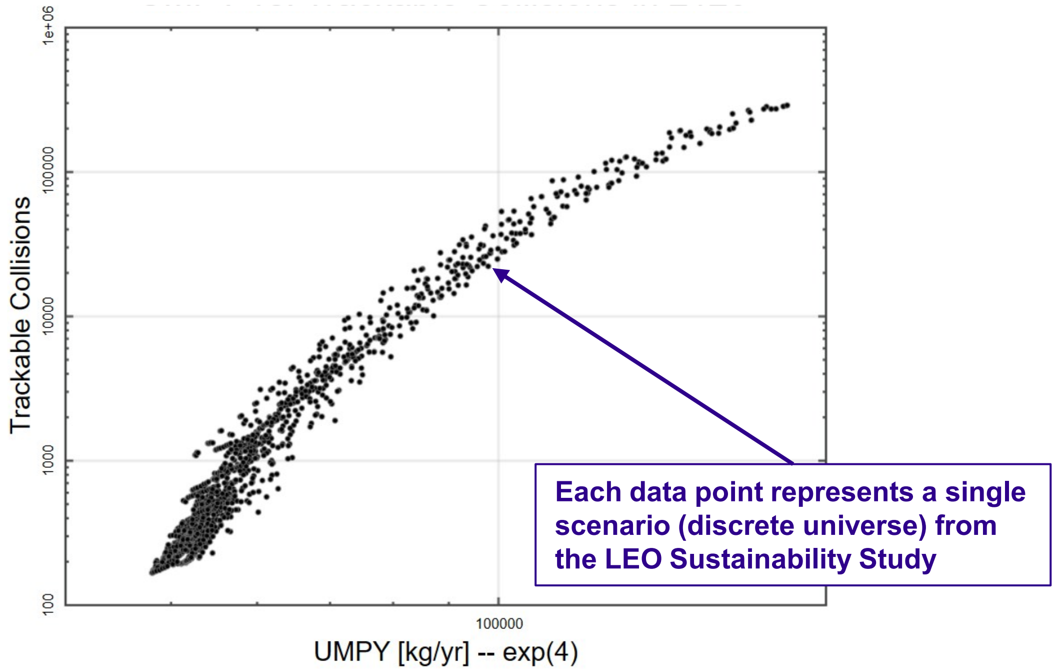
- Models future debris environment based on space traffic and debris mitigation practices
- Used to determine the effects of operational behaviors on the environment
- Debris fragments from collisions are produced through a feedback process
  - Feedback loop enables studying multiple generations of collisions and fragments



Uncontrolled Mass Per Year (UMPY)

Plotting the multiverse

- **Single parameter accounts for the rate of uncontrolled mass left on orbit**
- **Correlates "level of activity" to operational effects**
  - Rate of on-orbit collisions over time
  - Debris fragment count over time
  - Change in operational satellite conjunction/COLA rates
  - Change in satellite loss rate due to small debris collisions
- **Metric can compare relative differences between scenarios**
- **Exponential formula uses lifetime as proxy for nonlinear altitude effects**



"Trackable Collisions" = Collisions between two objects both >10cm

$$UMPY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{objs}} m_i \left[\frac{e^{X\left(\frac{life_i}{t_{sim}}\right)} - 1}{e^{X} - 1} \right]$$

$t_{sim} =$ *study duration [years]*
$n_{objs} =$ *# uncontrolled objects*
$m_i =$ *uncontrolled object mass [kg]*
$life_i =$ *uncontrolled object lifetime [years]*
$X =$ *lifetime scaling exponent**

**$X = 4$ found to be reasonable value for strong correlation

Aerospace Debris Environment Projection Tool (ADEPT)

ADEPT Population Model

- Initial Population Model (IPM)
  - Unclassified USSTRATCOM catalog objects, “unknown” objects, and subtrackable (<10 cm) debris
- Future Launch Model (FLM)
  - Replicates historical launch traffic for different orbital regimes
  - Replenishment of constellation and non-constellation objects
  - Future constellation model (FCM) consisting of Large LEO Constellations (LLCs)

Future Traffic Scenarios

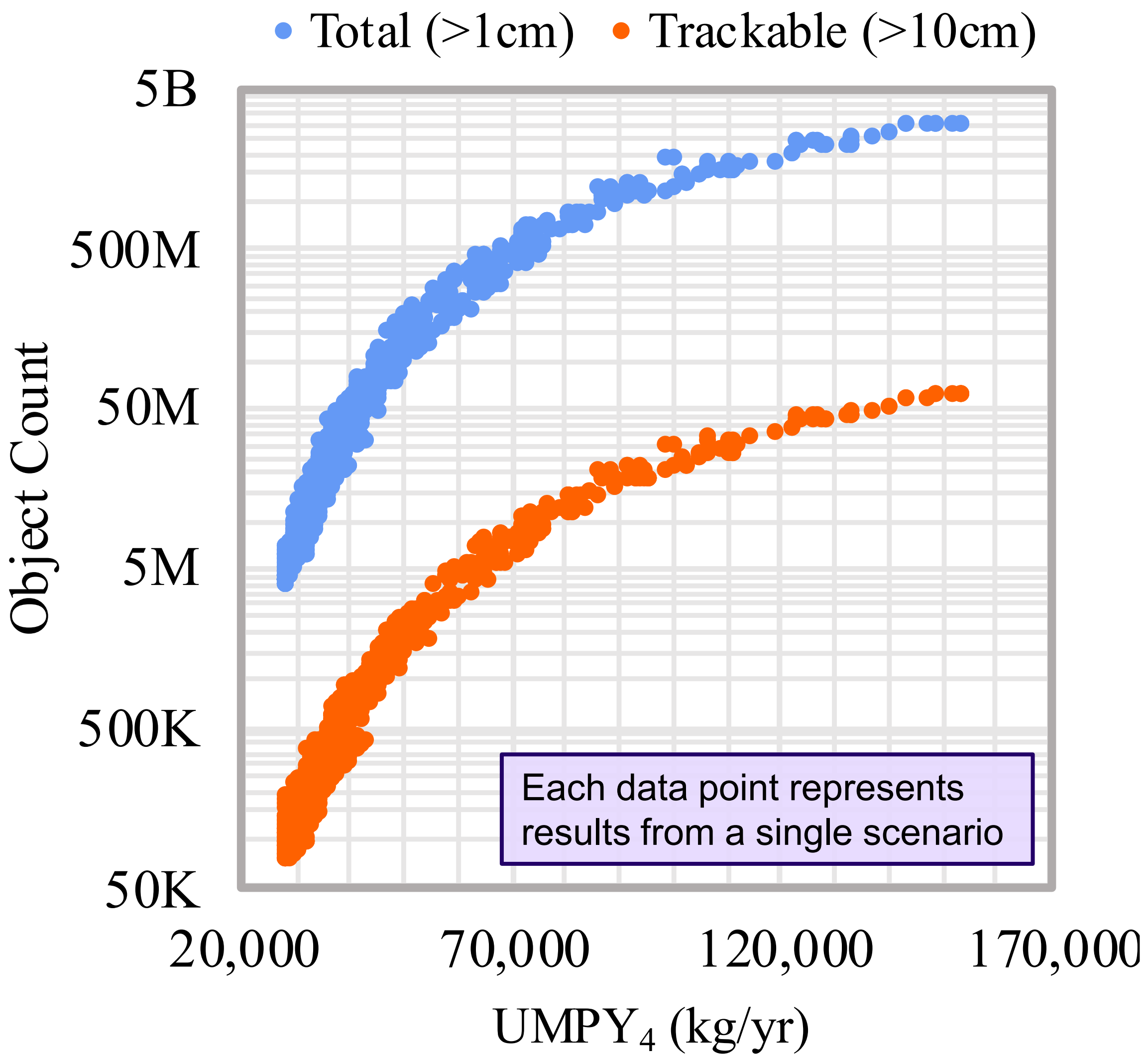
- Scenarios are defined by a combination of FCM traffic, PMD success rates, and debris mitigation methods
- Scenarios represent a subset of the total activity modeled in ADEPT
- Wide range of possible future traffic activity exhibited across over 1,200 total scenarios

Scenario Name	LLCs Included	Total # FCM Sats	Low LEO (<600 km)	Mid LEO (600-800 km)	High LEO (>800 km)
no-new	IPM	0	0	0	0
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, 3 MID, 3 HI	19135	12800	3060	3275
intermediate-2	baseline + 4 LO, 1 MID, 1 HI	23172	18960	144	4068
intermediate-3	baseline + 6 LO, 6 MID, 4 HI	31211	20772	5000	5439
intermediate-4	baseline + 6 LO, 7 MID, 5 HI	31995	19840	5820	6335
intermediate-5	baseline + 5 LO, 5 MID, 6 HI	32083	20068	5852	6163
intermediate-6	baseline + 6 LO, 2 MID, 2 HI	36360	29520	468	6372
intermediate-7	baseline + 8 LO, 8 MID, 7 HI	44163	28720	5964	9479
intermediate-8	baseline + 9 LO, 7 MID, 7 HI	50206	34384	6222	9600
intermediate-9	baseline + 10 LO, 9 MID, 10 HI	55415	35492	7416	12507
intermediate-10	baseline + 9 LO, 9 MID, 10 HI	62760	40804	6386	15570
intermediate-11	baseline + 10 LO, 14 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
proj-0	baseline + 3 LO, 2 MID	15080	10864	2452	1764
proj-1	proj-0 + 4 HI	16868	10864	2452	3552
proj-2	proj-1 + 3 MID, 3 HI	22538	10864	6016	5658
proj-3	proj-2 + 4 LO, 2 MID	42446	30304	6484	5658
proj-4	proj-3 + 2 HI	47054	30304	6484	10266
proj-5	proj-4 + 2 LO, 1 MID	53134	34384	8484	10266
proj-6	proj-5 + 4 HI	60046	34384	8484	17178
proj-7	proj-6 + 2 MID	61348	34384	9786	17178
proj-8	proj-7 + 1 HI	62788	34384	9786	18618
proj-9	proj-8 + 1 MID, 1 HI	62986	34384	9804	18798
proj-10	proj-9 + 3 LO, 3 MID	76606	45668	12140	18798
tiered-deorbit-lo	portions of 6 LO, 3 MID, 6 HI	14147	9868	2304	1975
tiered-deorbit-mid	portions of 9 LO, 5 MID, 10 HI	26769	17800	3779	5190
tiered-deorbit-hi	portions of 13 LO, 10 MID, 12 HI	65210	45556	8558	11096

Uncontrolled Mass Per Year (UMPY)

Overview

- Characterize “level of activity” in a future traffic scenario
  - Allows easy comparison of multiple simulation results
- Average amount of uncontrolled mass left on orbit per year, scaled by a lifetime weighting factor
- Figure displays strong correlation between UMPY and the future number of objects in LEO
  - Previous studies show similar correlations with collision rates and conjunction frequencies
- Can achieve desired environmental outcomes by improving debris mitigation behaviors and targeting UMPY values



Uncontrolled Mass Per Year (UMPY)

Parameter Selection

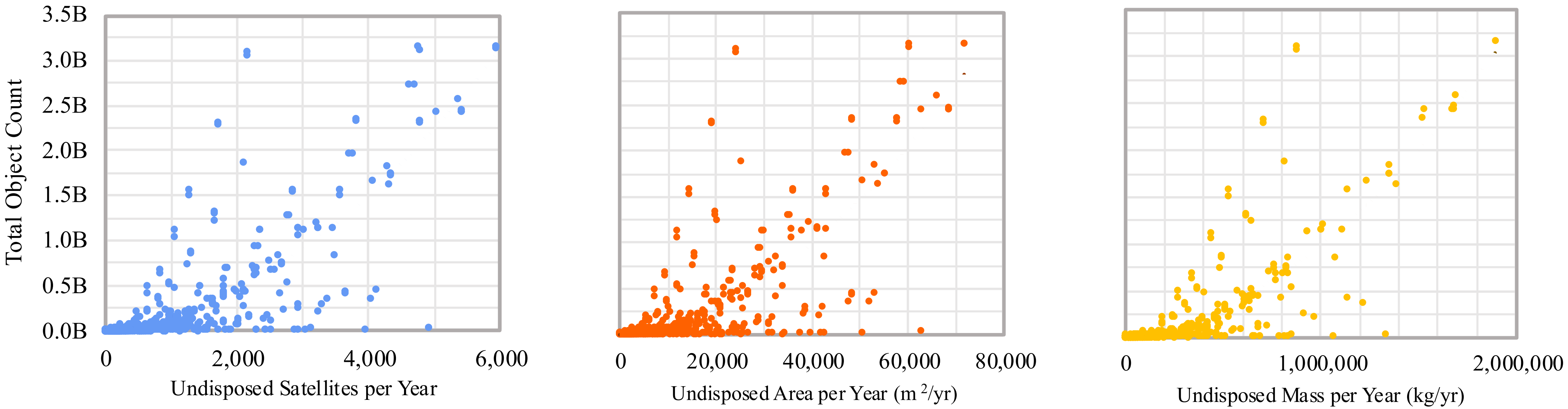
- Selecting a simple parameter that holds the most explanatory power
  - Three parameters: satellite count, area, and mass
- Undisposed Parameter per Year (UPPY) equation used to compare parameter performance
- Weak correlations observed for each parameter
- Non-random variance suggests that some confounding variable exists

$$UPPY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{fail}} P_i$$

t_{sim} = *simulation duration (100 years)*

n_{fail} = *number of undisposed objects*

P_i = *parameter value {count, area, mass}*



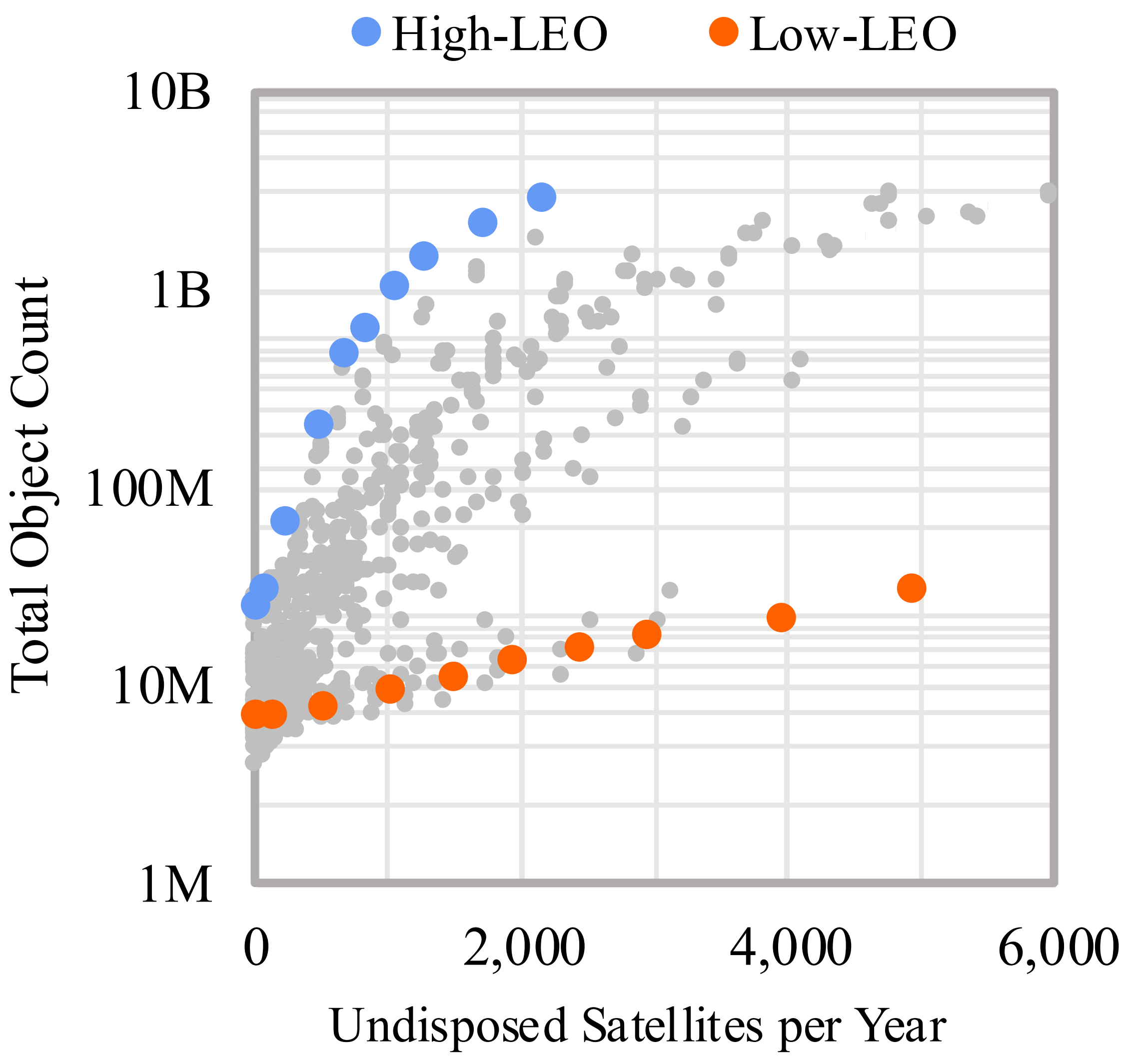
Uncontrolled Mass Per Year (UMPY)

Parameter Selection

- Altitude and lifetime have some unaccounted effect on total object count
- UPPY formulation over-emphasizing contribution of objects in low-LEO relative to objects in high-LEO
- New UPPLY formulation accounts for this effect through object lifetime

$$UPPLY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{fail}} P_i \frac{life_i}{t_{sim}}$$

$life_i$ = object lifetime (years)



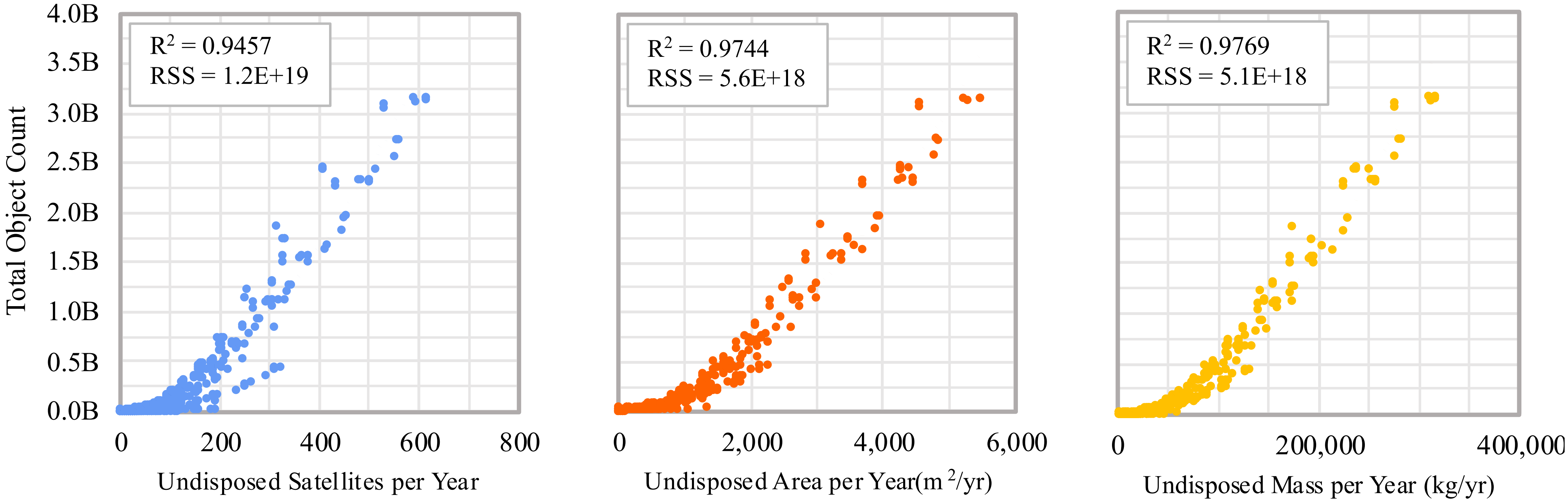
Uncontrolled Mass Per Year (UMPY)

Parameter Selection

- Accounting for object lifetime drastically improves correlations
- Correlations strongest when using the mass parameter
- Similar results seen when examining collision count trends

$$UPPLY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{fail}} P_i \frac{life_i}{t_{sim}}$$

$life_i$ = object lifetime (years)



Uncontrolled Mass Per Year (UMPY)

Lifetime vs Altitude

$$UPPLY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{fail}} P_i \frac{life_i}{t_{sim}}$$

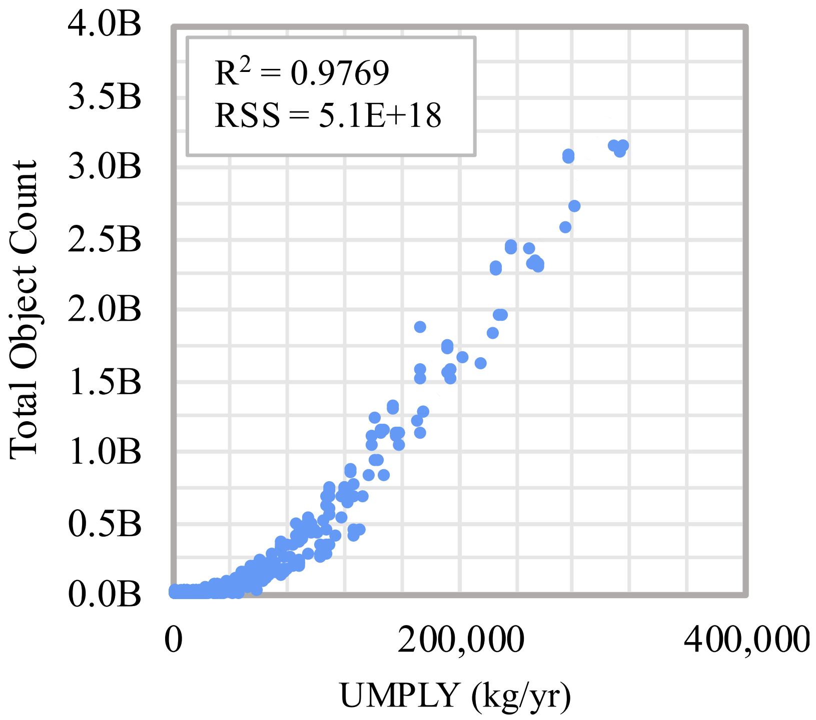
$life_i$ = *object lifetime (years)*

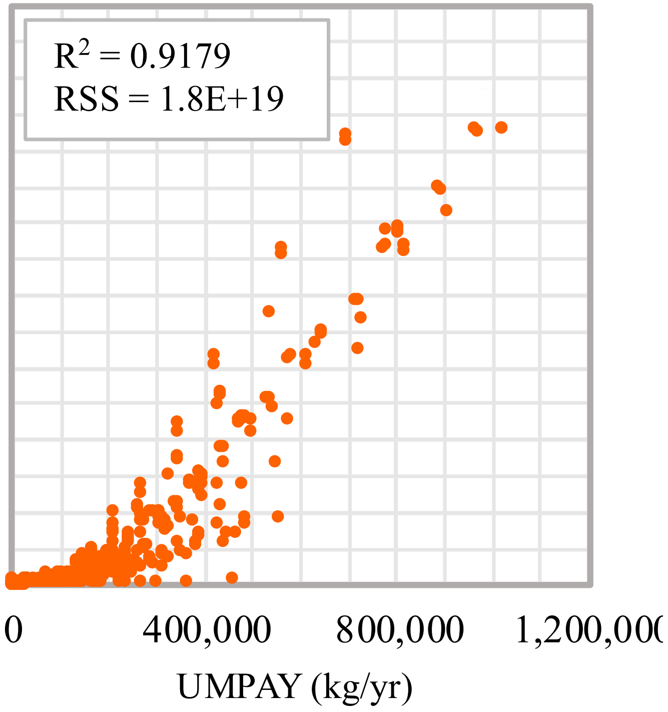
$$UMPAY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{fail}} m_i A_i$$

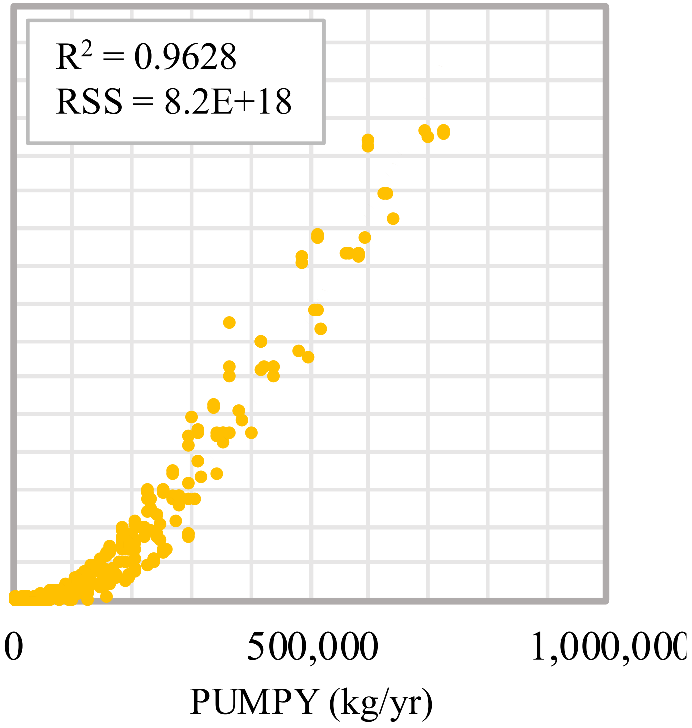
$$A_i = \begin{cases} \left(\dfrac{alt_i - 340km}{310km}\right)^2 & , 340\ km \le alt_i \\ 1 & , 650\ km < alt_i \end{cases}$$

$$PUMPY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{fail}} m_i$$

n_{fail} = *number of undisposed objects above 650 km*







Uncontrolled Mass Per Year (UMPY)

Accounting for All Uncontrolled Objects

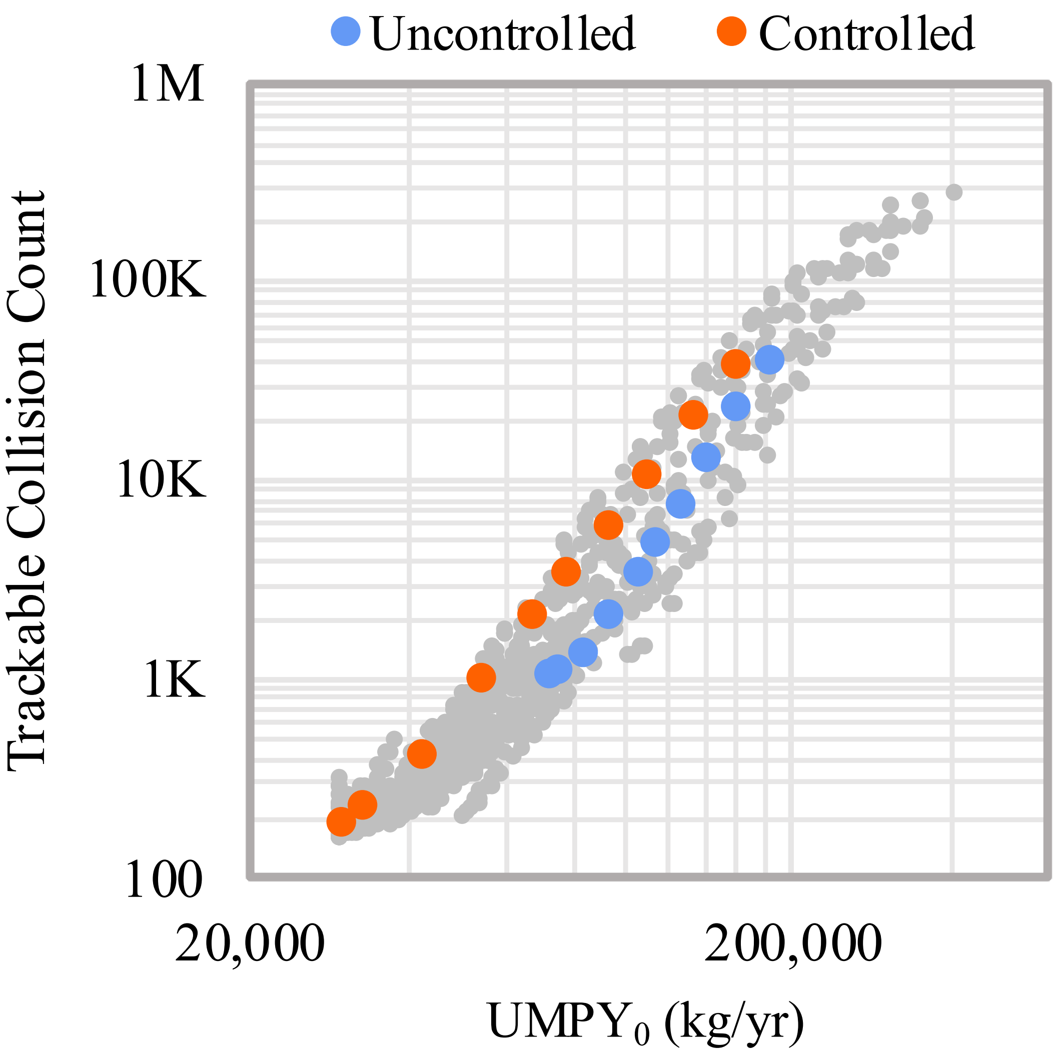
- All uncontrolled objects included in UMPY summation to evaluate effectiveness of various disposal methods

$$UMPY_0 = \frac{1}{t_{sim}} \sum_{i=1}^{n_{obj}} m_i \frac{life_i}{t_{sim}}$$

$n_{obj} = number\ of\ uncontrolled\ objects$

Constellation Disposal Method Comparison Example

Disposal Method	UMPLY (kg/yr)	$UMPY_0$ (kg/yr)
25-Year Uncontrolled Disposal	17.5	96.25
5-Year Uncontrolled Disposal	17.5	33.25
5-Year Control to Reentry	17.5	0



Undisposed Mass Per Year (UMPY)

Non-linear Formulation

- Non-linear scaling factor $\boldsymbol{Y_i}$ used to modify effect of lifetime
- Degree of non-linearity is dependent on $\boldsymbol{X}$
  - $\boldsymbol{UMPY_X \rightarrow UMPY}$ as $\boldsymbol{X \rightarrow 0}$

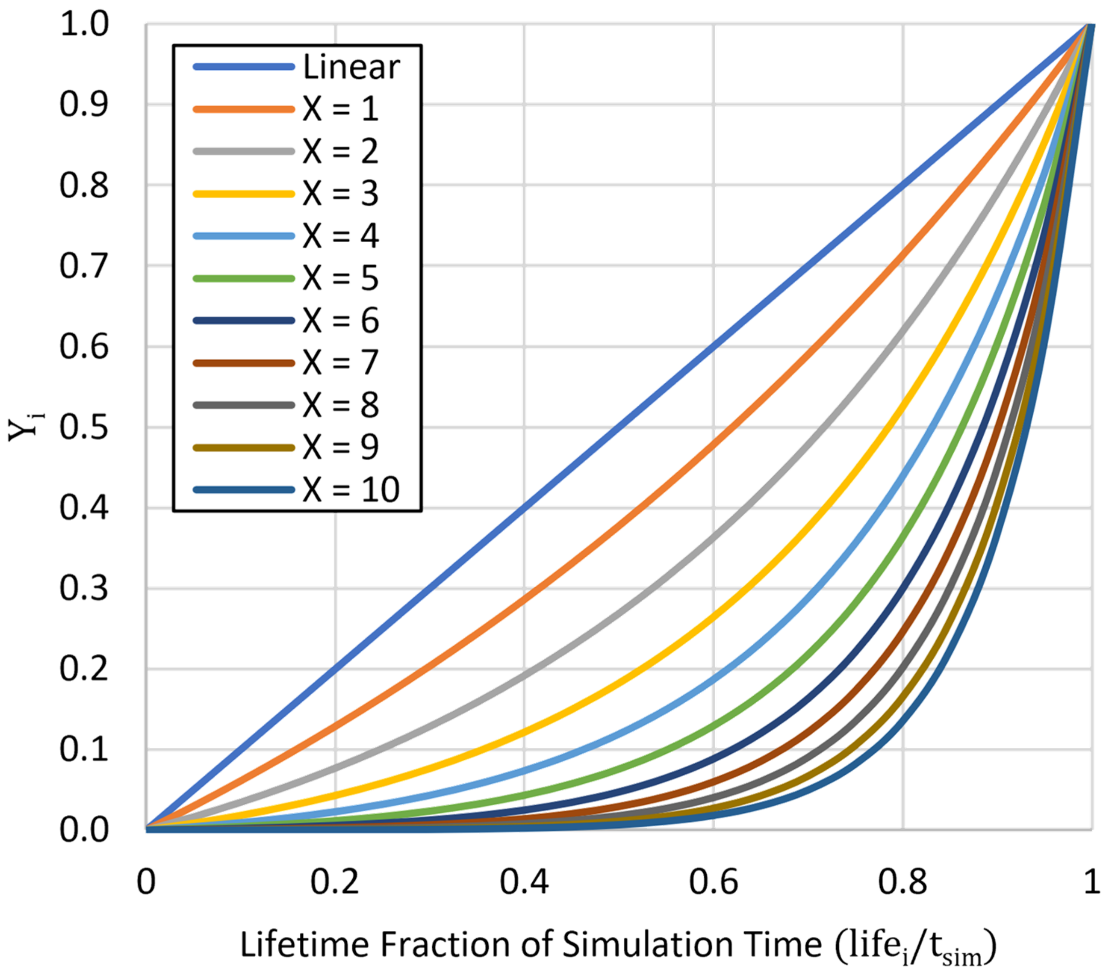
Linear

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

Non-linear

$$UMPY_X = \frac{1}{t_{sim}} \sum_{i=1}^{n_{obj}} m_i Y_i$$

$$Y_i = \frac{e^{X\left(\frac{life_i}{t_{sim}}\right)} - 1}{e^X - 1}, \qquad X > 0$$



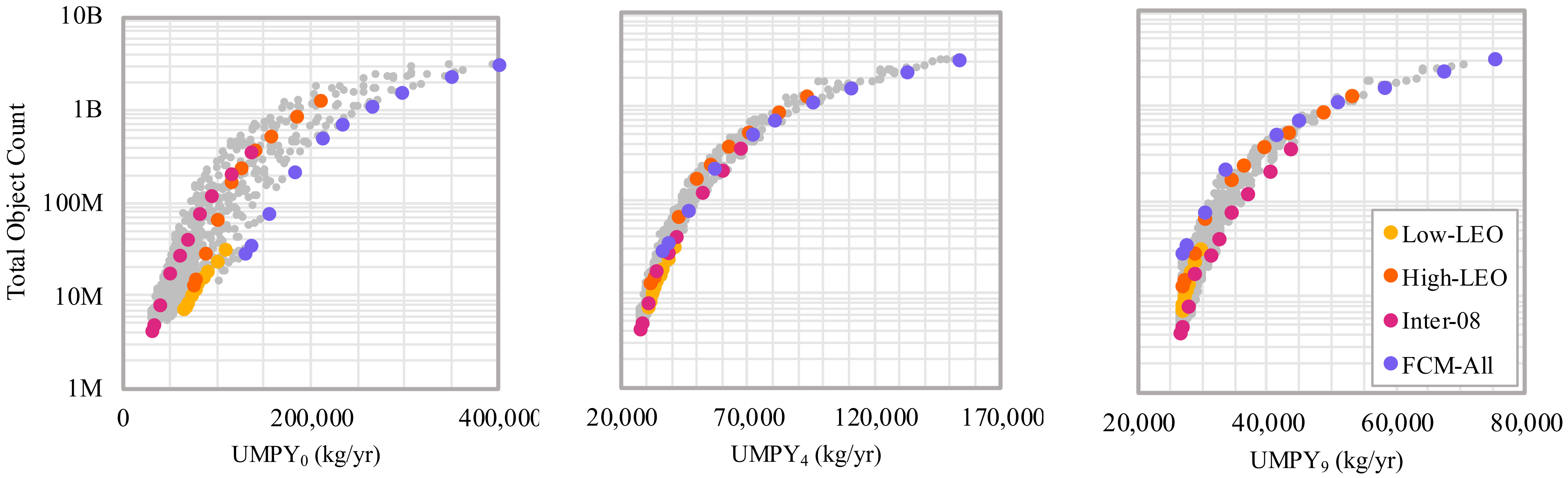
Uncontrolled Mass Per Year (UMPY)

Non-Linear Lifetime Weighting Factor

- Non-linear scaling factor Y_i used to modify effect of lifetime
- Degree of non-linearity is dependent on X
  - $UMPY_X \rightarrow UMPY$ as $X \rightarrow 0$
- Optimal value of X will minimize variance in UMPY trends

$$UMPY_X = \frac{1}{t_{sim}} \sum_{i=1}^{n_{obj}} m_i Y_i$$

$$Y_i = \frac{e^{X\left(\frac{life_i}{t_{sim}}\right)} - 1}{e^X - 1}, \qquad X > 0$$



“Turn the Dial” on Mitigation Methods to reduce UMPY

...and which variable they affect

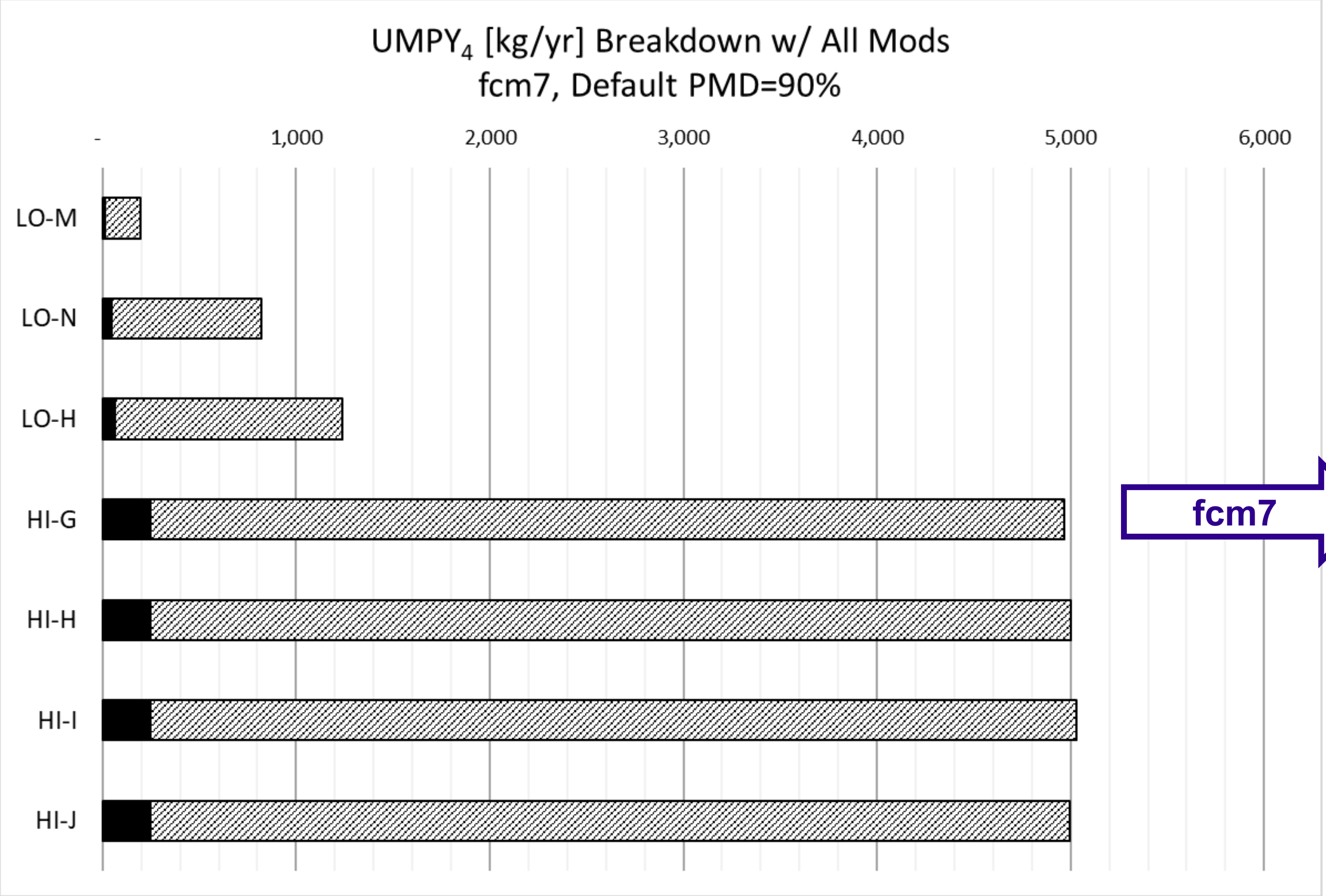
- Improve PMD success rate [$life_i$]
- Reduce disposal lifetime (5 vs. 25 year) [$life_i$]
- Apply Control-to-Reentry (C2R) [n_{objs}]
- Extend satellite lifetime [n_{objs}]
- Rocket body disposal improvement [m_i, n_{objs}]
- **(Future Work)** Active Debris Removal [$life_i$]

$$UMPY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{objs}} m_i \left[\frac{e^{4\left(\frac{life_i}{t_{sim}}\right)} - 1}{e^4 - 1} \right]$$

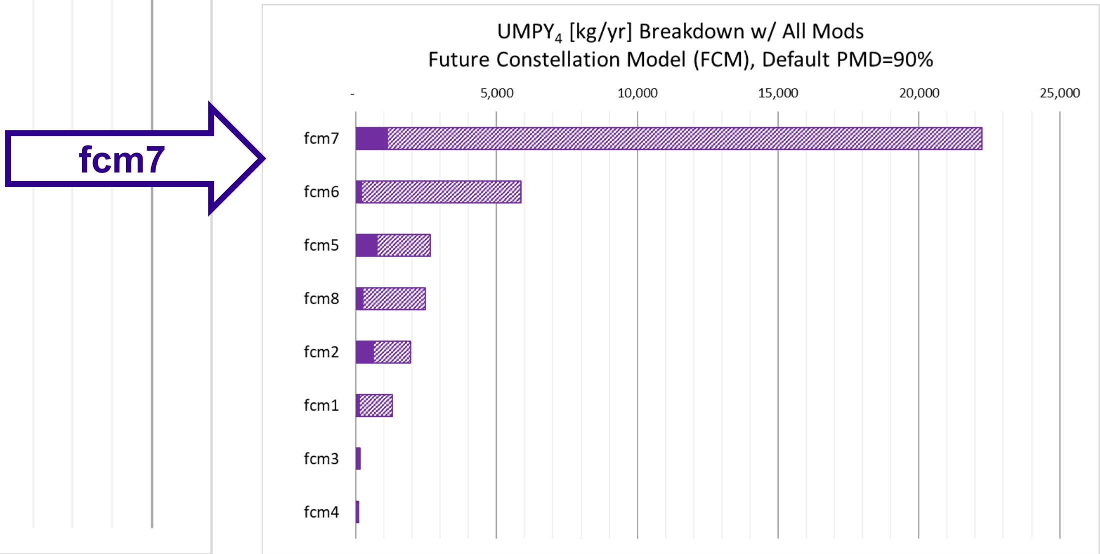
t_{sim} = study duration [years]
n_{objs} = # uncontrolled objects
m_i = uncontrolled object mass [kg]
$life_i$ = uncontrolled object lifetime [years]

Apply Custom Mitigations to All FCM Traffic

Turn all the dials



FCM	PMD %	C2R	R/B Disp	Ops Life
fcm1	90	✓	1.0	1.0
fcm2	99	✓	0.05	1.0
fcm3	90		1.0	1.0
fcm4	90		1.0	1.0
fcm5	95	✓	0.05	1.3
fcm6	95/99	✓/ ✓	0.10/0.05	1.0/1.4
fcm7	95/99	✓/ ✓	0.05/0.005	1.0/2.0
fcm8	99	✓	0.70	1.0

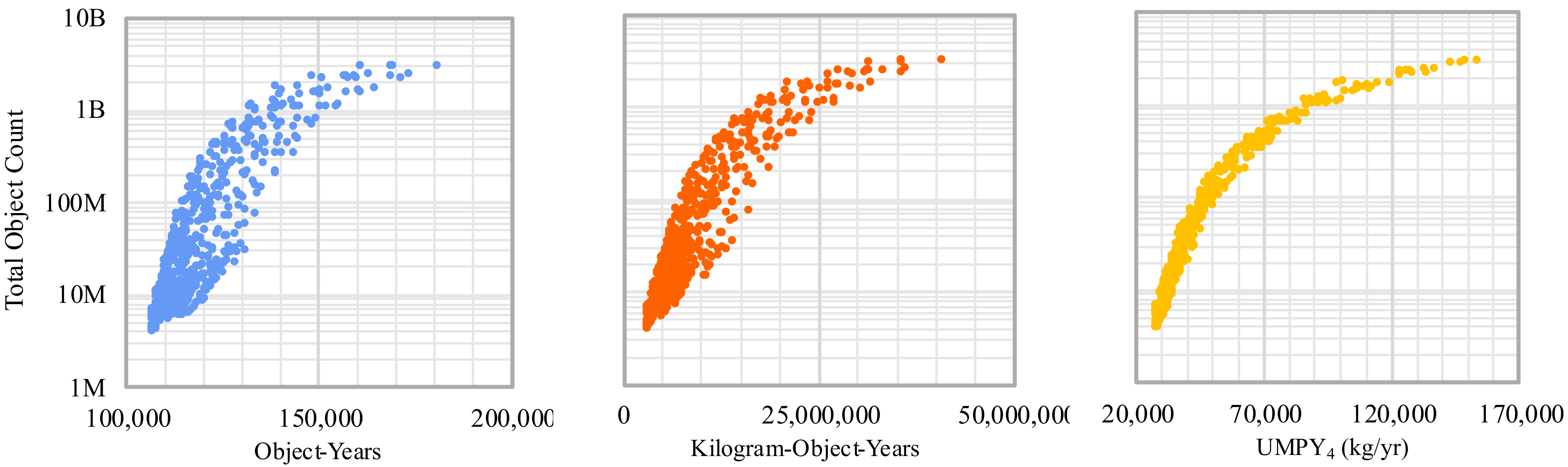


Multiple mitigation methods have compounding effects that are more than the sum

Examining Other Environmental Indices

Regulatory Composite Metrics

- Object-years and kilogram-object-years correlate well to total object count
- Similar characteristics exhibited in trends for each index, less variance in UMPY trend
- Scaling linearly by lifetime doesn't fully account for effect of altitude and lifetime on collision risk



Examining Other Environmental Indices

Collision Risk Balance Model

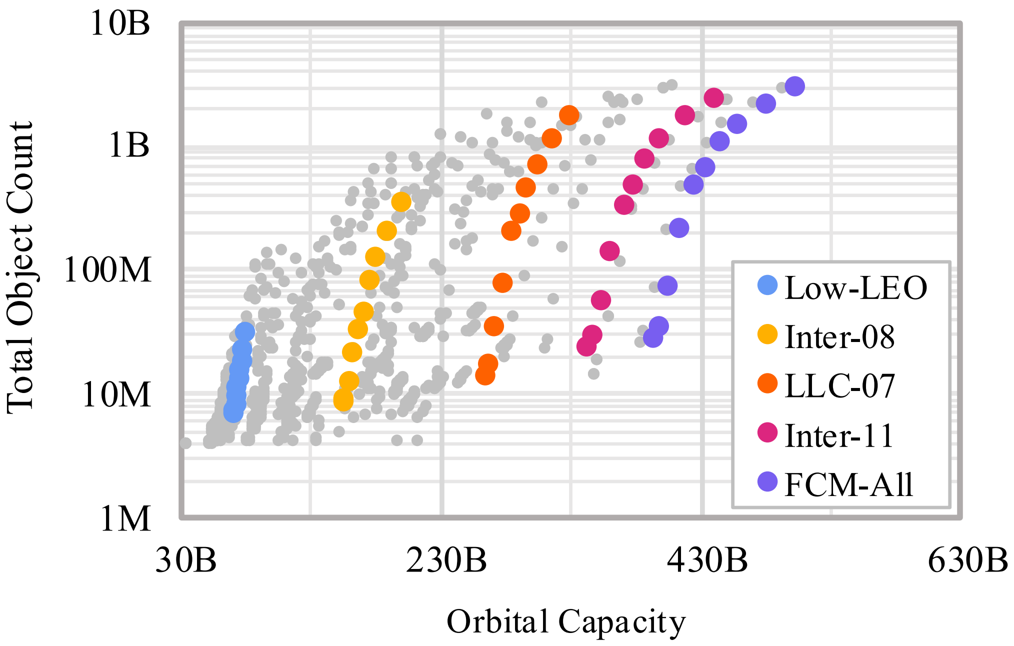
- Developed by McKnight and Dale
- Orbital capacity as a function of the risk posed, risk abated, and on-orbit persistence of each object

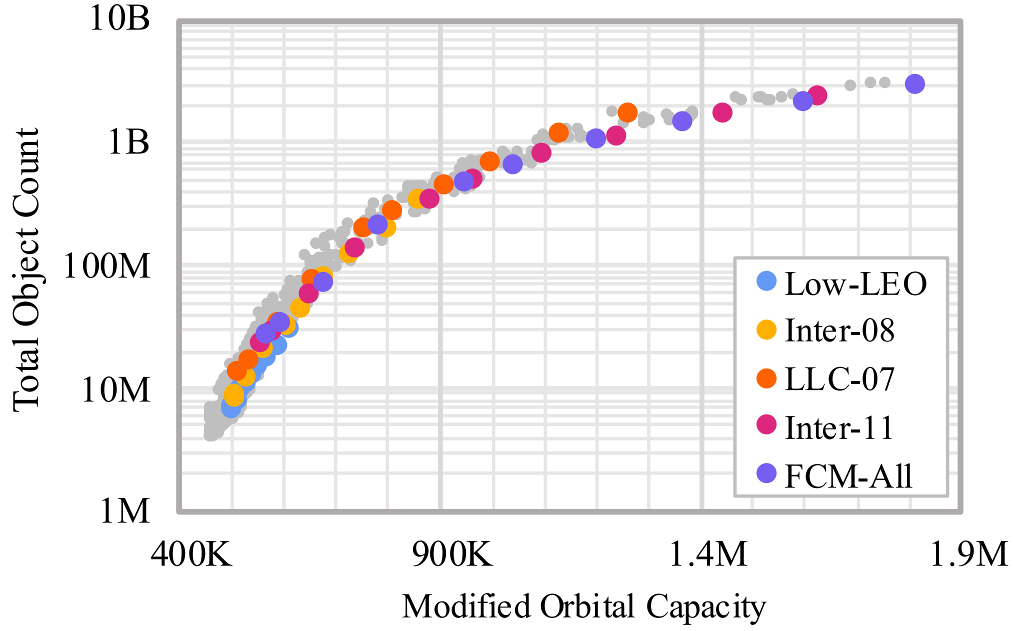
$$OC = \sum_{i=1}^{n_{obj}} RBP_i * (10 - RBA_i) * AA_i$$

RBP_i = *risk burden posed*
RBA_i = *risk burden abated*
AA_i = *altitude adjustment*

- Modified orbital capacity formula created to account for modeling differences in the ADEPT framework

$$OC_{mod} = \sum_{i=1}^{n_{obj}} RBP_i * Y_i$$

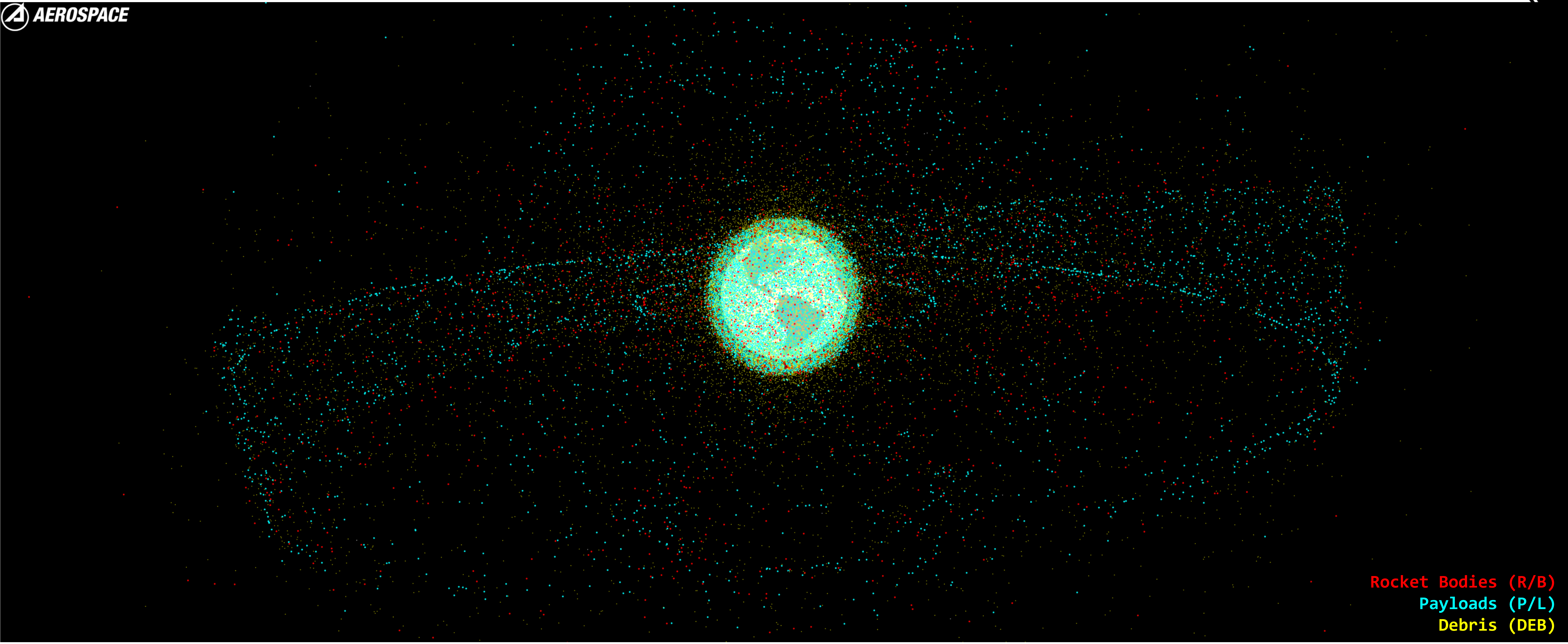




Questions?

Post-Processing and Visualization

Satellite Orbit Analysis Program (SOAP) Screen Capture



Sample projection of trackable (>10cm) objects in 2050

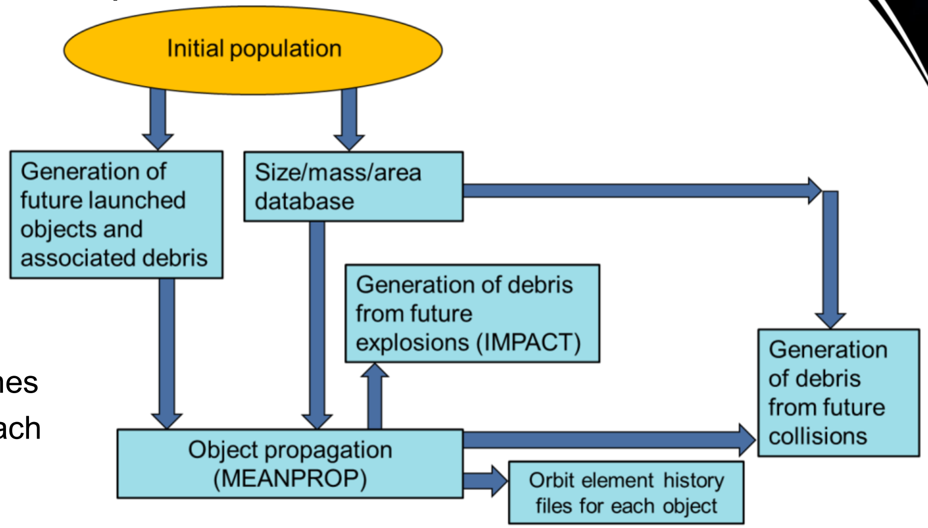
Introduction

- **Motivation:**
  - Very large LEO constellation (**LLC**) proposals indicate a significant increase in LEO activity
  - Collisions, object counts, conjunctions, and collision avoidance (**COLA**) rates will increase in LEO
  - 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

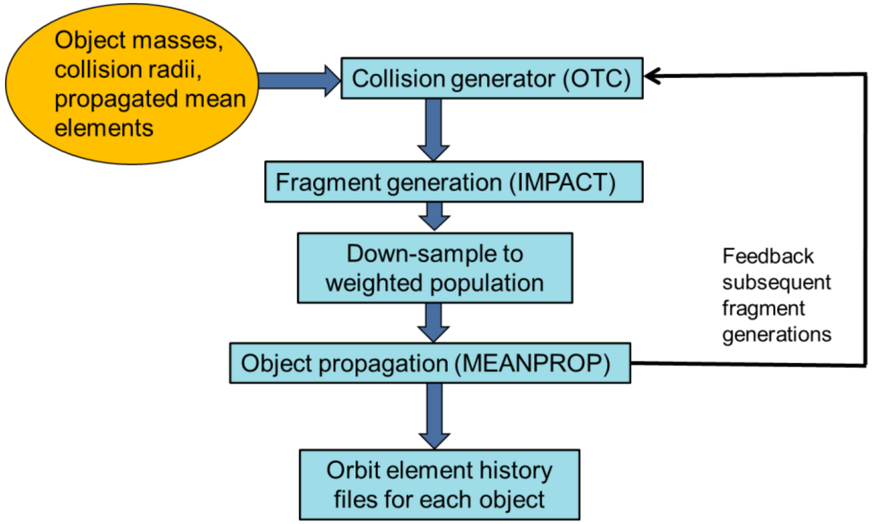
- **Goal:**
  - Leverage existing LEO Sustainability Study to examine mitigation methods effects
  - Make use of ***Uncontrolled Mass Per Year*** (**UMPY**) [kg/yr] metric to "target" desirable debris outcomes
  - Test effectiveness of focused "knob-turning" to demonstrate simple sustainability assessment approach

- **Aerospace Debris Environment Projection Tool (ADEPT)**
  - Projects future space environment evolution due to launch traffic, debris mitigations, and other options
  - Used to determine how activity levels, operator behaviors, and events affect debris environment
  - Included sources:
    - Current objects on orbit in the Initial Population Model (**IPM**)
    - New launch traffic (satellites and launch vehicles)
    - Debris from explosions and collisions between objects (including feedback)
  - Included sinks
    - Atmospheric reentry due to drag
    - Active debris removal (recently added)
  - Results consistent with half-a-dozen+ international models over several studies
  - Representative Large LEO Constellations (**LLC**) included in Future Constellation Model (**FCM**)

Population Generation Process

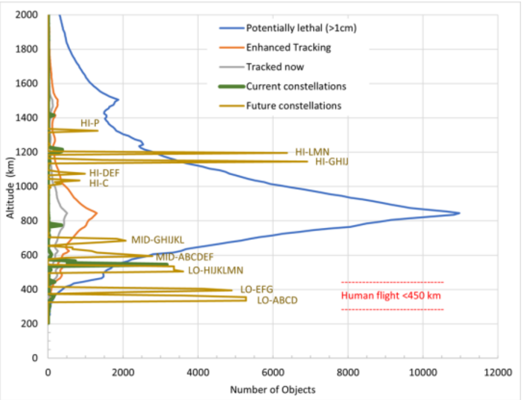


Generation of Debris from Future Collisions



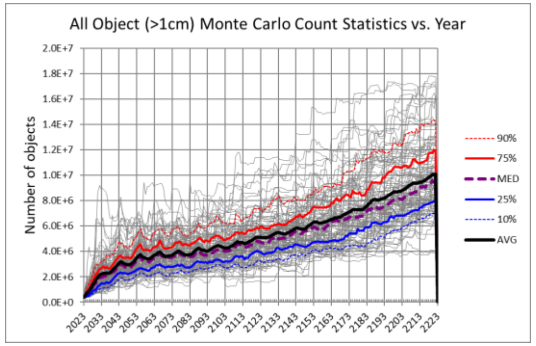
Aerospace Debris Environment Projection Tool (ADEPT) Overview

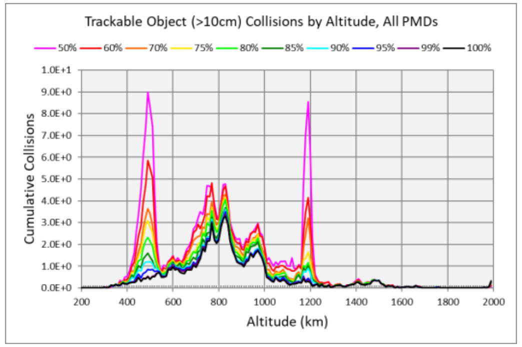
What is ADEPT?



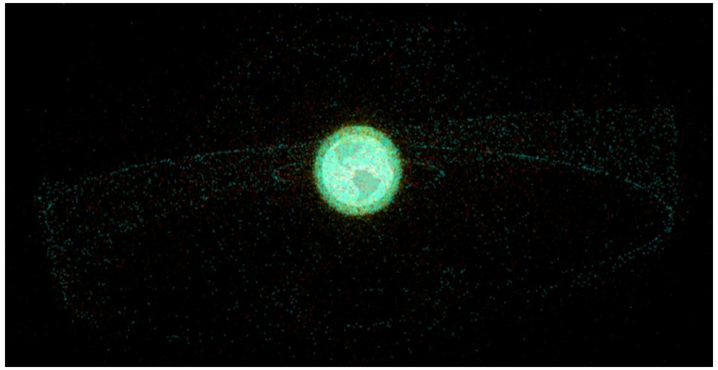
- **ADEPT models the long-term effects on the space environment** from:
  - Varying future traffic, disposal behavior, mitigation policy, and remediation
  - Explosions and collisions involving derelict objects and undisposed satellite

- **ADEPT generates breakups and debris using a Monte Carlo approach**
  - Propagates current space objects and modeled future launch traffic into the future
  - Finds conjunctions and generates randomized collisions
  - Creates breakup debris using the Aerospace-developed IMPACT model
  - Simulates disposals through reentry of objects due to atmospheric drag





- **ADEPT employs a novel simultaneous batch processing approach**
  - Scenarios are defined in post-processing with near-unlimited input options



- **Purpose: Helps with debris mitigation policy, space sustainability, and future space situational awareness**

ADEPT projects the future space debris environment subject to different inputs and assumptions

Background and Previous Study Context

It all started before IAC 2022…

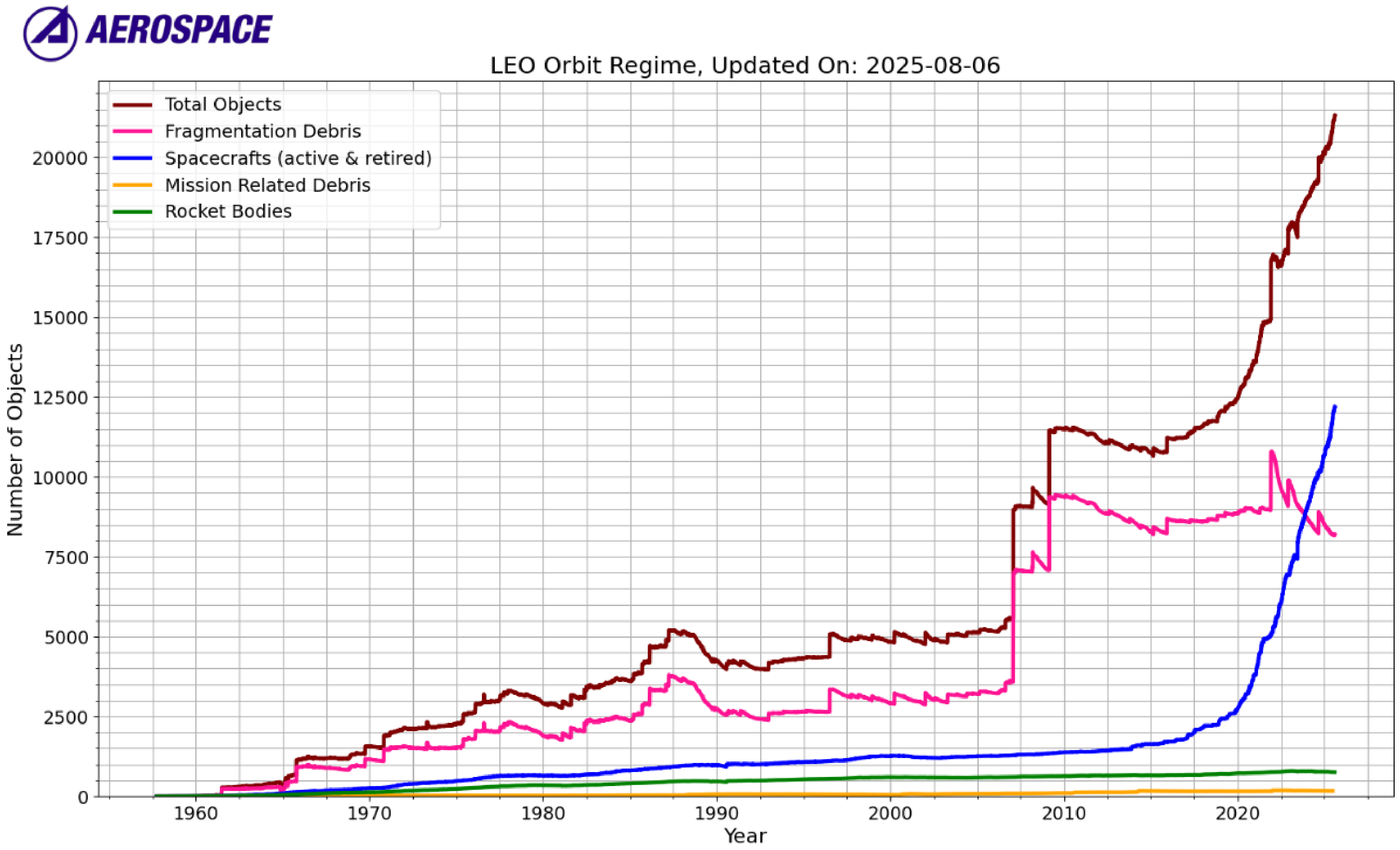
- Aerospace was asked a complicated, open-ended question:
  - *"What is the upper threshold of LEO activity at which point the orbital regime becomes unsustainable for permanent residents and transients passing through on their way to other orbital regimes?"*

- ADEPT was used in a study that begin in late 2021 to explore the extremes of potential future scenarios, looking for conditions that lead to unsustainable operations

- The results informed our customers of the potential for degraded operations, informed Aerospace's position on policy implementation, and pushed our capabilities forward dramatically

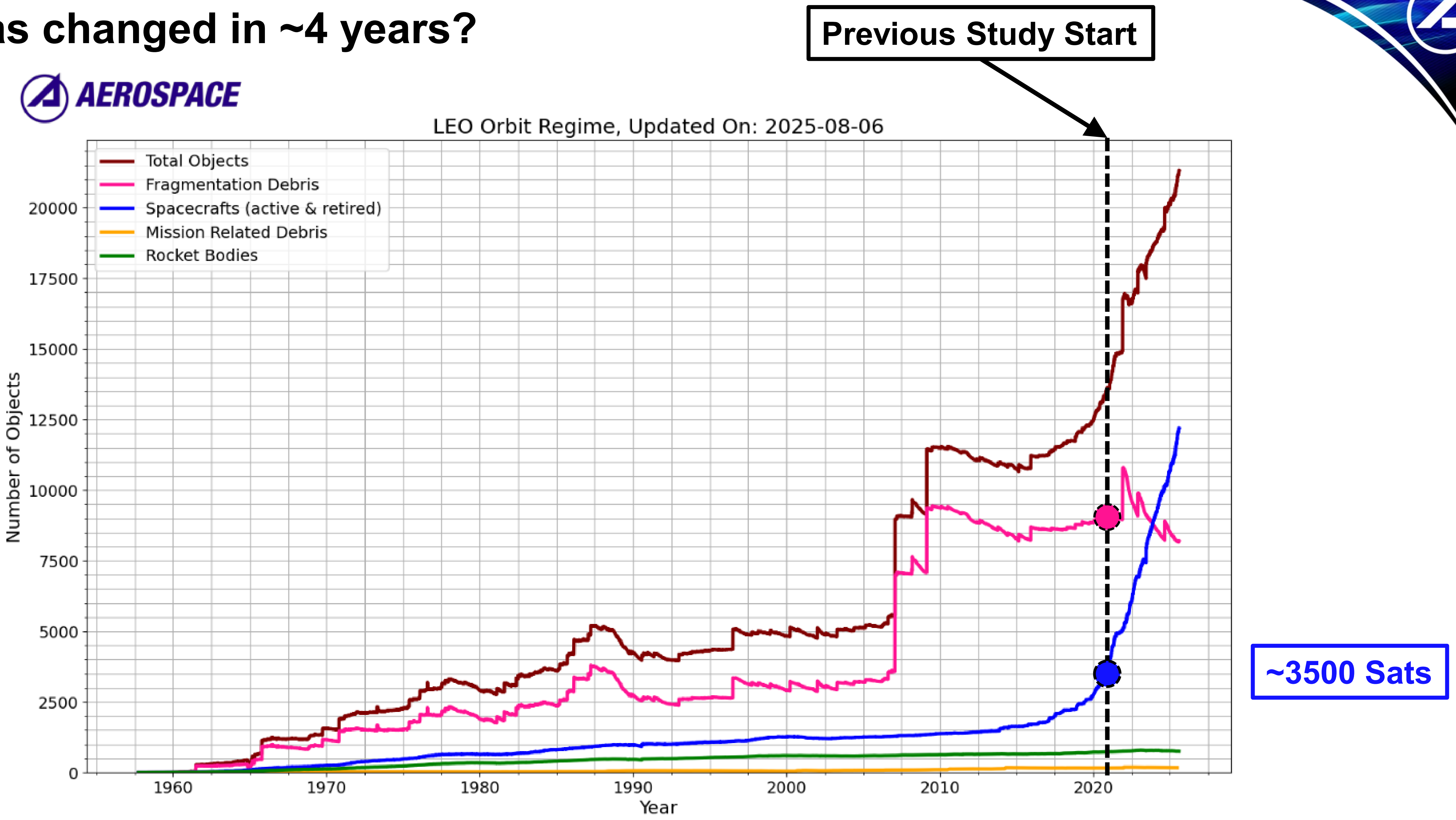
- Much has changed in 4 years, and this study needs a refresh – This paper is a report on what has changed, what Aerospace is implementing, and where we are at with our effort.

What has changed in ~4 years?



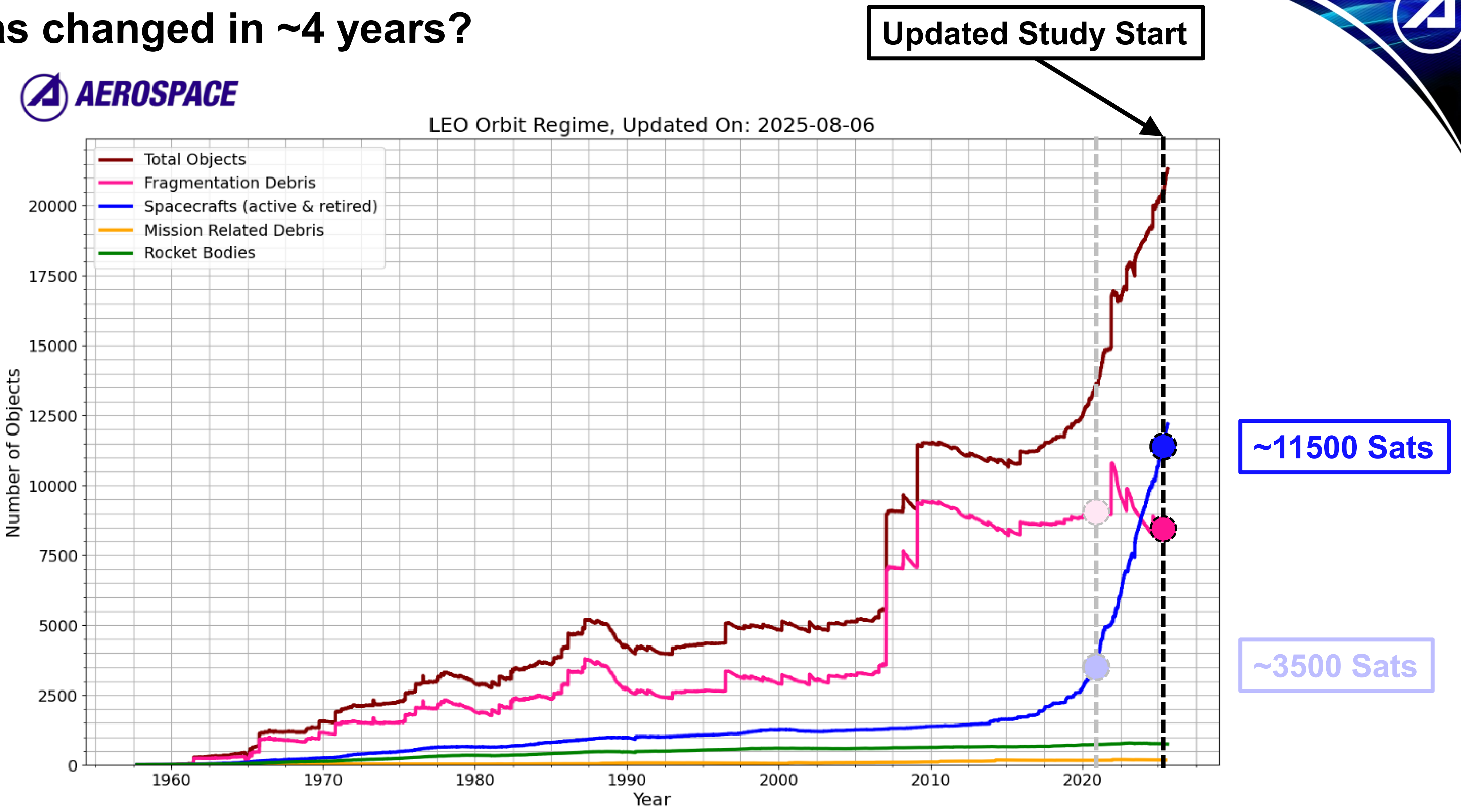
Courtesy of Aerospace's SODACT Team

What has changed in ~4 years?



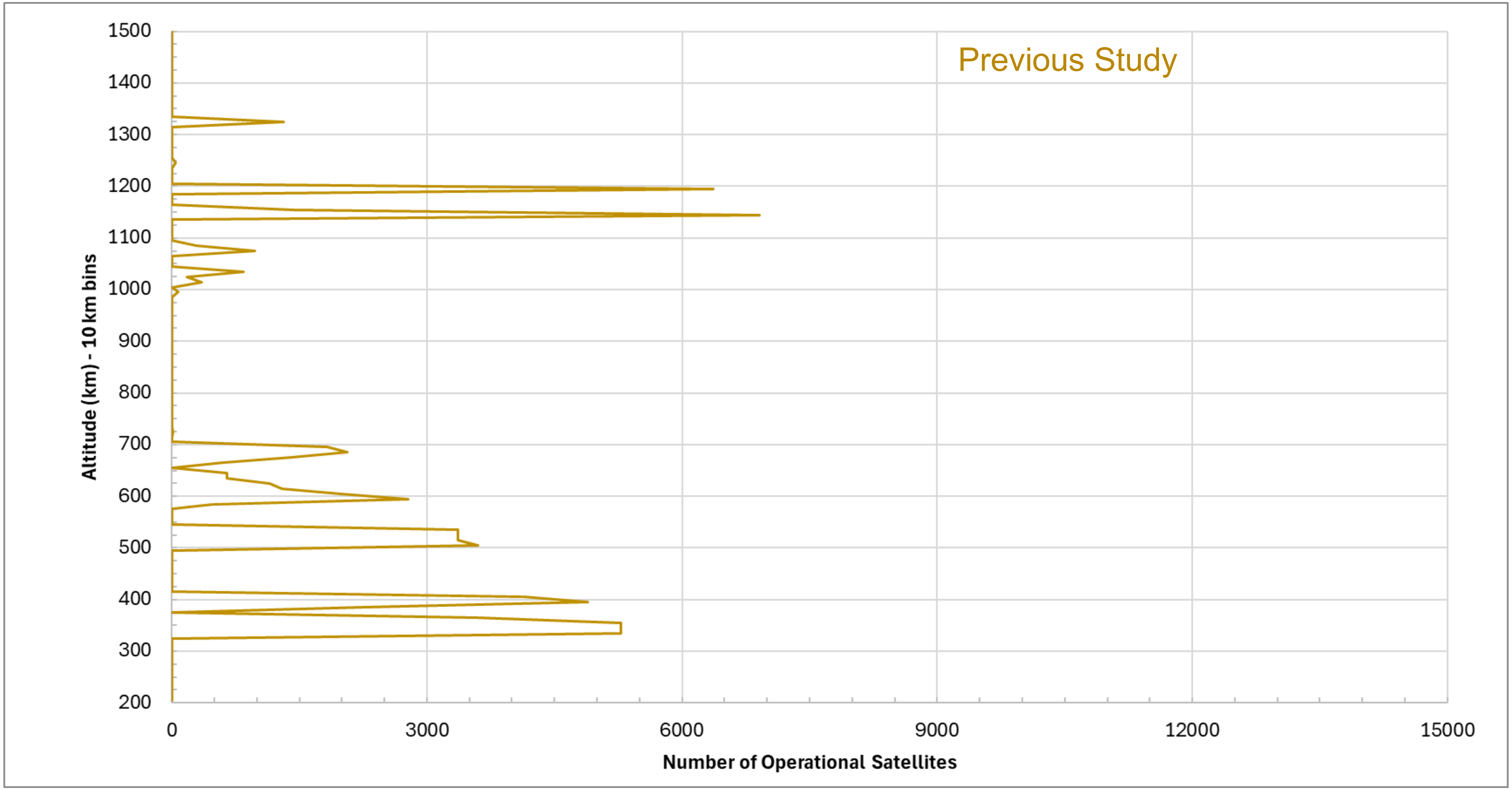
About twice as much debris as satellites

What has changed in ~4 years?

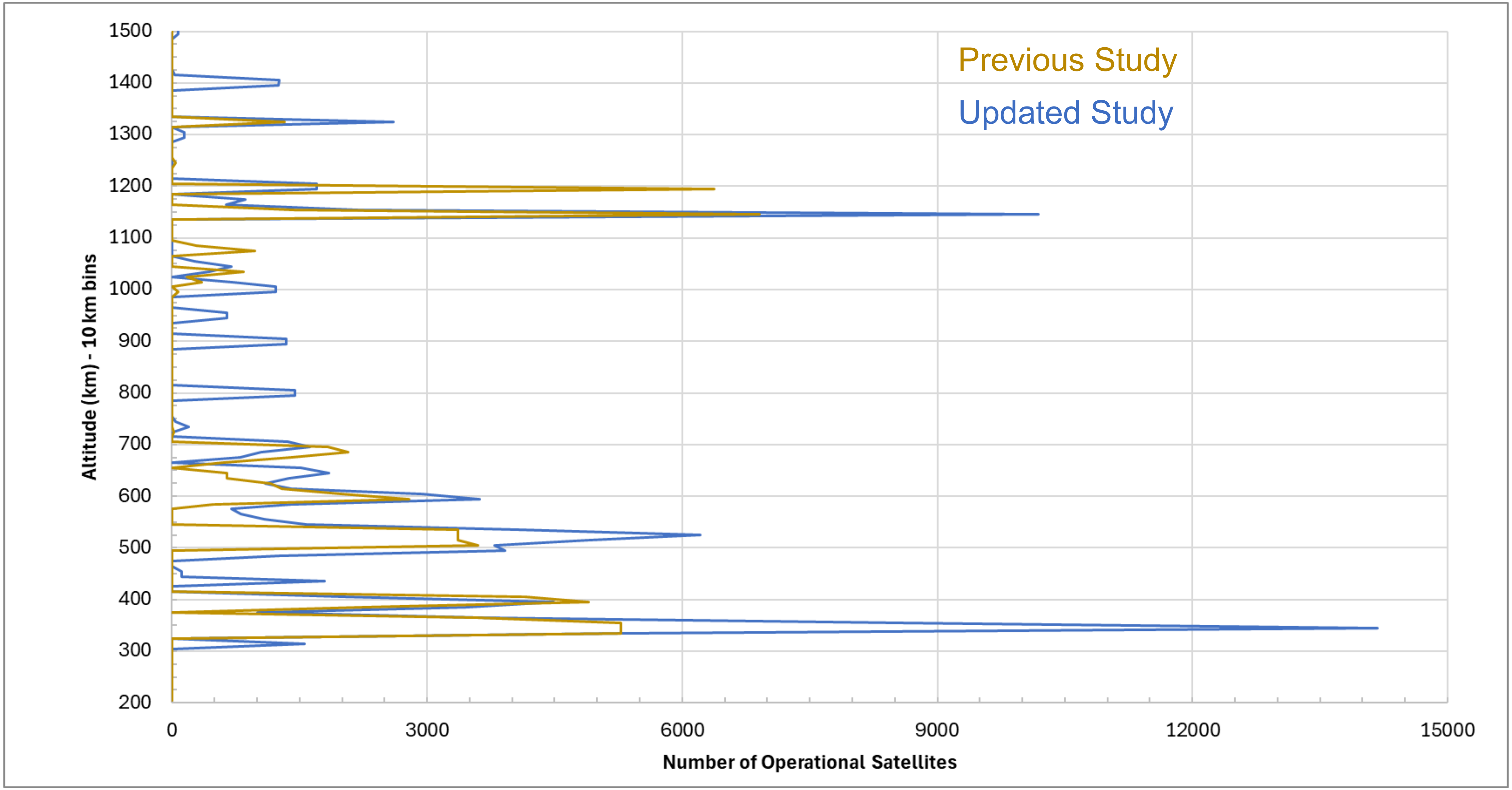


Number of satellites on orbits has nearly tripled

LLC Altitude Distribution Changes



LLC Altitude Distribution Changes



Overall increase of maximum possible operational LCCs from ~80,000 to ~130,000

Updated Study LLC Shells by Altitude

Low LEO (LO) Constellations: Altitude < 600 km

LLC Name	Number	Alt (km)	Inc (deg)	Mass (kg)	Start Year (in model)
LO-AA	1560	315	30	250	2029
LO-AC	2592	340	48	250	2030
LO-AD	2592	340	53	250	2030
LO-AB	5301	340	53	800	2030
LO-AE	4620	345	46	2000	2026
LO-AF	2976	347	50.2	250	2028
LO-AG	5170	350	38	2000	2025
LO-AH	2976	355	50	250	2030
LO-AI	3600	360	96.9	2000	2027
LO-AJ	1848	365	40	250	2028
LO-AK	2240	380	97	250	2028
LO-AL	4896	390	30	250	2028
LO-AM	4148	400	55	250	2033
LO-AN	1800	435	50	250	2029
LO-AO	216	450	63.4	250	2030
LO-AP	16	452	45	56	2025
LO-AQ	1260	485	55	250	2034
LO-AR	3240	495	50	250	2028
LO-AS	1350	500	60	250	2028
LO-AT	36	507	90	700	2027
LO-AU	3600	508	55	250	2025
LO-AV	2592	508	55	250	2028
LO-AW	100	515	70	250	2031
LO-AX	3360	522.5	53	250	2030
LO-AZ	640	525	54.5	250	2028
LO-AY	640	525	54.5	250	2029
LO-BA	3129	525	53	800	2024
LO-BB	3155	530	43	300	2024
LO-BC	2543	535	33	800	2025
LO-BD	1584	540	60	250	2030
LO-BE	1584	550	53	250	2030
LO-BF	580	560	97.6	250	2030
LO-BG	11	563	97	100	2025
LO-BH	324	570	70	250	2031
LO-BI	720	570	70	250	2030
LO-BJ	12	575	97.5	10	2025
LO-BK	384	580	26	250	2031
LO-BL	152	585	98	250	2029
LO-BM	813	590	33	500	2025
LO-BN	540	590	42	500	2026
LO-BO	784	590	33	500	2028
LO-BP	780	595	97.8	250	2030

42 LO LEO Shells (+28)

Middle LEO (MID) Constellations: Altitude ≥ 600 km, ≤ 800 km

LLC Name	Number	Alt (km)	Inc (deg)	Mass (kg)	Start Year (in model)
MID-AD	900	600	55	250	2035
MID-AB	480	600	85	250	2025
MID-AA	2000	600	50	250	2025
MID-AC	162	600	80.9	250	2031
MID-AE	144	604	148	800	2030
MID-AF	765	610	42	500	2026
MID-AG	1296	610	42	500	2030
MID-AH	324	614	115.7	800	2028
MID-AI	100	620	98	250	2029
MID-AJ	1134	630	51.9	500	2024
MID-AK	1156	630	52	500	2028
MID-AM	4	640	53	165	2025
MID-AL	654	640	72	500	2028
MID-AQ	25	650	98	28	2025
MID-AN	654	650	80	500	2033
MID-AO	2160	650	50	250	2031
MID-AP	216	650	86.4	250	2030
MID-AR	96	680	60	150	2025
MID-AS	96	680	62	150	2025
MID-AT	96	680	64	150	2025
MID-AU	96	680	66	150	2025
MID-AV	96	680	68	150	2025
MID-AW	96	680	70	150	2026
MID-AX	96	680	72	150	2026
MID-AY	96	680	74	150	2026
MID-AZ	96	680	76	150	2026
MID-BA	96	680	78	150	2026
MID-BB	96	680	80	150	2026
MID-BC	96	680	82	150	2026
MID-BD	96	680	84	150	2026
MID-BE	96	680	86	150	2026
MID-BF	96	680	88	150	2026
MID-BG	96	680	90	150	2027
MID-BH	64	680	98.1	150	2026
MID-BI	504	690	98	250	2027
MID-BJ	90	698	35	1500	2027
MID-BK	105	698	85	1500	2027
MID-BL	40	700	0	250	2030
MID-BM	1792	700	55	250	2028
MID-BN	720	700	55	250	2029
MID-BO	18	730	0	3000	2028
MID-BP	155	735	40	1500	2026
MID-BQ	75	740	55	3000	2026
MID-BR	4	743	96	250	2031
MID-BS	96	800	88	150	2026
MID-BT	600	800	50	250	2030
MID-BU	600	800	60	250	2031
MID-BV	600	800	80	250	2030
MID-BW	600	800	90	250	2028
MID-BX	500	800	88	250	2028

50 MID LEO Shells (+37)

High LEO (HI) Constellations: Altitude > 800 km

LLC Name	Number	Alt (km)	Inc (deg)	Mass (kg)	Start Year (in model)
HI-AC	80	900	46	250	2031
HI-AD	60	900	80.4	250	2031
HI-AA	1400	900	80.4	250	2028
HI-AB	1152	900	87	250	2027
HI-AE	275	950	85	250	2025
HI-AF	150	950	85	250	2026
HI-AG	250	950	85	250	2027
HI-AH	325	950	85	250	2030
HI-AI	300	950	85	250	2032
HI-AJ	100	1000	0	250	2033
HI-AK	1000	1000	45	250	2026
HI-AL	336	1000	77	250	2026
HI-AM	336	1000	81	250	2025
HI-AN	336	1000	85	250	2028
HI-AO	336	1000	90	250	2026
HI-AP	78	1015	98.98	750	2026
HI-AQ	313	1015	99.5	750	2028
HI-AR	78	1015	98.98	750	2028
HI-AS	273	1015	98.98	750	2030
HI-AT	864	1040	85.5	250	2026
HI-AU	216	1050	97	250	2025
HI-AV	312	1050	97	250	2026
HI-AW	6	1095	50	250	2027
HI-BB	1728	1145	30	250	2029
HI-AX	1728	1145	30	250	2026
HI-AY	1728	1145	40	250	2027
HI-AZ	1728	1145	50	250	2027
HI-BA	1728	1145	60	250	2030
HI-BD	1728	1150	50	250	2031
HI-BC	1440	1150	55	250	2025
HI-BE	1296	1160	90	250	2025
HI-BF	864	1175	86.5	250	2026
HI-BJ	100	1200	0	250	2033
HI-BK	1000	1200	45	250	2027
HI-BL	336	1200	77	250	2026
HI-BM	336	1200	81	250	2025
HI-BN	336	1200	85	250	2028
HI-BO	336	1200	90	250	2026
HI-BG	360	1200	40	150	2026
HI-BH	360	1200	55	150	2026
HI-BI	247	1200	87.9	150	2028
HI-BP	288	1300	45	250	2025
HI-BQ	110	1325	50.88	750	2026
HI-BR	1320	1325	51	750	2027
HI-BS	220	1325	51	750	2029
HI-BT	440	1325	51	750	2032
HI-BU	660	1325	51	750	2032
HI-BV	50	1400	98	1500	2027
HI-BW	100	1400	0	250	2033
HI-BX	1000	1400	45	250	2027
HI-BY	336	1400	77	250	2026
HI-BZ	336	1400	81	250	2025
HI-CA	336	1400	85	250	2028
HI-CB	336	1400	90	250	2027
HI-CC	42	1414	52	250	2031
HI-CD	152	1500	98	250	2030

56 HI LEO Shells (+40)

148 Total LLC Shells (+105)

Updated Study LLC Shells by Altitude

Low LEO (LO) Constellations: Altitude < 600 km

LLC Name	Number	Alt (km)	Inc (deg)	Mass (kg)	Start Year (in model)
LO-AA	1560	315	30	250	2029
LO-AC	2592	340	48	250	2030
LO-AD	2592	340	53	250	2030
LO-AB	5301	340	53	800	2030
LO-AE	4620	345	46	2000	2026
LO-AF	2976	347	50.2	250	2028
LO-AG	5170	350	38	2000	[illegible]
LO-AH	2976	355	50	250	2030
LO-AI	3600	360	96.9	2000	2027
LO-AJ	1848	365	40	[illegible]	2028
LO-AK	2240	380	97	250	2028
LO-AL	4896	390	30	250	2028
LO-AM	4148	400	[illegible]	250	2033
LO-AN	1800	435	50	250	2029
LO-AO	216	450	63.4	250	2030
LO-AP	16	[illegible]	45	56	2025
LO-AQ	1260	485	55	250	2034
LO-AR	3240	495	50	250	2028
LO-AS	[illegible]	500	60	250	2028
LO-AT	36	507	90	700	2027
LO-AU	3600	508	55	250	2025
LO-AV	2592	508	55	250	2028
LO-AW	100	515	70	250	2031
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
LO-AZ	640	525	54.5	250	2028
LO-AY	640	525	54.5	250	2029
LO-BA	3129	525	53	800	2024
LO-BB	3155	530	43	300	2024
LO-BC	2543	535	33	800	2025
LO-BD	1584	540	60	250	2030
LO-BE	1584	550	53	250	2030
LO-BF	580	560	97.6	250	2030
LO-BG	11	563	97	100	2025
LO-BH	324	570	70	250	2031
LO-BI	720	570	70	250	2030
LO-BJ	12	575	97.5	10	2025
LO-BK	384	580	26	250	2031
LO-BL	152	585	98	250	2029
LO-BM	813	590	33	500	2025
LO-BN	540	590	42	500	2026
LO-BO	784	590	33	500	2028
LO-BP	780	595	97.8	250	2030

LO-AZ	640	525	54.5	250	2028
LO-AY	640	525	54.5	250	2029
LO-BA	3129	525	53	800	2024
LO-BB	3155	530	43	300	2024
LO-BC	2543	535	33	800	2025
LO-BD	1584	540	60	250	2030
LO-BE	1584	550	53	250	2030
LO-BF	580	560	97.6	250	2030
LO-BG	11	563	97	100	2025
LO-BH	324	570	70	250	2031
LO-BI	720	570	70	250	2030
LO-BJ	12	575	97.5	10	2025

At least 5 separate operators with 12 shells, Totalling nearly 15,000 sats, crammed into ~50 km

42 LO LEO Shells (+28)

Middle LEO (MID) Constellations: Altitude ≥ 600 km, ≤ 800 km

LLC Name	Number	Alt (km)	Inc (deg)	Mass (kg)	Start Year (in model)
MID-AD	900	600	55	250	2035
MID-AB	480	600	85	250	2025
MID-AA	2000	600	50	250	2025
MID-AC	162	600	80.9	250	2031
MID-AE	144	604	148	800	2030
MID-AF	765	610	42	500	2026
MID-BM	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MID-BU	600	800	60	250	2031
MID-BV	600	800	80	250	2030
MID-BW	600	800	90	250	2028
MID-BX	500	800	88	250	2028

50 MID LEO Shells (+37)

High LEO (HI) Constellations: Altitude > 800 km

LLC Name	Number	Alt (km)	Inc (deg)	Mass (kg)	Start Year (in model)
HI-AC	80	900	46	250	2031
HI-AD	60	900	80.4	250	2031
HI-AA	1400	900	80.4	250	2028
HI-AB	1152	900	87	250	2027
HI-AE	275	950	85	250	2025
HI-AF	150	950	85	250	2026
HI-AG	250	950	85	250	2027
HI-AH	325	950	85	250	2030
HI-AI	300	950	85	250	2032
[illegible]	[illegible]	[illegible]	0	250	2033
[illegible]	[illegible]	[illegible]	45	250	2026
[illegible]	[illegible]	[illegible]	77	250	2026
[illegible]	[illegible]	[illegible]	81	250	2025
[illegible]	[illegible]	[illegible]	85	250	2028
[illegible]	[illegible]	[illegible]	90	250	2026
[illegible]	[illegible]	[illegible]	98.98	750	2026
[illegible]	[illegible]	[illegible]	99.5	750	2028
[illegible]	[illegible]	[illegible]	98.98	750	2028
[illegible]	[illegible]	[illegible]	98.98	750	2030
[illegible]	[illegible]	[illegible]	85.5	250	2026
[illegible]	[illegible]	[illegible]	97	250	2025
[illegible]	[illegible]	[illegible]	97	250	2026
[illegible]	[illegible]	[illegible]	50	250	2027
[illegible]	[illegible]	[illegible]	30	250	2029
[illegible]	[illegible]	[illegible]	30	250	2026
[illegible]	[illegible]	[illegible]	40	250	2027
[illegible]	[illegible]	[illegible]	50	250	2027
[illegible]	[illegible]	[illegible]	60	250	2030
[illegible]	[illegible]	[illegible]	50	250	2031
[illegible]	[illegible]	[illegible]	55	250	2025
[illegible]	[illegible]	[illegible]	90	250	2025
[illegible]	[illegible]	[illegible]	86.5	250	2026
[illegible]	[illegible]	[illegible]	0	250	2033
[illegible]	[illegible]	[illegible]	45	250	2027
[illegible]	[illegible]	[illegible]	77	250	2026
[illegible]	[illegible]	[illegible]	81	250	2025
[illegible]	[illegible]	[illegible]	85	250	2028
[illegible]	[illegible]	[illegible]	90	250	2026
[illegible]	[illegible]	[illegible]	40	150	2026
[illegible]	[illegible]	[illegible]	55	150	2026
[illegible]	[illegible]	[illegible]	87.9	150	2028
HI-BP	288	1300	45	250	2025
[illegible]	[illegible]	[illegible]	50.88	750	2026
[illegible]	[illegible]	[illegible]	51	750	2027
[illegible]	[illegible]	[illegible]	51	750	2029
[illegible]	[illegible]	[illegible]	51	750	2032
[illegible]	[illegible]	[illegible]	51	750	2032
[illegible]	[illegible]	[illegible]	98	1500	2027
[illegible]	[illegible]	[illegible]	0	250	2033
HI-BX	1000	1400	45	250	2027
HI-BY	336	1400	77	250	2026
HI-BZ	336	1400	81	250	2025
HI-CA	336	1400	85	250	2028
HI-CB	336	1400	90	250	2027
HI-CC	42	1414	52	250	2031
HI-CD	152	1500	98	250	2030

56 HI LEO Shells (+40)

148 Total LLC Shells (+105)

Scenarios

Previous Study – Initially presented with ~270 scenarios

- Scenarios are defined by a combination of:
  - *Future Launch Model (**FLM**) traffic*
  - *PMD method & success rate*
- Scenario list constructed to span full range of possible traffic, and explore varying configurations
  - *baseline: closely matches initial traffic level, replenished for the simulation duration*
  - *background: excludes LLCs, includes all other traffic*
  - *no-llc: is a future with no LLC replenishment*
  - *fcm-all: ALL possible LLCs*
  - *intermediate-X: distribution between baseline and fcm-all*
  - *lo-leo/hi-leo: explore imbalanced altitude distribution*
  - *fcm-llcX: mimic real-world potential LLCs*
  - *proj-X: likely progressions from baseline to fcm-all*

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

Scenarios

Updated Study – Initially planning ~2000 scenarios; grown unlimited

- Scenarios are defined by a combination of:
  - *Future Launch Model (**FLM**) traffic (includes FCM)*
  - *PMD method & success rate*
  - *Custom mitigation methods and modifications*

- Scenario list constructed to span full range of possible traffic, and explore varying configurations
  - *baseline: closely matches initial traffic level, replenished for the simulation duration*
  - *background: excludes LLCs, includes all other traffic*
  - *no-llc: is a future with no LLC replenishment*
  - *fcm-all: ALL possible LLCs*
  - *inter-XX: distribution between baseline and fcm-all*
  - *lo-leo/mid-leo/hi-leo: explore imbalanced altitude distribution*
  - *fcm-XX: mimic real-world potential LLCs*
  - *proj-XX: likely progressions from baseline to fcm-all*
  - *tiered-X: low/mid/high traffic used for tiered disposal*
  - ***Copies of all scenarios with ADR and C2R options***

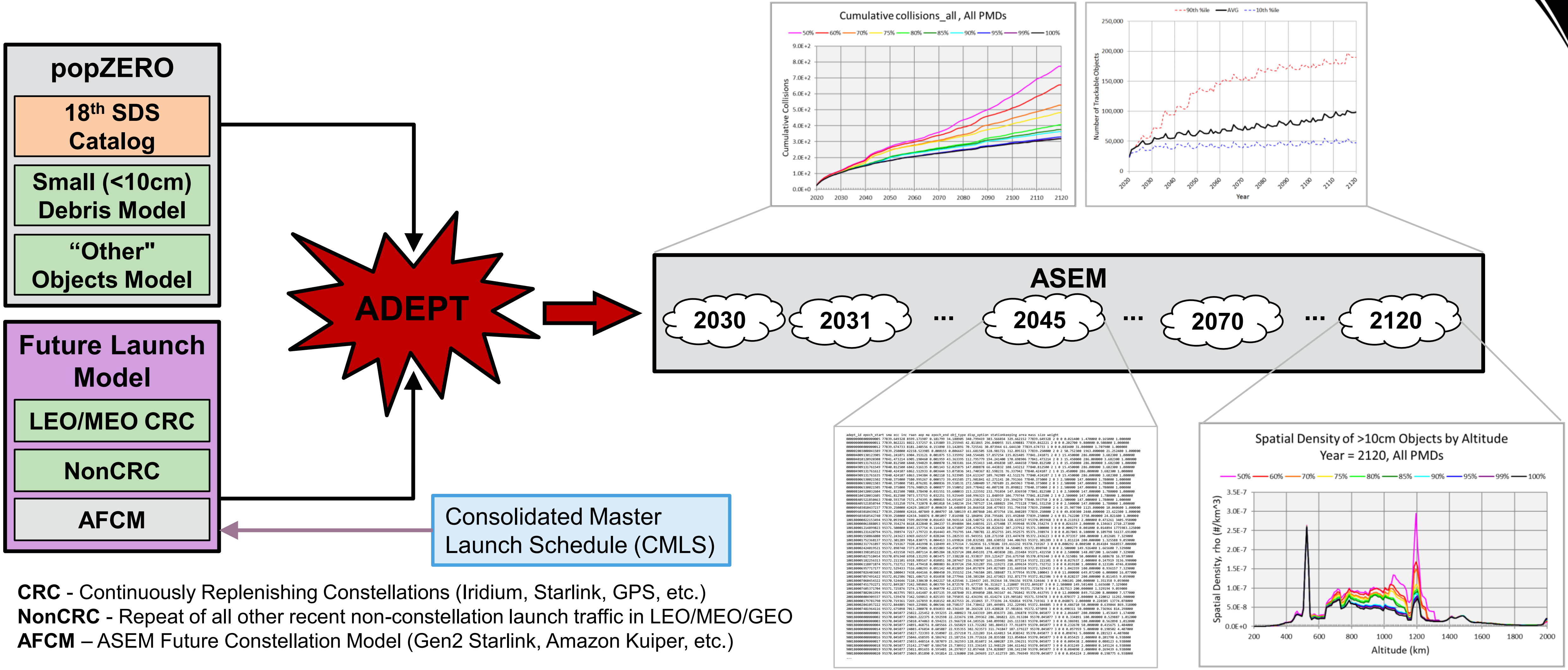
Scenario Name	LLCs Included	Total # FCM Sats	Low LEO (<600 km)	Mid LEO (600-800 km)	High LEO (>800 km)
baseline	current LLCs with continuous replenishment	-	-	-	-
no-llc	baseline with no replenishment	-	-	-	-
inter-01	baseline + 5% FCM LLCs	6,631	4,026	1,018	1,587
inter-02	baseline + 10% FCM LLCs	13,255	8,046	2,034	3,175
inter-03	baseline + 15% FCM LLCs	19,855	12,070	3,036	4,749
inter-xx	...	...	...	...	...
inter-17	baseline + 85% FCM LLCs	112,570	68,396	17,238	26,936
inter-18	baseline + 90% FCM LLCs	119,171	72,419	18,244	28,508
inter-19	baseline + 95% FCM LLCs	125,794	76,440	19,256	30,098
fcm-all	all proposed FCM LLCs	132,418	80,464	20,273	31,681
lo-leo-1	baseline + 25% of all LO LEO FCM LLCs	20,117	20,117	-	-
lo-leo-2	baseline + 50% of all LO LEO FCM LLCs	40,235	40,235	-	-
lo-leo-3	baseline + 75% of all LO LEO FCM LLCs	60,349	60,349	-	-
lo-leo-4	baseline + 100% of all LO LEO FCM LLCs	80,464	80,464	-	-
mid-leo-1	baseline + 25% of all MID LEO FCM LLCs	5,071	-	5,071	-
mid-leo-2	baseline + 50% of all MID LEO FCM LLCs	10,139	-	10,139	-
mid-leo-3	baseline + 75% of all MID LEO FCM LLCs	15,208	-	15,208	-
mid-leo-4	baseline + 100% of all MID LEO FCM LLCs	20,273	-	20,273	-
hi-leo-1	baseline + 25% of all HI LEO FCM LLCs	7,924	-	-	7,924
hi-leo-2	baseline + 50% of all HI LEO FCM LLCs	15,843	-	-	15,843
hi-leo-3	baseline + 75% of all HI LEO FCM LLCs	23,765	-	-	23,765
hi-leo-4	baseline + 100% of all HI LEO FCM LLCs	31,681	-	-	31,681
proj-01	1st projection of increasingly likely* FCM LLCs	TBD	TBD	TBD	TBD
proj-02	2nd projection of increasingly likely* FCM LLCs	TBD	TBD	TBD	TBD
proj-03	3rd projection of increasingly likely* FCM LLCs	TBD	TBD	TBD	TBD
proj-xx	...	...	...	...	...
tiered-01	alternate tiered PMD rules applied to proj-01	TBD	TBD	TBD	TBD
tiered-02	alternate tiered PMD rules applied to proj-02	TBD	TBD	TBD	TBD
tiered-03	alternate tiered PMD rules applied to proj-03	TBD	TBD	TBD	TBD
tiered-xx	...	...	...	...	...
fcm-31	baseline + shells comprising LLC 31	27,986	27,518	468	-
fcm-41	baseline + shells comprising LLC 41	3,492	-	-	3,492
fcm-52	baseline + shells comprising LLC 52	15,200	9,192	2,160	3,848
fcm-65	baseline + shells comprising LLC 65	5,522	1,360	4,120	42
fcm-xx	...	...	...	...	...

Constellations by Object Count

Constellation Name	High Traffic Satellite Count	Constellation Name	Medium Traffic Satellite Count	Constellation Name	Low Traffic Satellite Count
LLC31	25678	LLC31	15291	LLC31	5070
LLC57	16036	LLC57	8018	LLC24	4408
LLC33	7592	LLC33	4800	LLC33	3252
LLC513-6	6912	LLC24	4408	LLC32	1300
LLC55	6864	LLC55	3460	LLC23	1278
LLC517-9	6080	LLC513-6	3456	LLC25	828
LLC24	4408	LLC517-9	3035	LLC517-9	675
LLC41	3323	LLC41	1637	LLC52	144
LLC65	3128	LLC65	1565	LLC61	108
LLC53	1772	LLC32	1300	LLC45	76
LLC35-6	1696	LLC23	1278	LLC64	72
LLC394	1440	LLC61	967	LLC21	66
LLC32	1300	LLC53	902	LLC22	48
LLC23	1278	LLC35-6	864	LLC394	40
LLC52	1278	LLC25	828	LLC26	36
LLC56	1252	LLC394	720	LLC62	36
LLC61	967	LLC56	632	LLC27	18
LLC511-2	870	LLC52	630	LLC63	15
LLC54	864	LLC511-2	438	LLC395	12
LLC25	828	LLC54	432	LLC392	12
LLC64	528	LLC34	241	LLC391	7
LLC34	488	LLC64	240	LLC34	5
LLC45	304	LLC45	152	LLC44	4
LLC395	288	LLC395	144	LLC393	1
LLC21	66	LLC21	66	LLC57	0
LLC22	48	LLC22	48	LLC55	0
LLC26	36	LLC26	36	LLC513-6	0
LLC62	36	LLC62	36	LLC41	0
LLC27	36	LLC27	36	LLC65	0
LLC63	15	LLC63	15	LLC53	0
LLC392	12	LLC392	12	LLC35-6	0
LLC44	11	LLC391	8	LLC56	0
LLC391	9	LLC44	4	LLC511-2	0
LLC393	1	LLC393	1	LLC54	0

ASEM (ADEPT Standard Environment Model)

What does it look like?



CRC - Continuously Replenishing Constellations (Iridium, Starlink, GPS, etc.)
NonCRC - Repeat of all other recent non-constellation launch traffic in LEO/MEO/GEO
AFCM – ASEM Future Constellation Model (Gen2 Starlink, Amazon Kuiper, etc.)

Years of Lessons Learned, New Features, Efficient Innovations, etc.

Updated study is leveraging advancements in ADEPT capabilities

Environmental “INDICES” integration

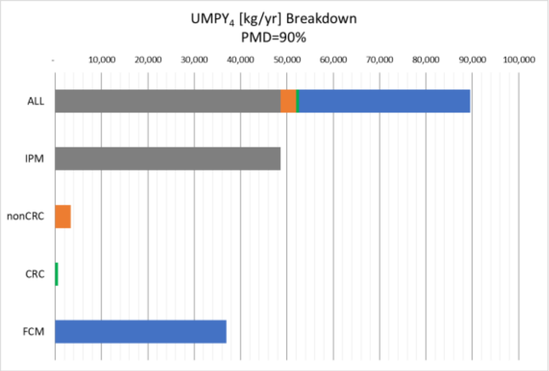
$$UMPY = \frac{1}{t_{sim}} \sum_{i=1}^{n_{objs}} m_i \left[\frac{e^{4\left(\frac{life_i}{t_{sim}}\right)} - 1}{e^4 - 1} \right]$$

t_{sim} = study duration [years]

n_{objs} = # uncontrolled objects

m_i = uncontrolled object mass [kg]

$life_i$ = uncontrolled object lifetime [years]



New conjunction capability; V&V with high fidelity tools

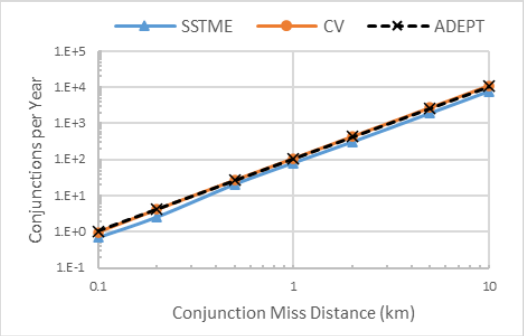
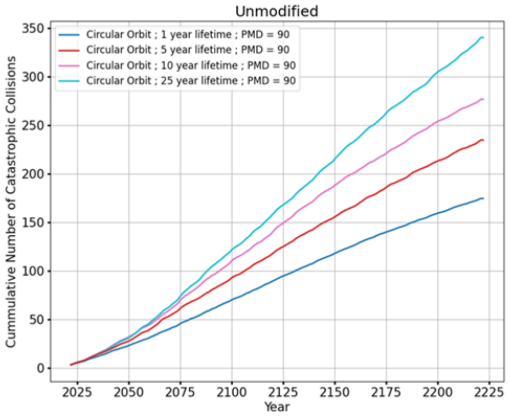
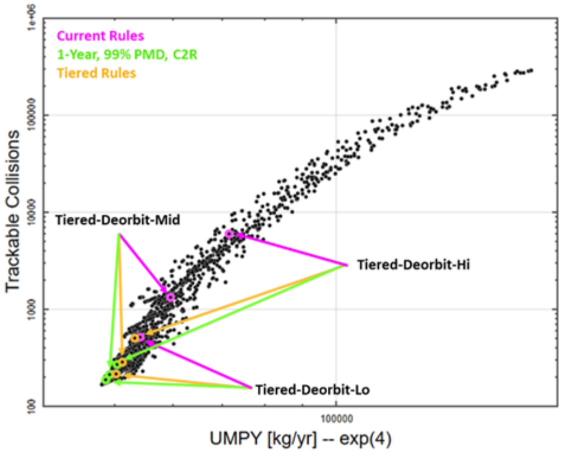


Table 2. Table of COLA violations per year values comparing different models

Dist (km)	SSTME	CV	ADEPT
0.1	0.7	0.99	1.06
0.2	2.6	4.18	4.25
0.5	20.7	26.98	26.58
1	81.2	107.6	106.3
2	309	433.9	425.2
5	1920	2740	2658
10	7687	11121	10630
0.1	0.7	0.99	1.06

Scenario modification methods to “target” outcomes



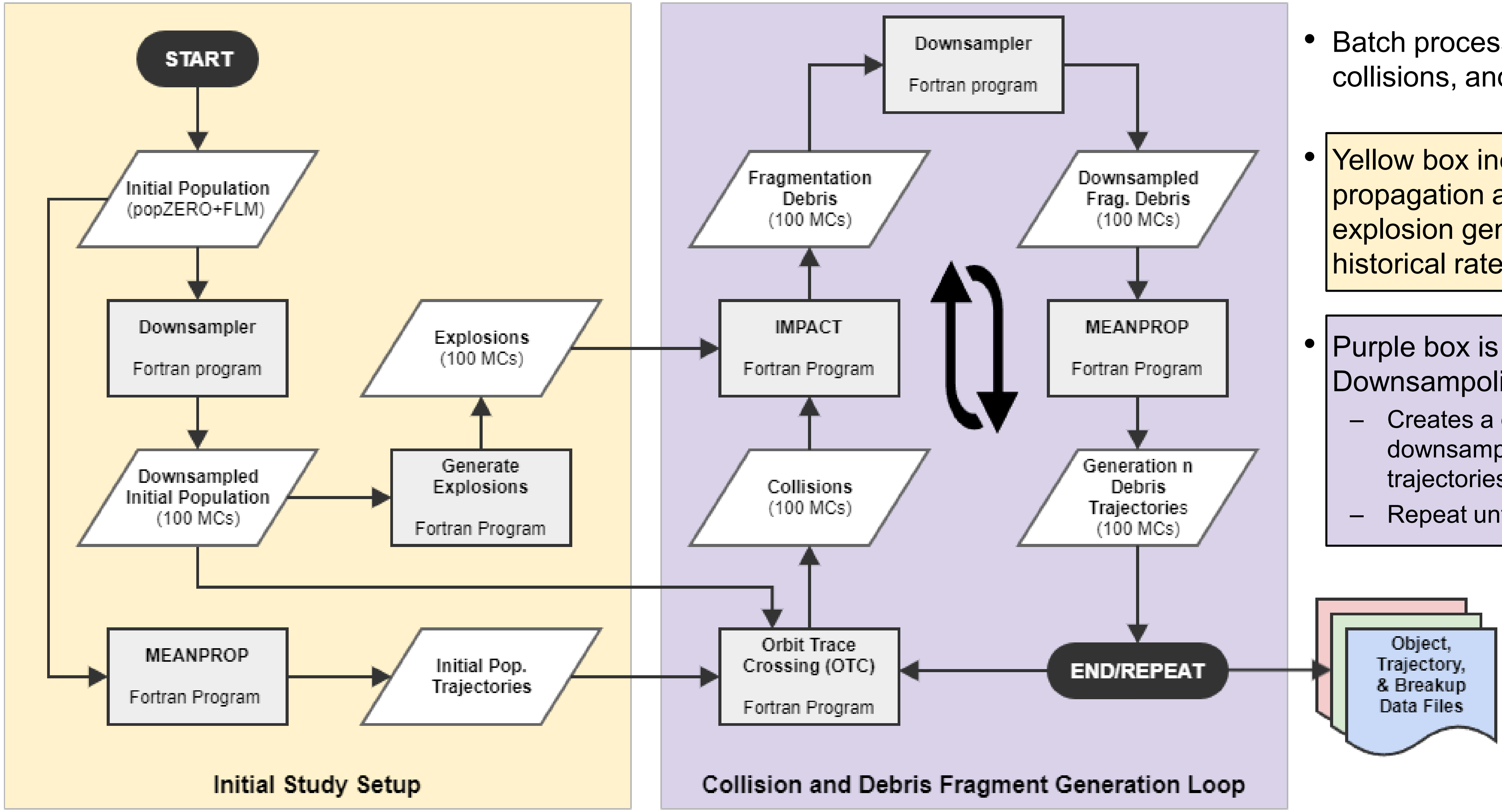


Tool, Environment, and Process Improvements

- *Codebase modernization effort*
- *Upgraded corporate high-power computing system*
- *Numerous algorithm efficiency enhancements*
- *Streamlining analysis process for quicker turnaround*
- *Developing cross-corporate interfaces for tool compatibility*

Breakup and Fragmentation Generation Process

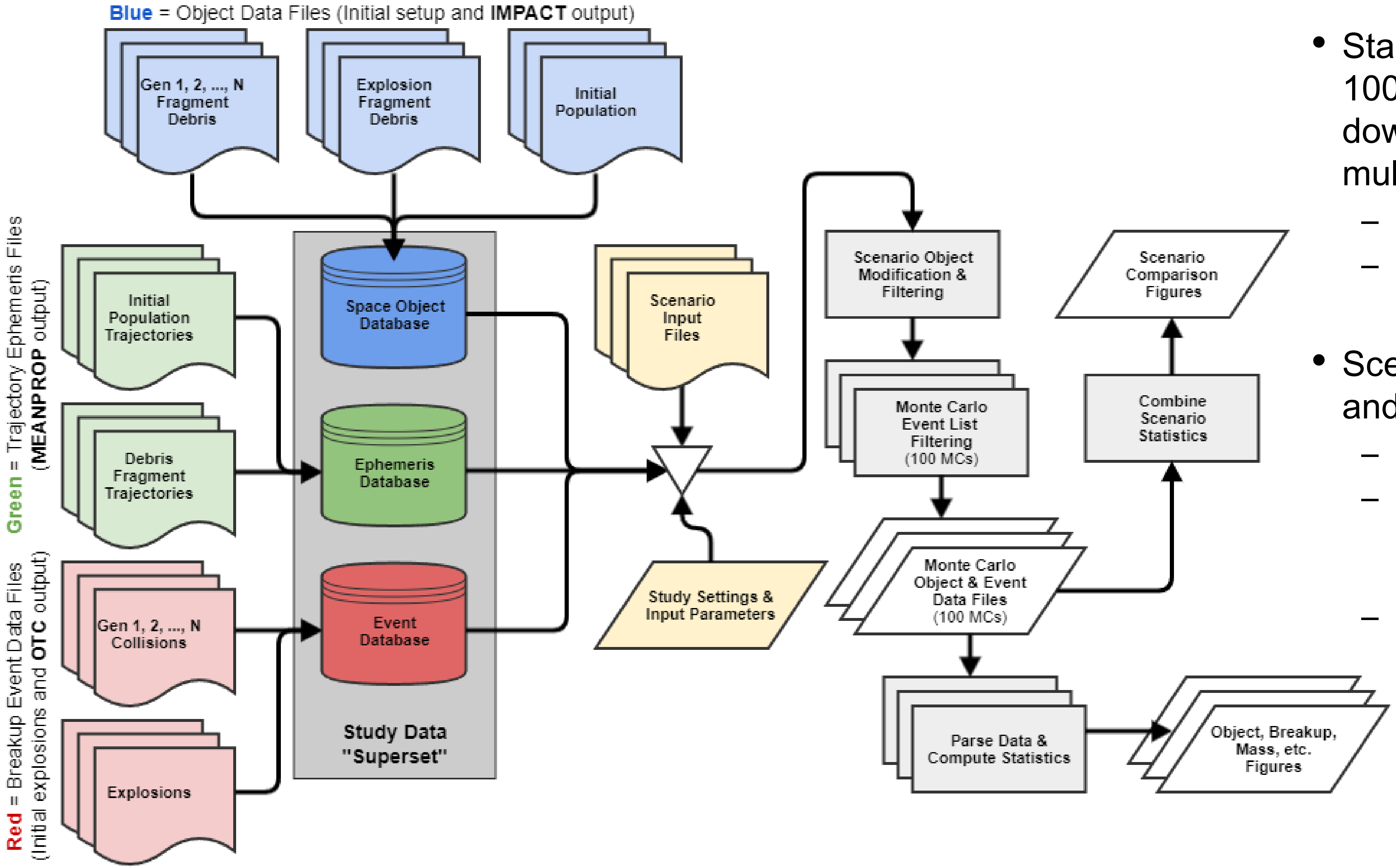
Everything, everywhere, all at once



- Batch process to generate all explosions, collisions, and debris fragments for 100 MCs
- Yellow box includes study setup steps, IPM propagation and downsampling, and explosion generation (based on observed historical rates)
- Purple box is a loop of OTC, IMPACT, Downsampoling and MEANPROP tools
  - Creates a generation of collisions, downsampled debris fragments, and fragment trajectories for those fragments
  - Repeat until feedback is no longer significant

Adept Simulation Post-processing Program (ASPPP)

Across the Debris-verse



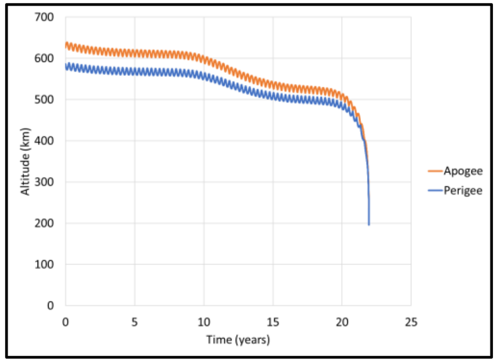
- Start with superset of all possible input objects, 100 MCs of all possible breakups, downsampled debris fragment population, and multiple feedback generations
  - Represents the future environment “multiverse”
  - Each scenario (discrete universe) is a subset
- Scenario defined by FLM traffic, PMD practice and success rate, etc.
  - Which FLM populations to include or exclude
  - PMD success rate and disposal practice set for each included full constellation, single constellation shell, or individual satellite
  - Scenario definition used to filter the possible breakup events in each MC

Breakup and Fragmentation Generation Process

Four main processes in collision and debris fragmentation loop

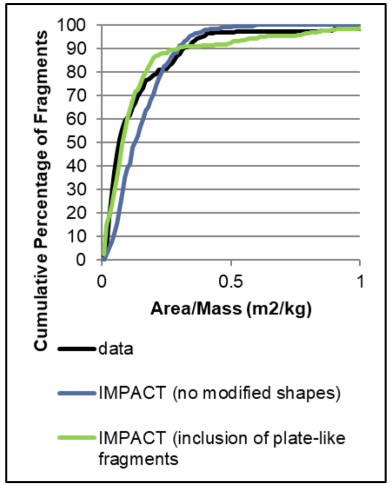
MEANPROP

- Long-term orbit prediction and stationkeeping software
- Mean element propagation based on Draper Semi-Analytic Orbit Propagator (SAOP)



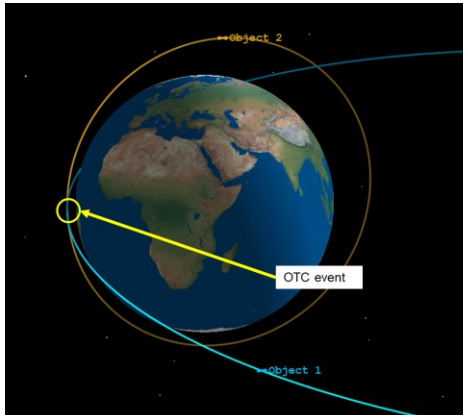
IMPACT

- Generates fragments from breakup events
- Semiempirical model used at Aerospace for >30 years
- Produces numbers, masses, area-to-mass ratios and spreading velocities for debris fragments



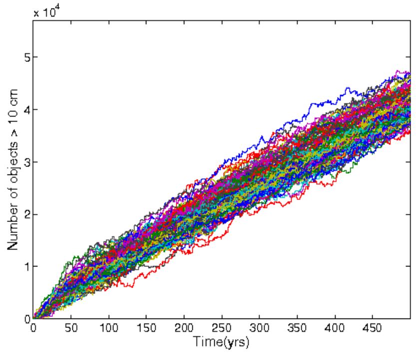
Orbit Trace Crossing (OTC)

- Computes Pc and generate collisions
- Finds OTC events between object pairs over study interval
- Orbit trace evolution accounted for by MEANPROP data
- Assume object mean anomalies (MA) are uniformly distributed over 360°
- Collisions generated by random draw on Pc for each OTC event



Downsampler

- Number of fragments generated by IMPACT for all collisions in 100 MC cases is too large to post-process
  - Especially when 1 cm fragments are retained
- Population is down-sampled to a smaller, weighted population by binning objects by mass in log space



Conclusions (From IAC 2024)

- ADEPT team ability to look at large number of scenarios has been enlightening and enables us to see patterns in behavior we would not otherwise notice

- Improved UMPY formulation results in better correlation and enables “targeting” desired outcomes by prescribing UMPY

- Successful test shows that very focused “turning the dial” on mitigation methods is very effective at targeting desired future environment
  - Lends itself to future work of finding cost-optimal combinations to achieve desired goal

- Method is extendable to arbitrary studies, such as tiered deorbit rule approach, and provides stable, consistent results across a wide variety of scenarios

Conclusions (From IAC 2025)

- Previous LEO Sustainability study provided significant value, both influencing policy and driving innovation in the ADEPT process
- LEO has changed significantly in the past 4 years, and will continue to evolve, potentially in far more drastic ways that we can yet anticipate
- Aerospace intends to keep up with the rapidly shifting landscape through tool modernization, process improvement, and moving toward shorter turnaround capabilities to advise policy and decisionmakers
- A significant update to the previous study is underway, pushing the limits of what the future LEO environment might be and leveraging the many new capabilities and approaches at our disposal

Conclusion (From 2025 ECSD)

- UMPY characterizes level of activity within a future environment simulation
  - Used to relate operational behaviors to environmental outcomes
- Multiple aspects considered when designing UMPY formulation
  - Correlations between scenario activity and environmental metrics are strongest when evaluating on-orbit mass
  - It is necessary to account for effect of lifetime and altitude on collision risk; effect is non-linear
  - Accounting for all uncontrolled objects allows different disposal strategies to be evaluated
- Approach to improving UMPY can be generally applied to developing environmental indices
- The intended use case and modeling approach can affect how indices are formulated
  - May be difficult to cleanly use different indices in different models

Thank you