OPUS: Orbital Debris Propagators Unified with Economic Systems

An Integrated Assessment Model of the Orbital Environment

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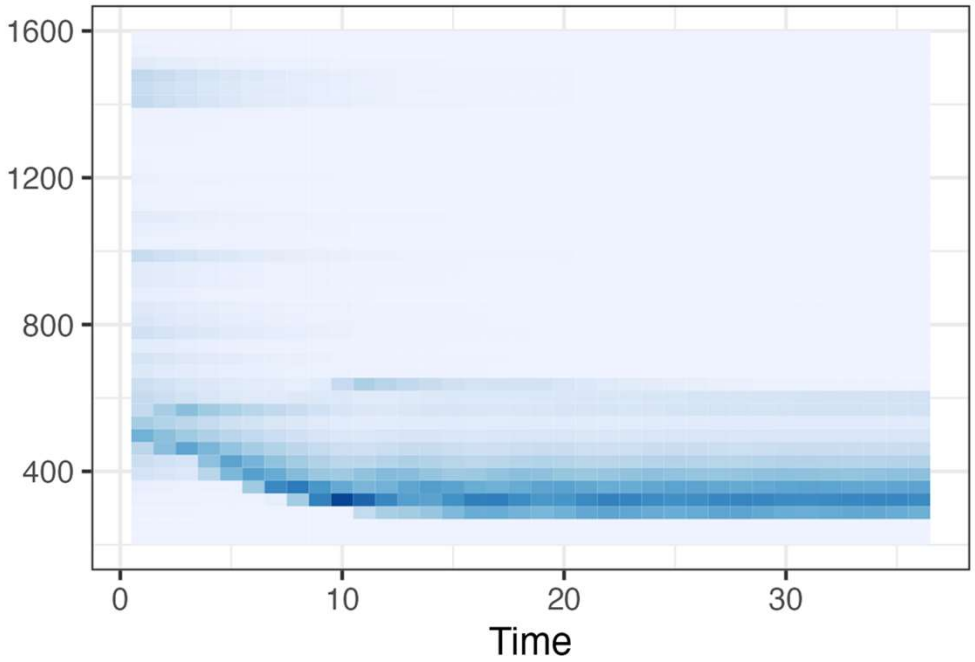
Background

- Radical shift underway in how we use space, primarily through the launching of large constellations and many more satellites with shorter lifespans
- Lots of policy proposals being offered to try and solve this issue
  - Technical (reduction in 25-yr rule, Pc vs Time/Area Product)
  - Regulatory (no propulsion above 400 km, mandatory propulsion
  - Economic (space debris bonds, orbit use fees)
- But lack of tools for policymakers to evaluate the efficacy of these proposals, and in particular how they could impact behavior
  - Many other fields have seen counterproductive outcomes as a result of unexpected changes in behavior to policy initiatives

OPUS: Orbital Debris Propagators Unified with Economic Systems

- Model architecture
  - I/O
  - Debris environment models
  - Economic behavior models
  - Revenues and costs
- Model validation
  - Emergent behaviors
  - Metrics
  - GMPHD
- Policy exercises
  - 25- vs 5-year disposal rule
  - 5-year disposal vs 25-year disposal with OUF
- Future R&D directions



Model architecture

User Inputs:

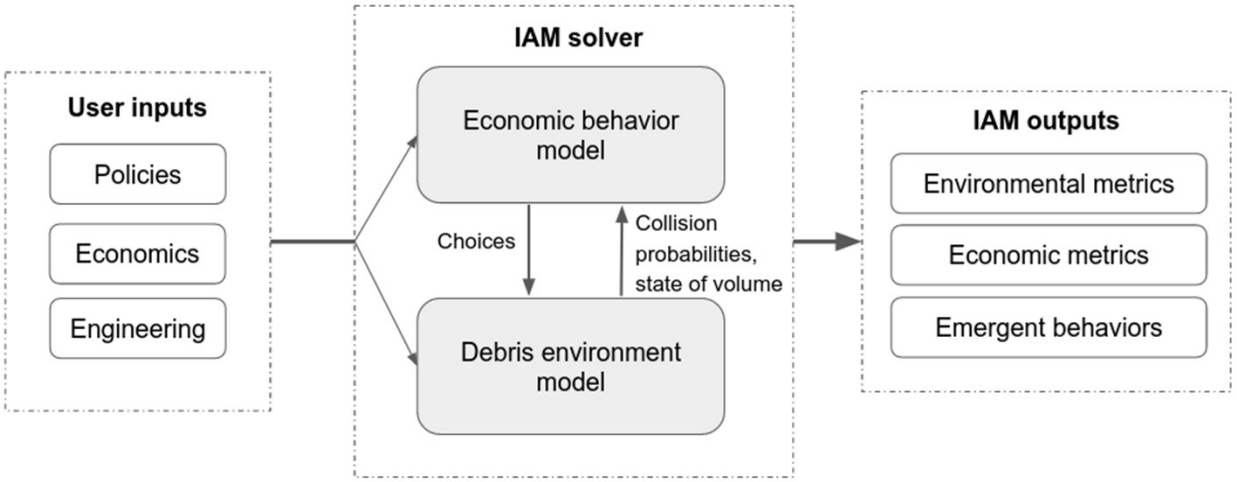
- CSV inputs, bash script

IAM solver:

- Environment model/propagator:
  - MOCAT-4S (main)
  - GMPHD (development)
- Economic model
  - Open-access launching
- MATLAB files: CSV outputs

IAM outputs:

- R files: images, CSV outputs



MOCAT-4S (MIT Orbital Capacity Assessment Tool 4S)

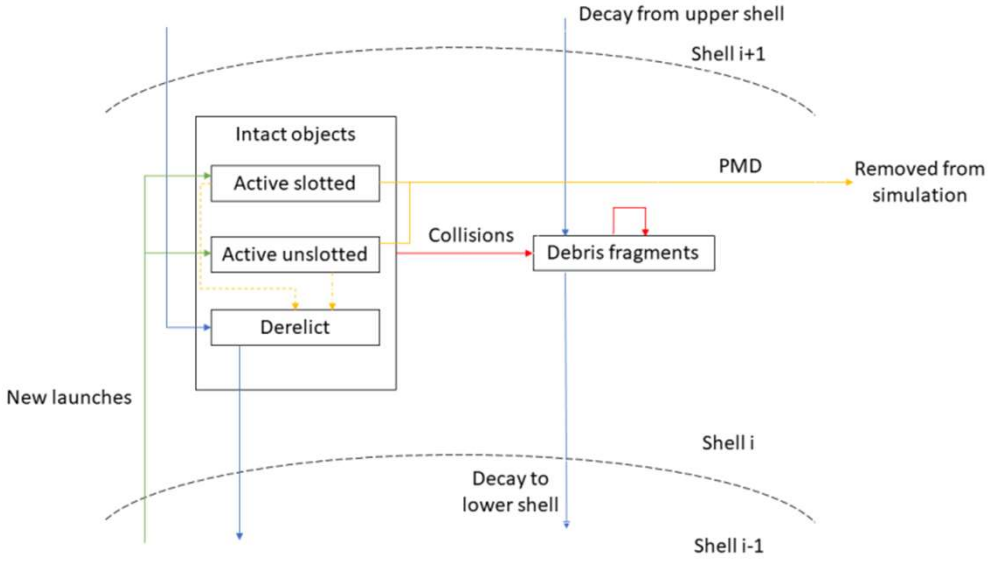
4-species source-sink evolutionary model (SSEM)

- Slotted = Constellation (exogenous)
- Unslotted = Fringe (endogenous)
- Derelicts = big intacts
- Debris = small fragments

Orbital locations parameterized as “shells”

- 40 shells, 200-1600 km altitude
- Each shell 35 km thick
- Annual time steps

Each species has a fixed size/mass



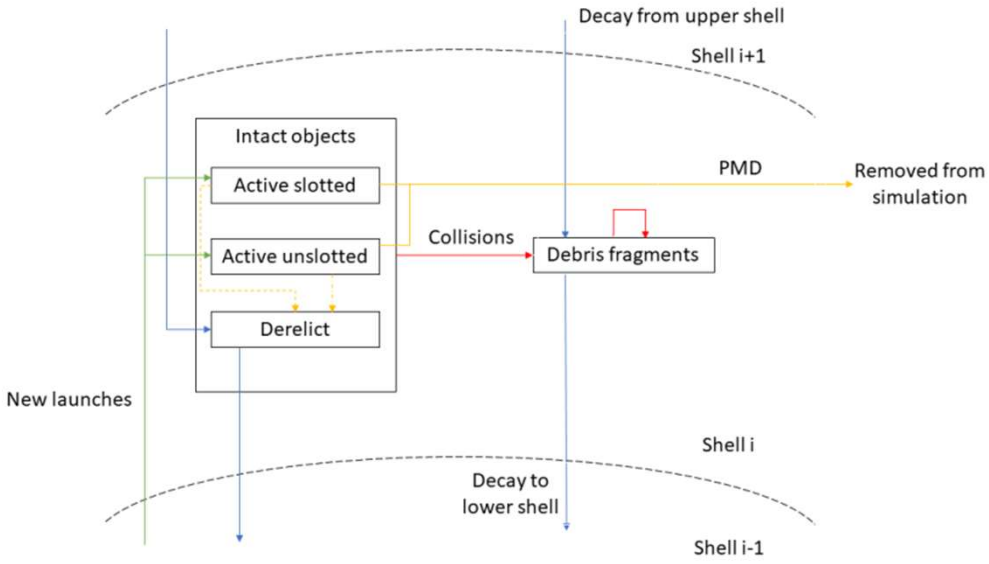
D’Ambrosio, Andrea, Miles Lifson, Daniel Jang, Celina Pasiecznik, and Richard Linares. "Projected Orbital Demand and LEO Environmental Capacity." (2022).

MOCAT-4S (MIT Orbital Capacity Assessment Tool 4S)

MOCAT-4S is the default propagator, integration is most-thoroughly tested

<u>Modifications from baseline state:</u>

- End-of-life disposal produces derelicts at highest naturally-compliant altitude
  - Only for satellites outside naturally-compliant zones
- “Disposal success rate” recast as “disposal non-compliance rate”
  - Default set to “full compliance”



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GMPHD (Gaussian Mixture Particle Hypothesis Density)

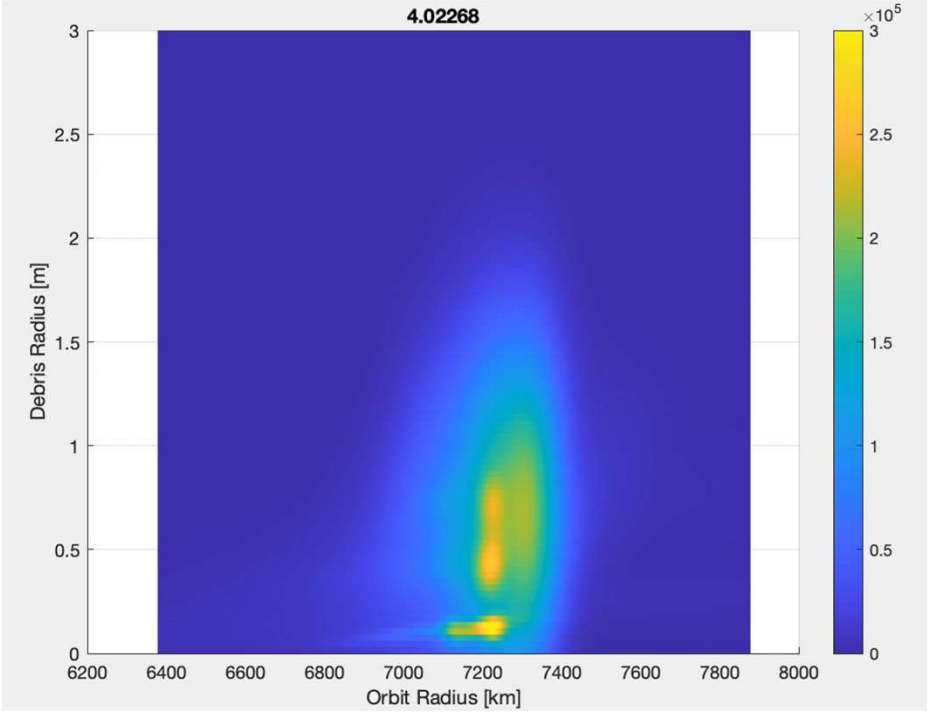
“2+∞”-species SSEM

- Slotted = Constellation (exogenous)
- Unslotted = Fringe (adaptive)
- Debris = all intacts+fragments

Continuous locations and debris sizes

- Calculate metrics in discrete “shell-bins”
- Annual time steps
- Can extend to arbitrary continuous indexing (inclination, RAAN, etc)

Debris have evolving distribution of sizes

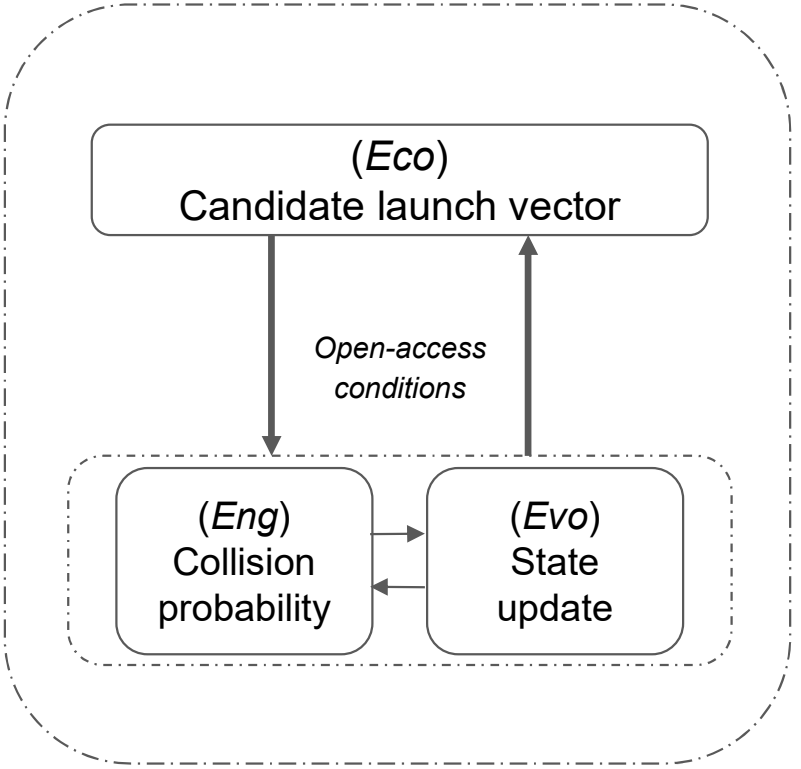


This is a new thing: show our framework is propagator-agnostic + plant seeds for future work + soft pitch on this extension

Economic behavior model

Two types of satellites:

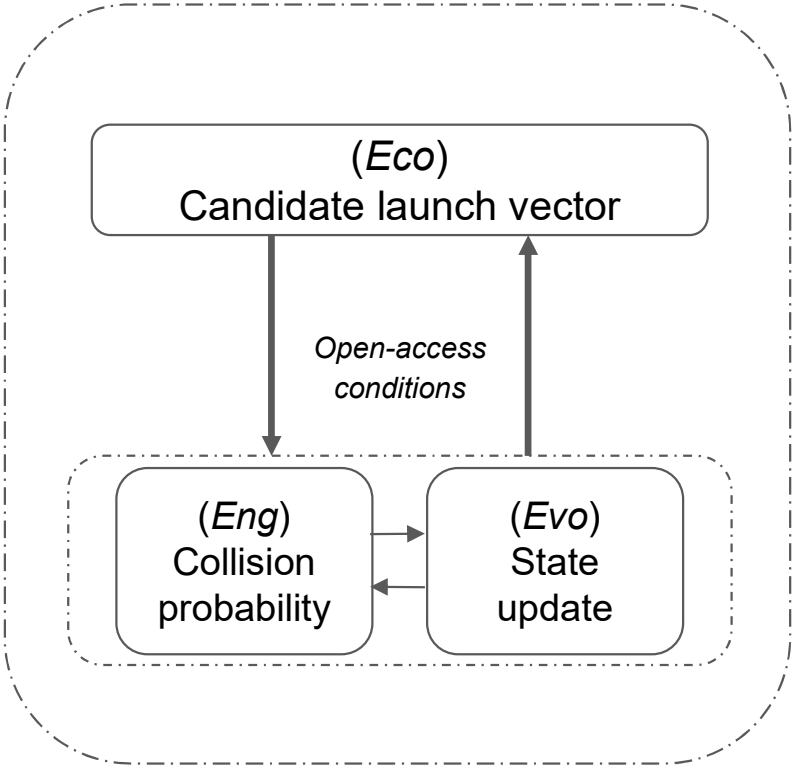
- Constellation
  - Many satellites under one operator
  - One operator per location
  - User-set locations, max launch rates, and target sizes
  - “Slotted”
- Open-access fringe
  - One satellite per operator
  - Many satellites per location
  - Endogenous locations and launch rates
  - “Unslotted”



Economic behavior (Fringe)

Open-access launching:

1. Economic actors make choices
   a. Launch if positive economic returns anticipated under "true" propagator
   b. Economic returns:
      Rate of return - discount rate - depreciation - collision chance - taxes
   c. Equilibrium: zero economic profits everywhere
2. Propagate state
3. Repeat



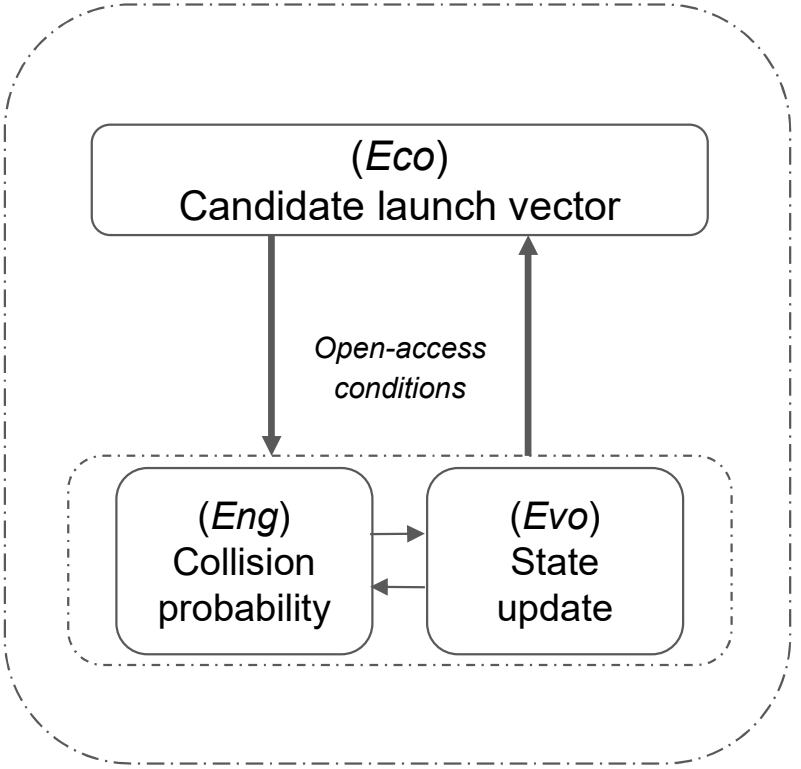
Economic behavior (Fringe)

<u>Open-access launching:</u>

1. Economic actors make choices
2. Propagate state
3. Repeat

<u>Null model: satellite feedback launching:</u>

- Launch rate to location k at time t proportional to satellites in k at time t-1
- Proportionality is location-specific: replenish natural decay only



Economic behavior (Constellations)

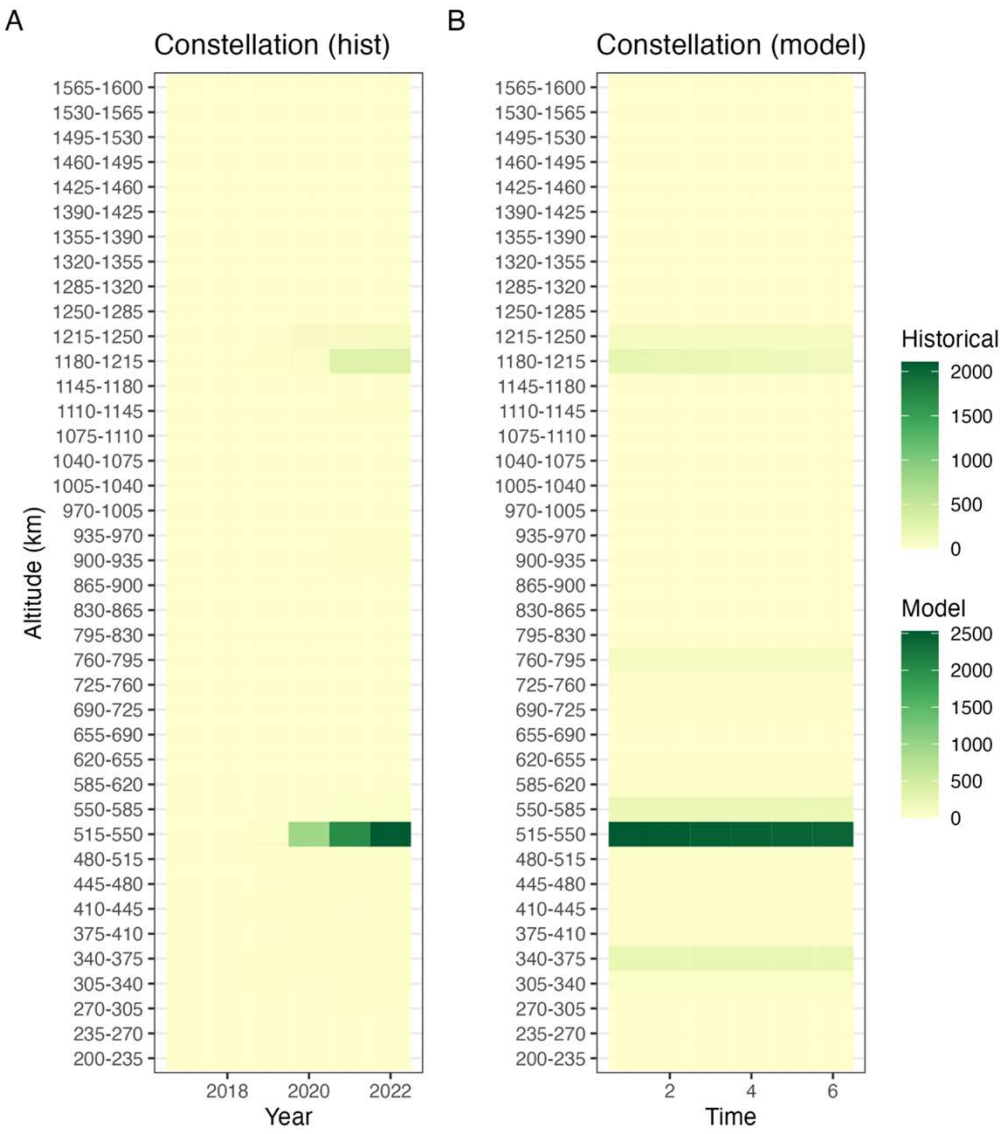
Constellation behaviors are set exogenously

User defines:

- The number of constellations
- Their locations
- Their maximum launch rates
- Their target sizes

Constellations build up to target size as fast as possible and maintain

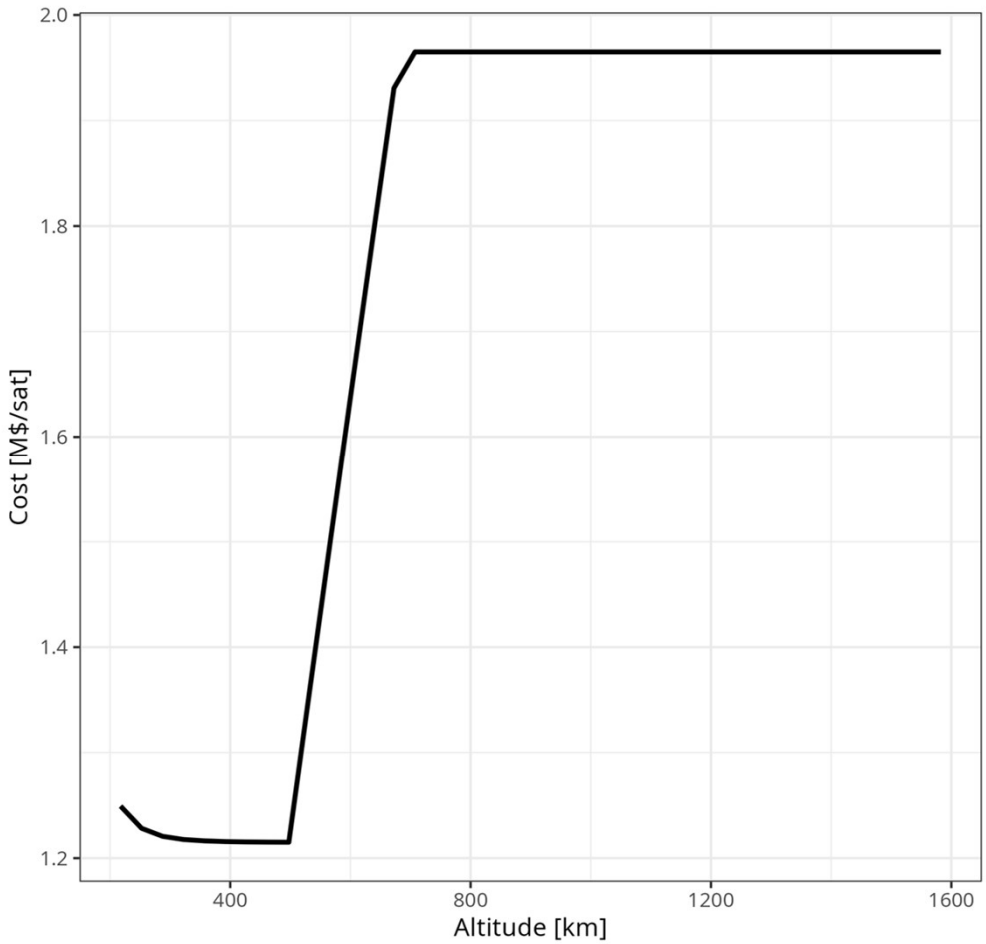
Same average compliance rate as fringe



Fringe costs and revenues

Revenue and costs:

- Costs:
  - Lift price: 5000 $/kg
  - Delta-v cost: 1000 $/m/s
  - Opportunity cost: forgone revenues from deorbit burns if compliant
- Revenues:
  - Linear inverse demand
  - Maximum: 750k $/year
  - Competition: -100 $/sat/year
- Benchmark:
  - No Pigouvian tax
  - 5-year lifetime (20% depreciation/year)\
  - Discount rate 5%



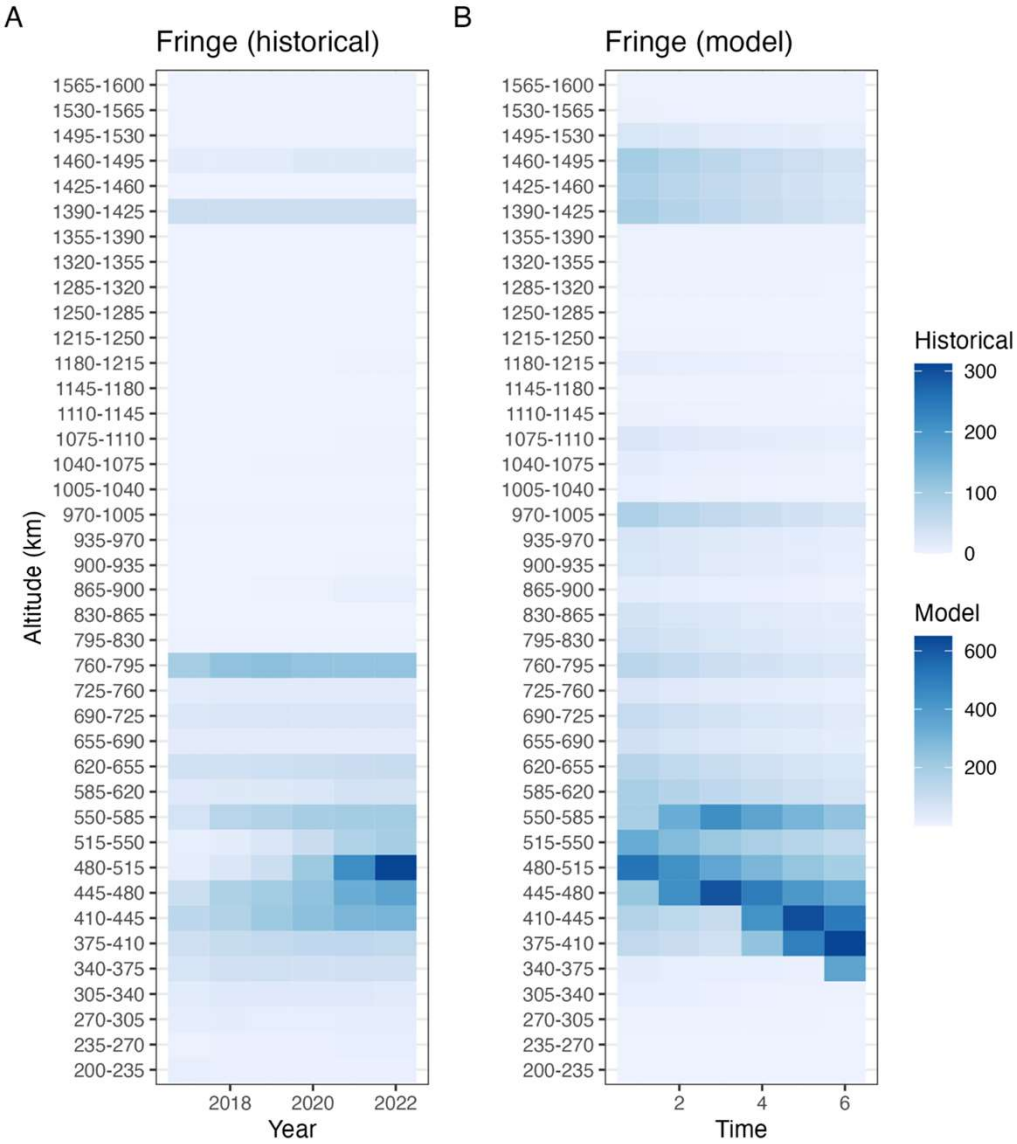
Model validation

Model predictions with 25-year disposal vs historical data 2017-2022

<u>Model captures:</u>

- Prefer naturally-compliant altitudes
- Avoid larger constellation
  - Prefer to be below it
- Avoidance of lowest shells
  - Highest drag

All “emergent” features!

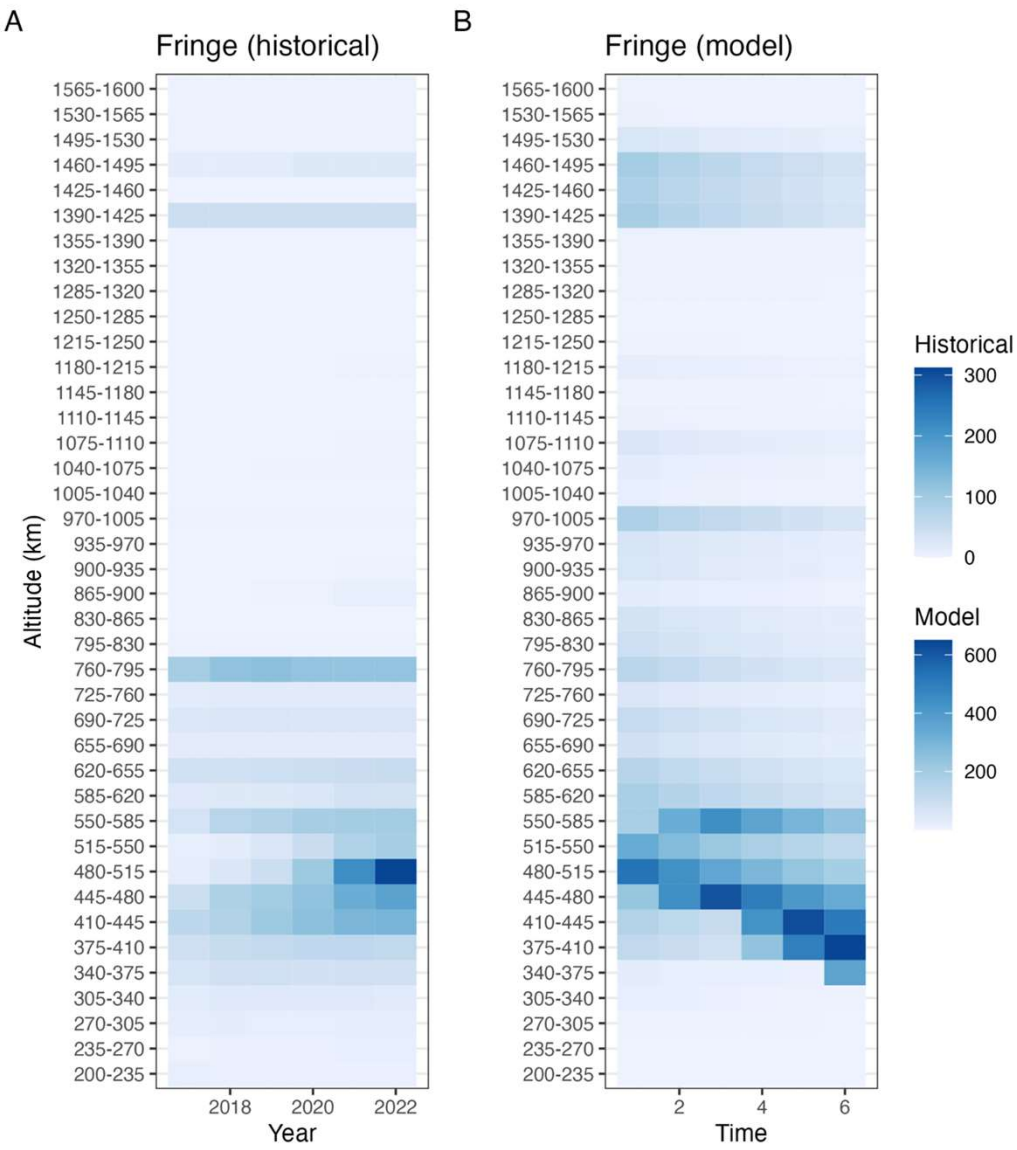


Model validation

Model predictions with 25-year disposal vs historical data 2017-2022

<u>Caveats:</u>

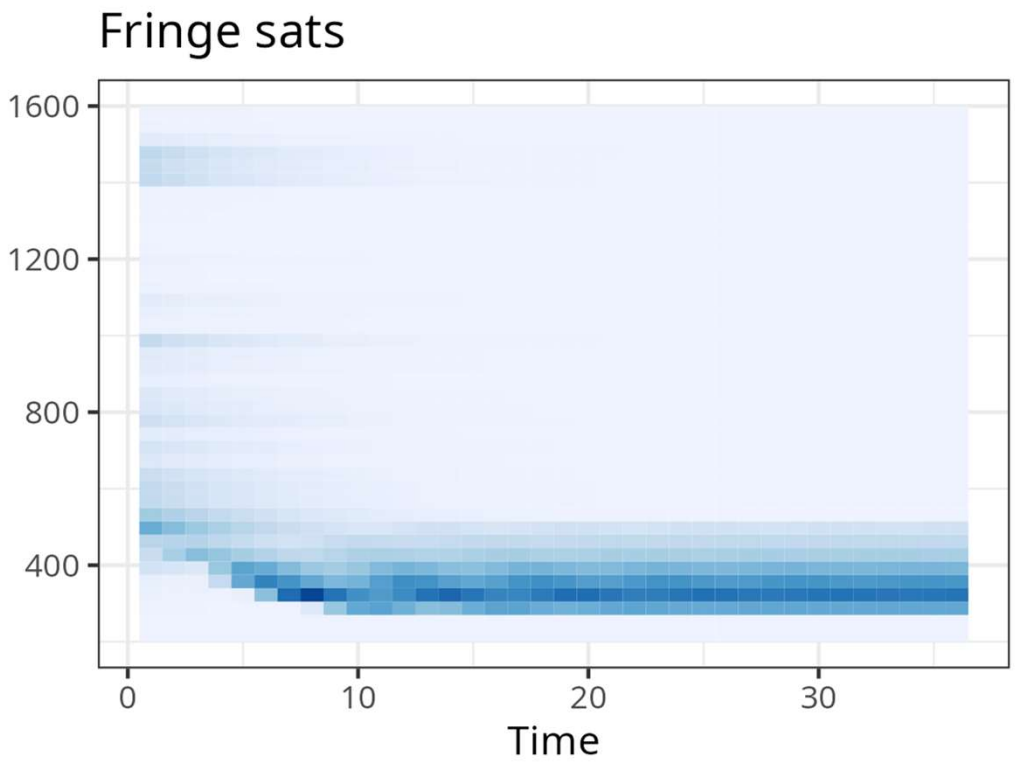
- Declining launch costs (real) vs static launch costs (model)
- Uncalibrated economic parameters
- Model starts from July 2022 population
- Model assumes full compliance
- Constellations start ~2020 (real) vs t=1 (model)



Emergent behaviors (5-year disposal, full compliance)

Some unexpected/plausible behaviors:

- Periodicity
  - Derelict decay + collective responses => damped oscillations in location values
- Minimum viable altitude
  - Stationkeeping costs => “floor” on how low it’s worth going
- Abandon higher altitudes
  - Too costly to dispose above naturally-compliant region

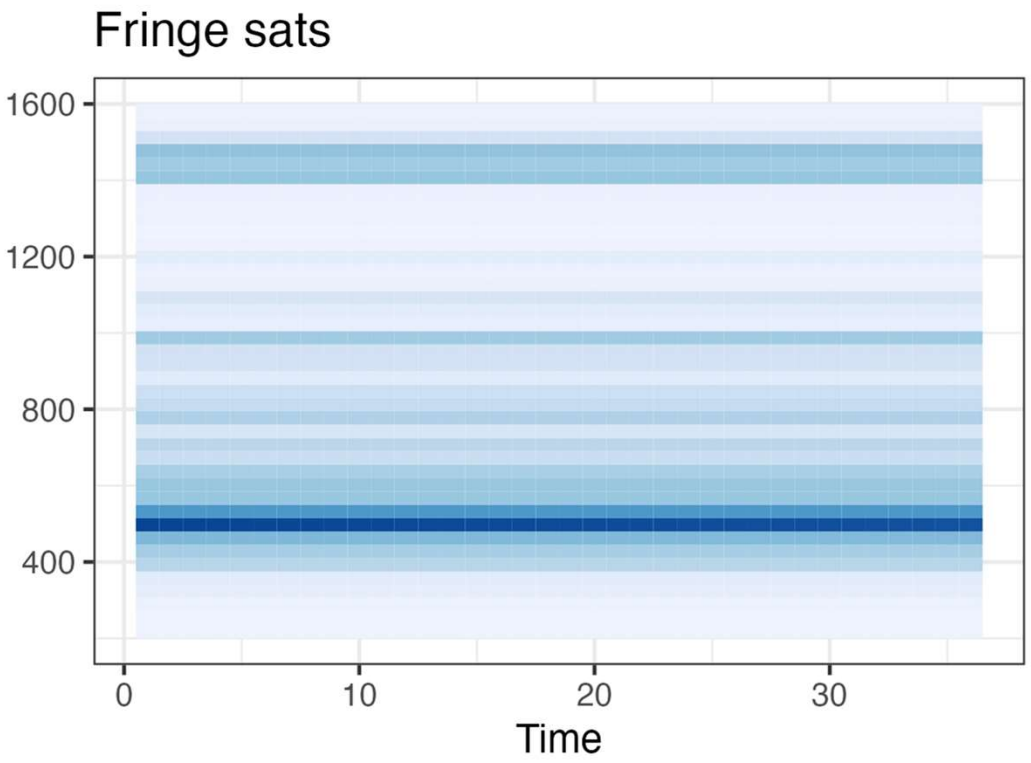


Emergent behaviors (5-year disposal, full compliance)

Some unexpected/plausible behaviors:

- Periodicity
- Minimum viable altitude
- Abandon higher altitudes

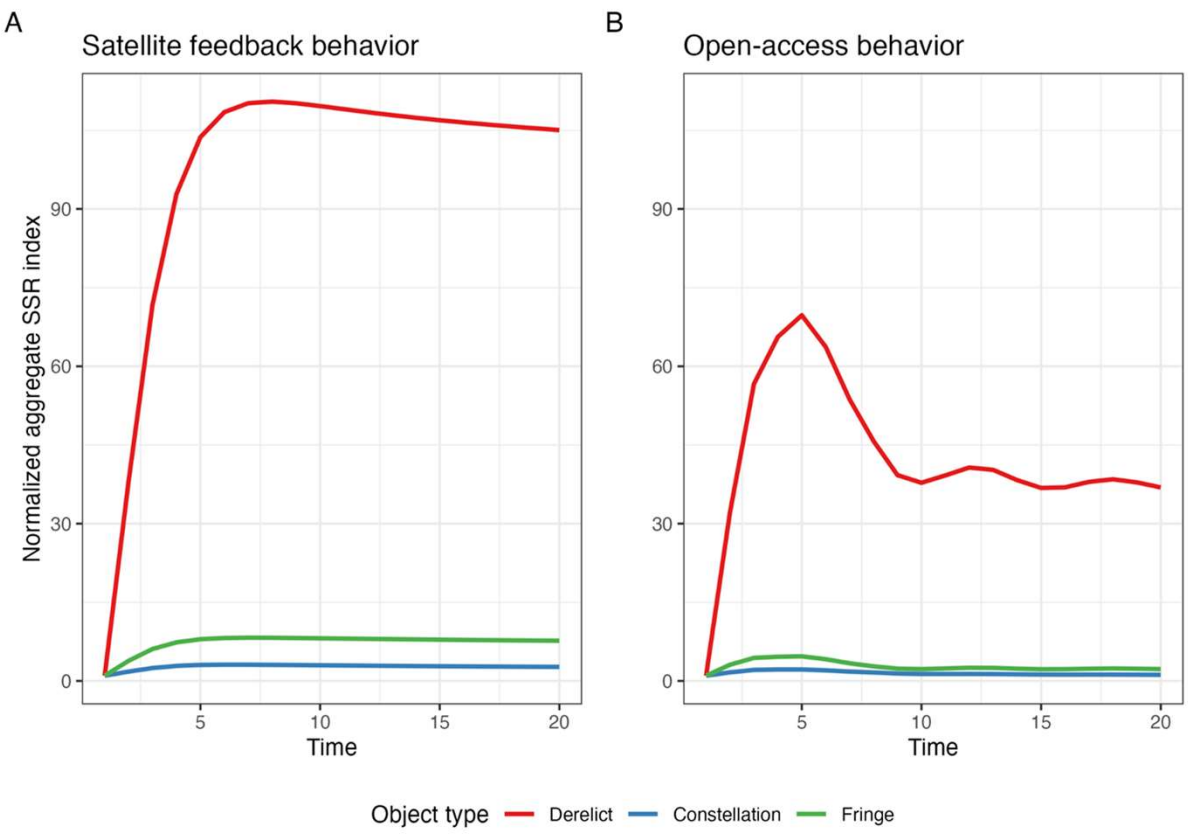
All absent in feedback behavior unless exogenously imposed



Metrics: SSR

Can calculate metrics to compare policies / illustrate effects of open-access behavior

- Peak as constellations build up derelicts
- Adaptive responses to collision risk => lower SSR index values (more sustainable)
- Still not maximizing social welfare
  (unpriced externalities)

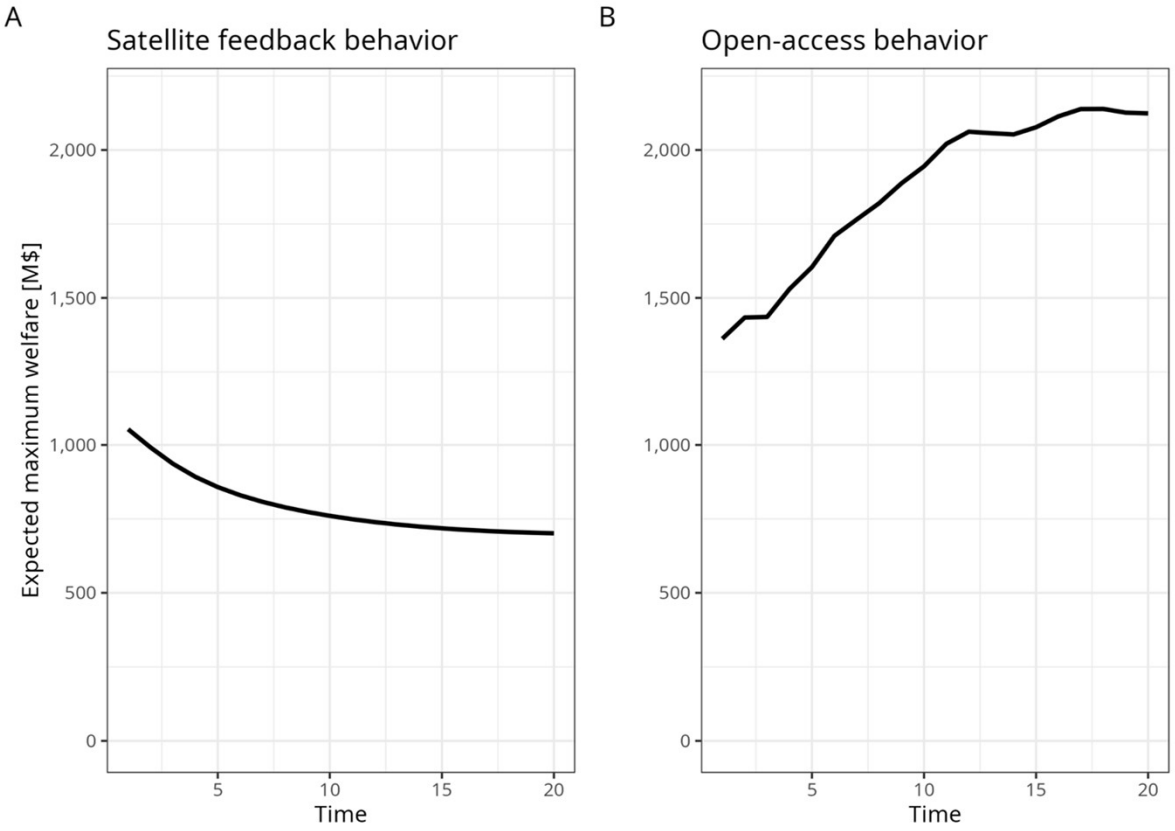


Model is uncalibrated – illustrative only

Metrics: Economic welfare

Can calculate metrics to compare policies / illustrate effects of open-access behavior

- Trough as constellations build up derelicts
- Open-access welfare increasing as firms adapt to environment
- Still not maximizing social welfare
  (unpriced externalities)



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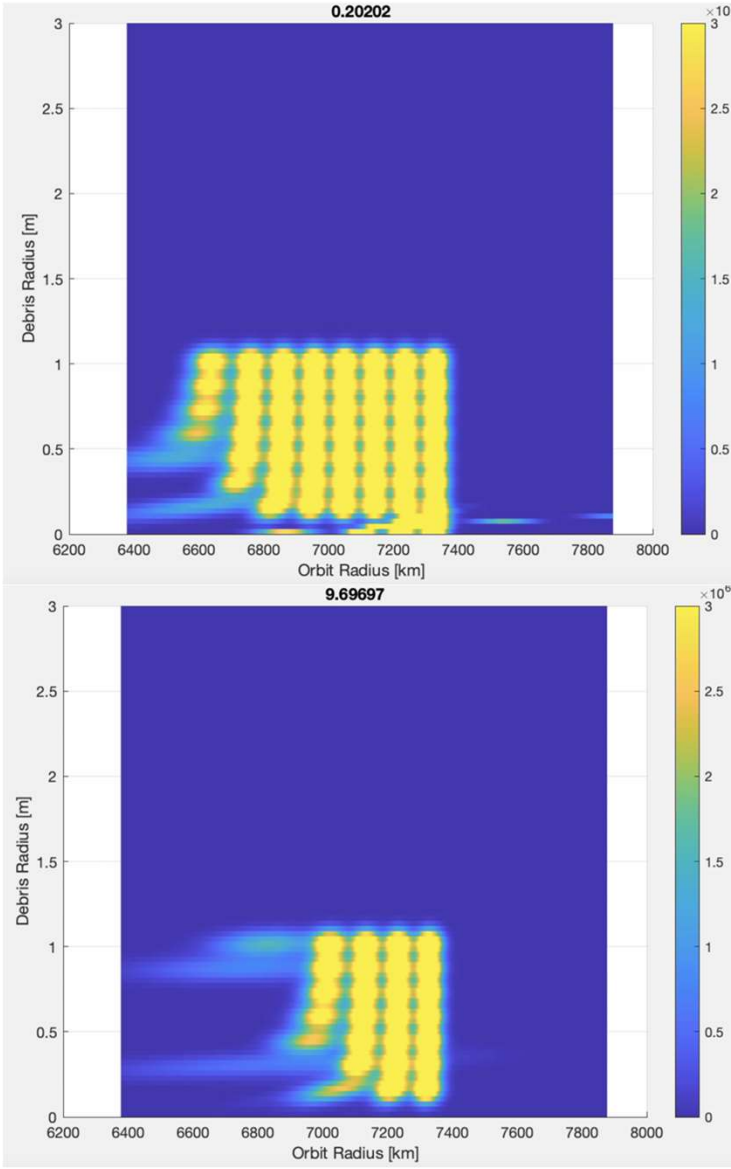
GMPHD

Currently in proof-of-concept stage

Requires further R&D to develop:

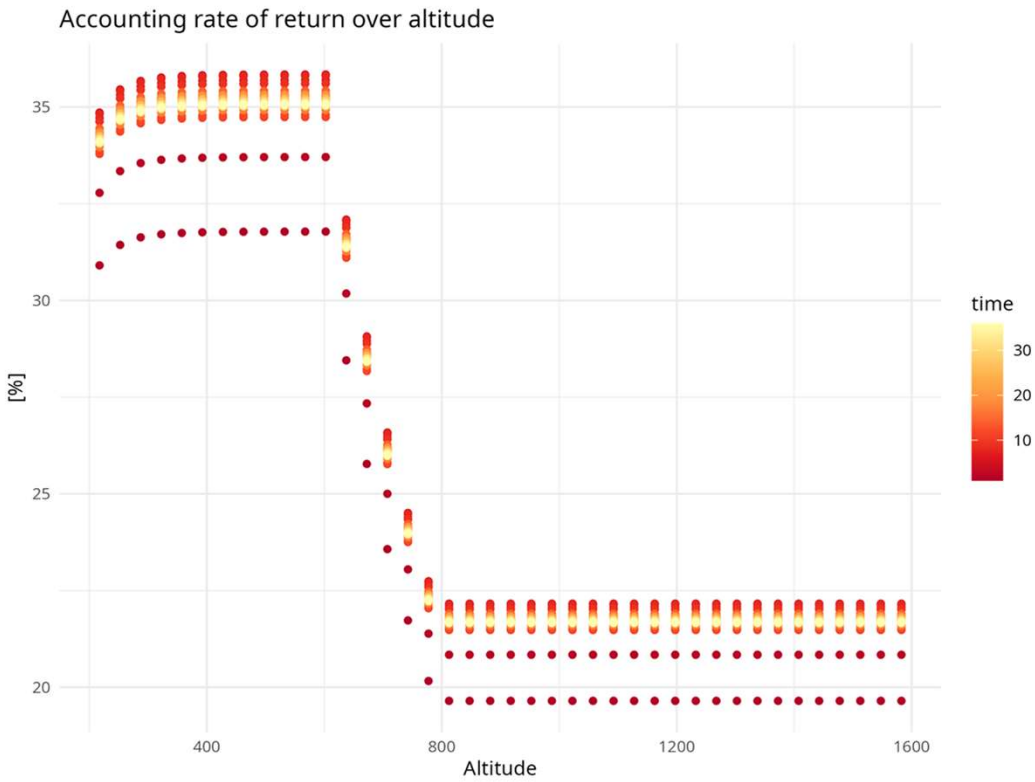
- Model calibration/data constraints
  - Size/altitude distribution of fragments per collision/fragmentation event
  - Minimum lethal sizes across altitudes/velocities
  - Effects of repeated non-lethal impacts across size distribution
- Useful hyperparameter settings
  - Number of Gaussians in mixture
  - Gaussian splitting/merging rates



Policy exercise: 25- vs 5-year PMD

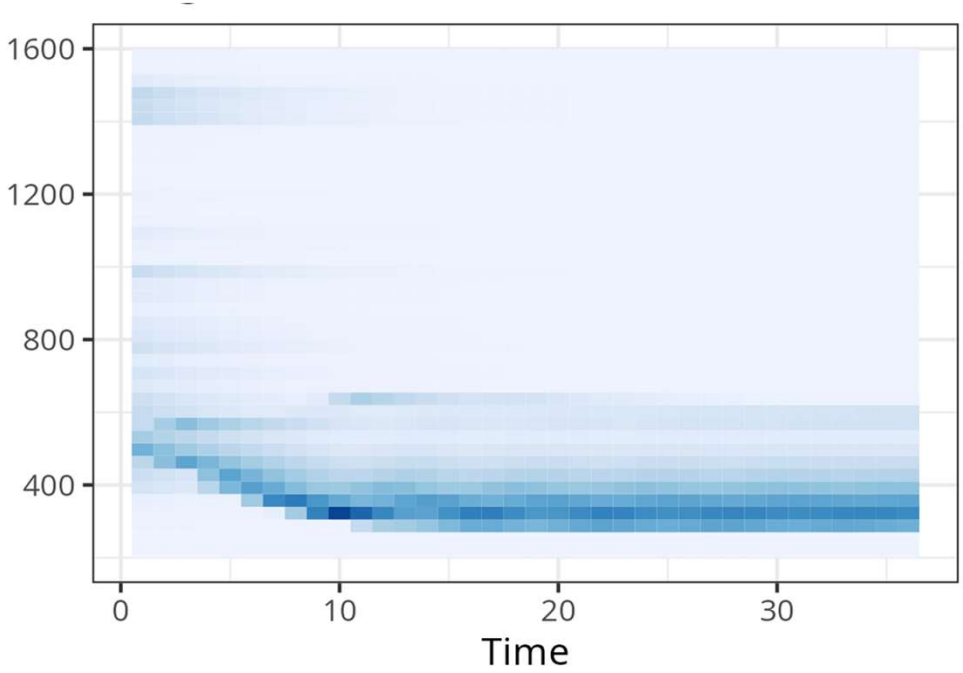
How much better is 25 vs 5 years PMD, accounting for behavior? Can simulate in OPUS

- Two separate scenarios
- Start from July 2022 initial population
- Assume full compliance

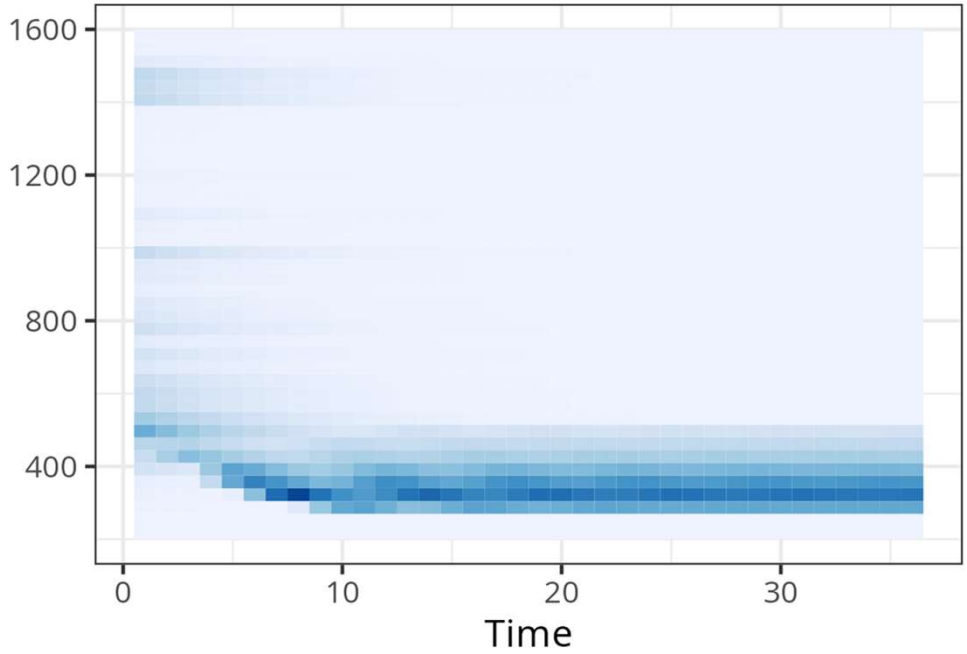


25- vs 5-year PMD (Fringe sats)

25 year PMD

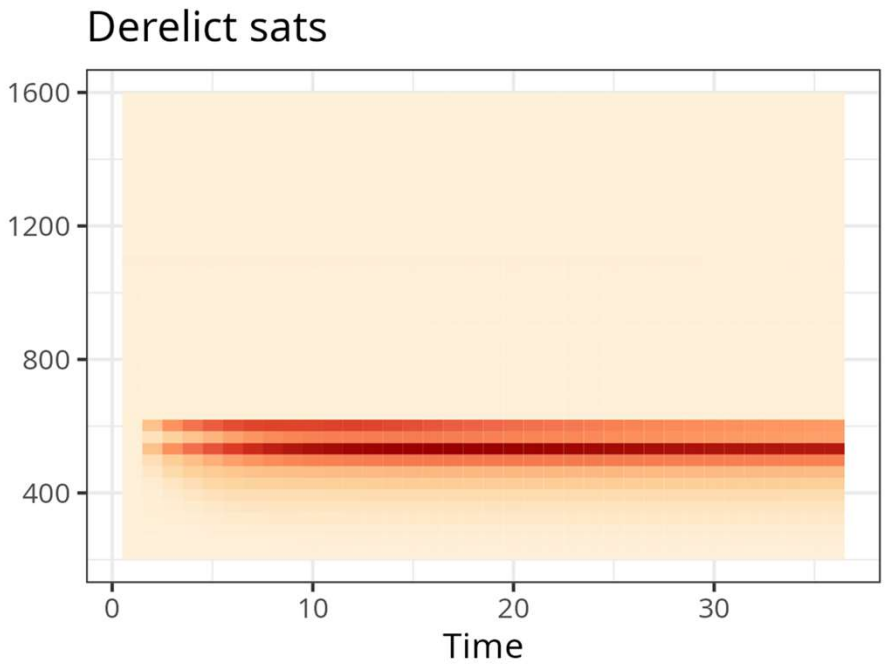


5 year PMD

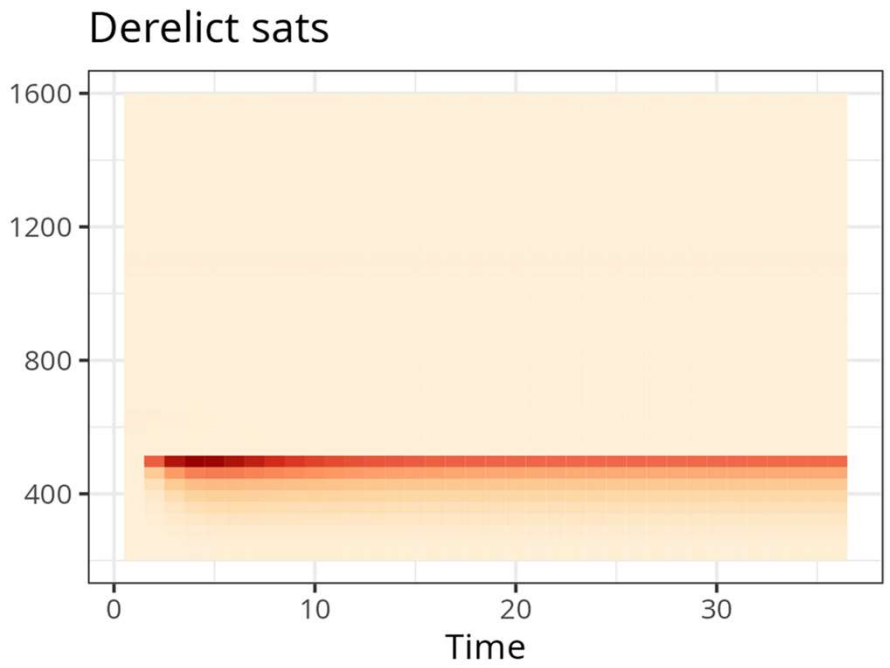


25- vs 5-year PMD (Derelict sats)

25 year PMD



5 year PMD

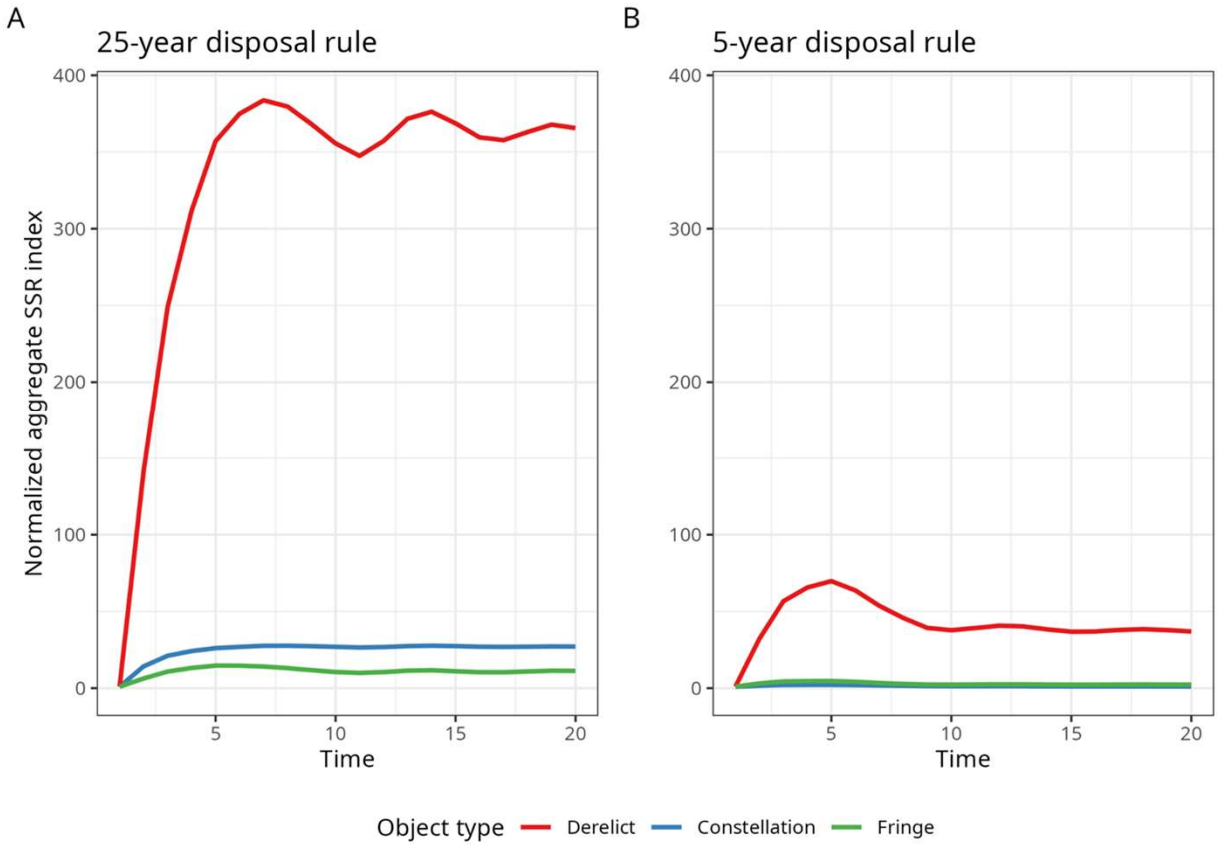


25- vs 5-year PMD (SSR)

Model is uncalibrated – illustrative only

“Aggregate” Space Sustainability Rating (SSR) to assess overall environment state

- Compute SSR across all objects of each type
- Normalize to 1 in initial state for comparison
- Higher numbers = less sustainable

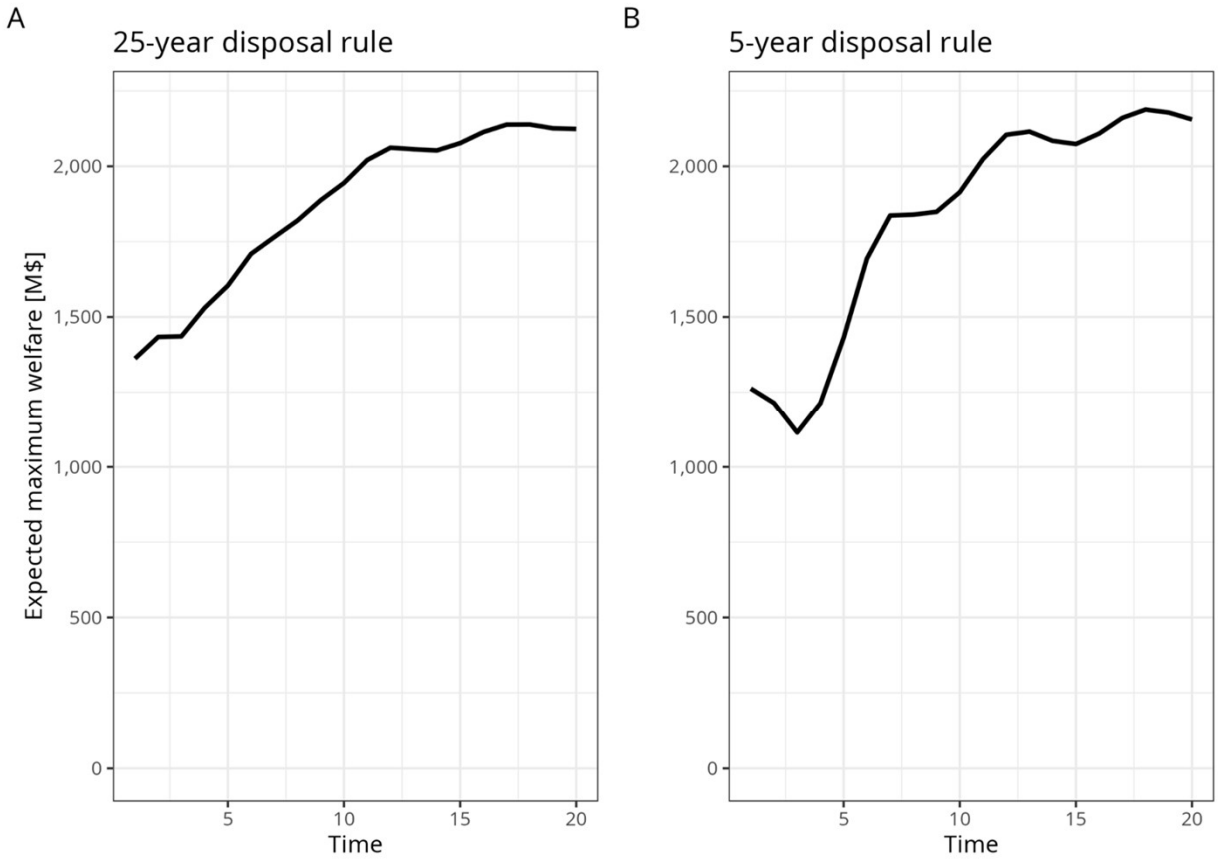


25- vs 5-year PMD (Economic welfare)

Model is uncalibrated – illustrative only

Expected maximum (upper bound) economic welfare to measure economic value to society from orbit use under policy

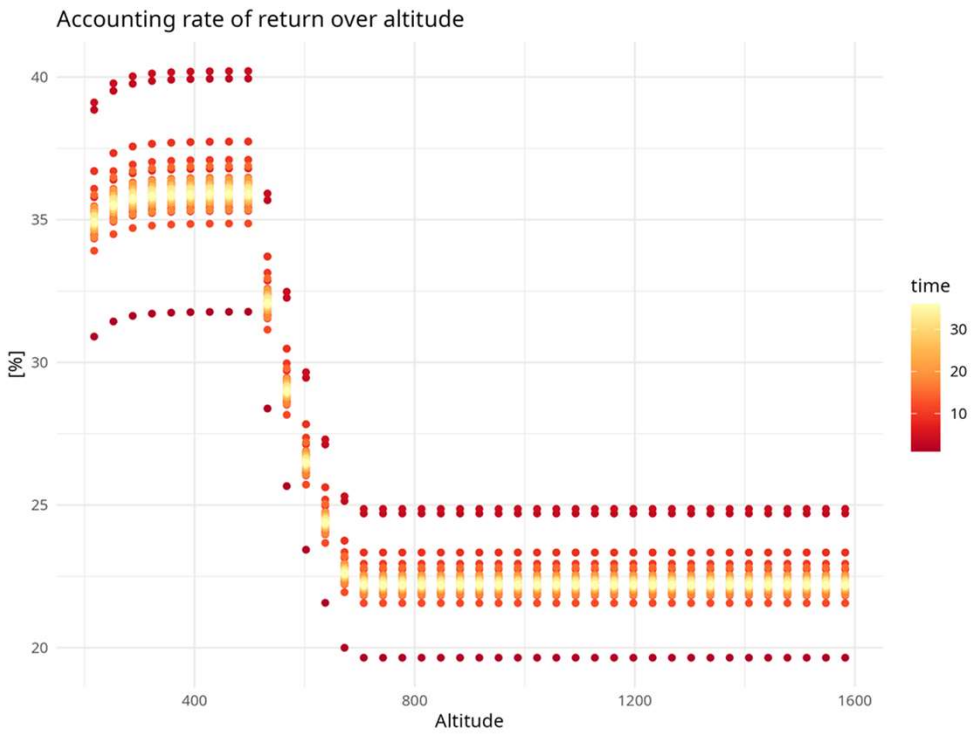
- Compute upper bound on expected NPV from fringe satellites
- Higher numbers = greater social value



Policy exercise: 5-year PMD vs 25-year w/ OUF

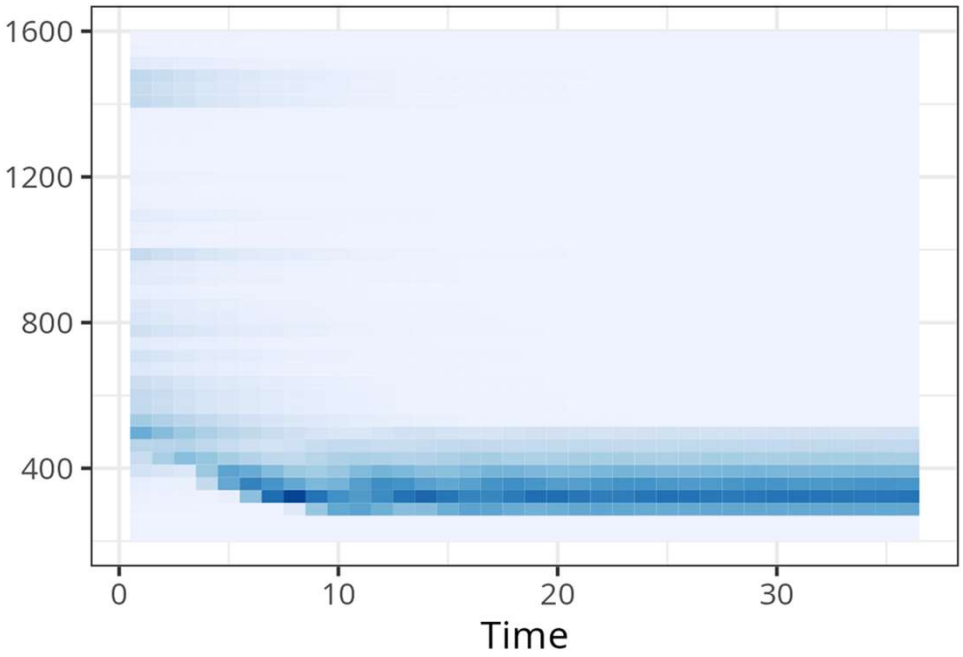
Are stricter disposal rules equivalent to taxes? Can assess in OPUS

- Two separate scenarios
- Start from July 2022 initial population
- Assume full compliance

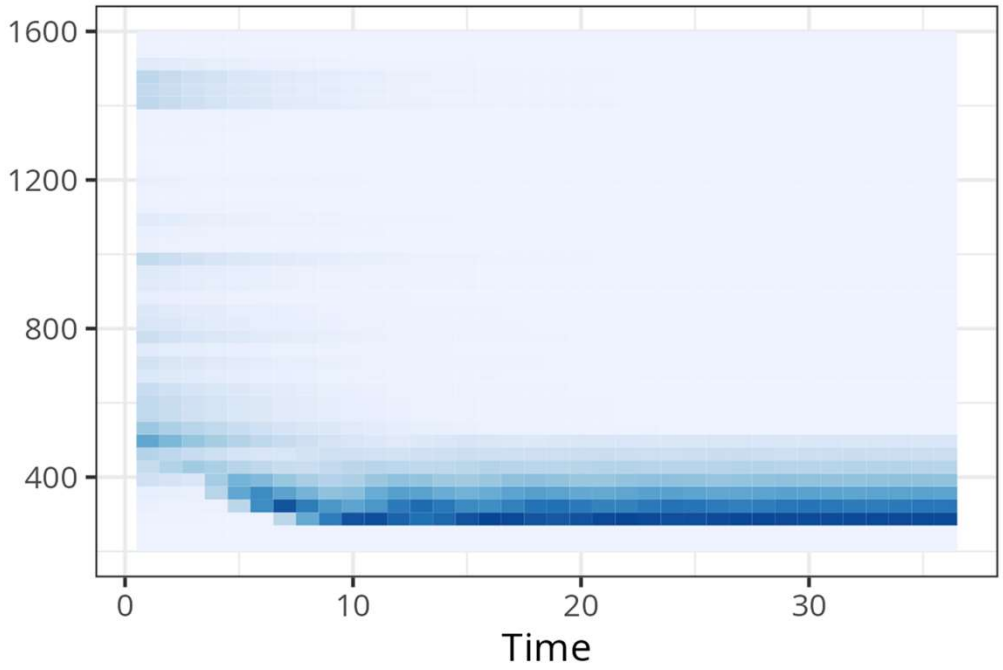


5-year PMD vs 25-year w/ OUF

5 year PMD

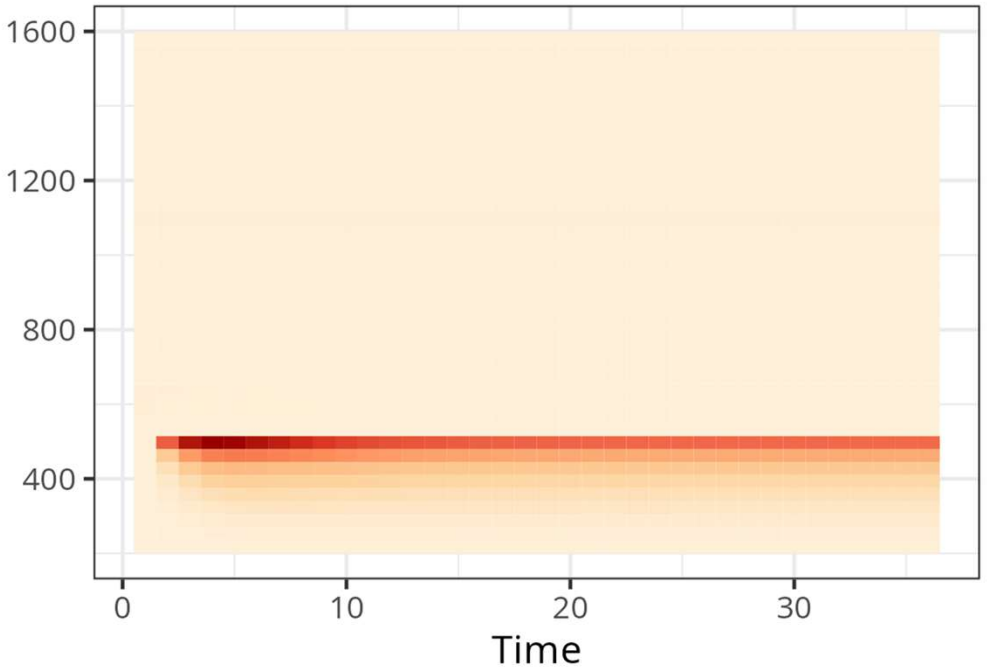


25 year PMD w/ OUF

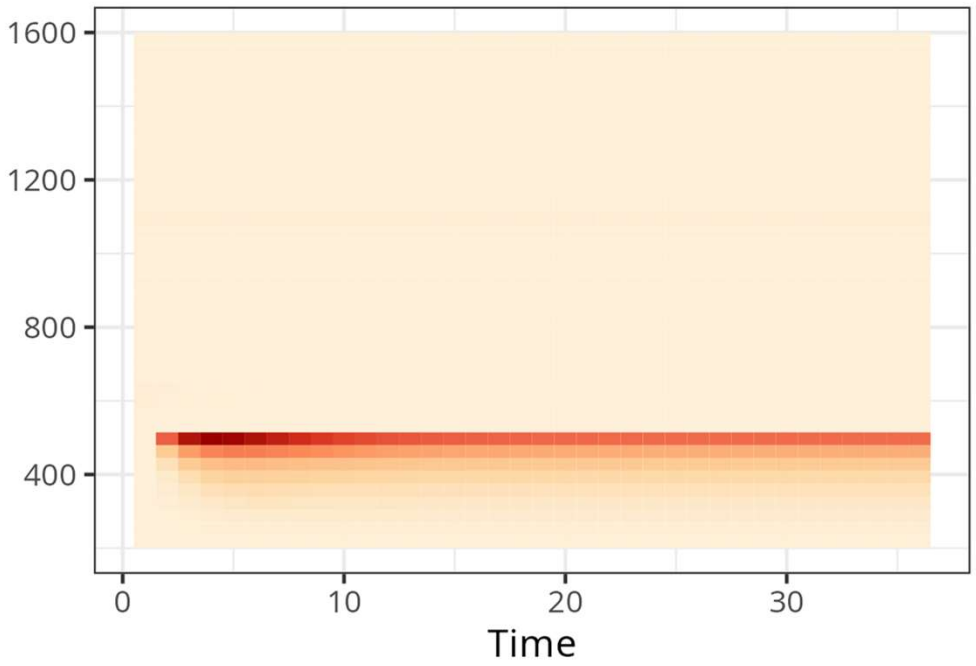


5-year PMD vs 25-year w/ OUF

5 year PMD



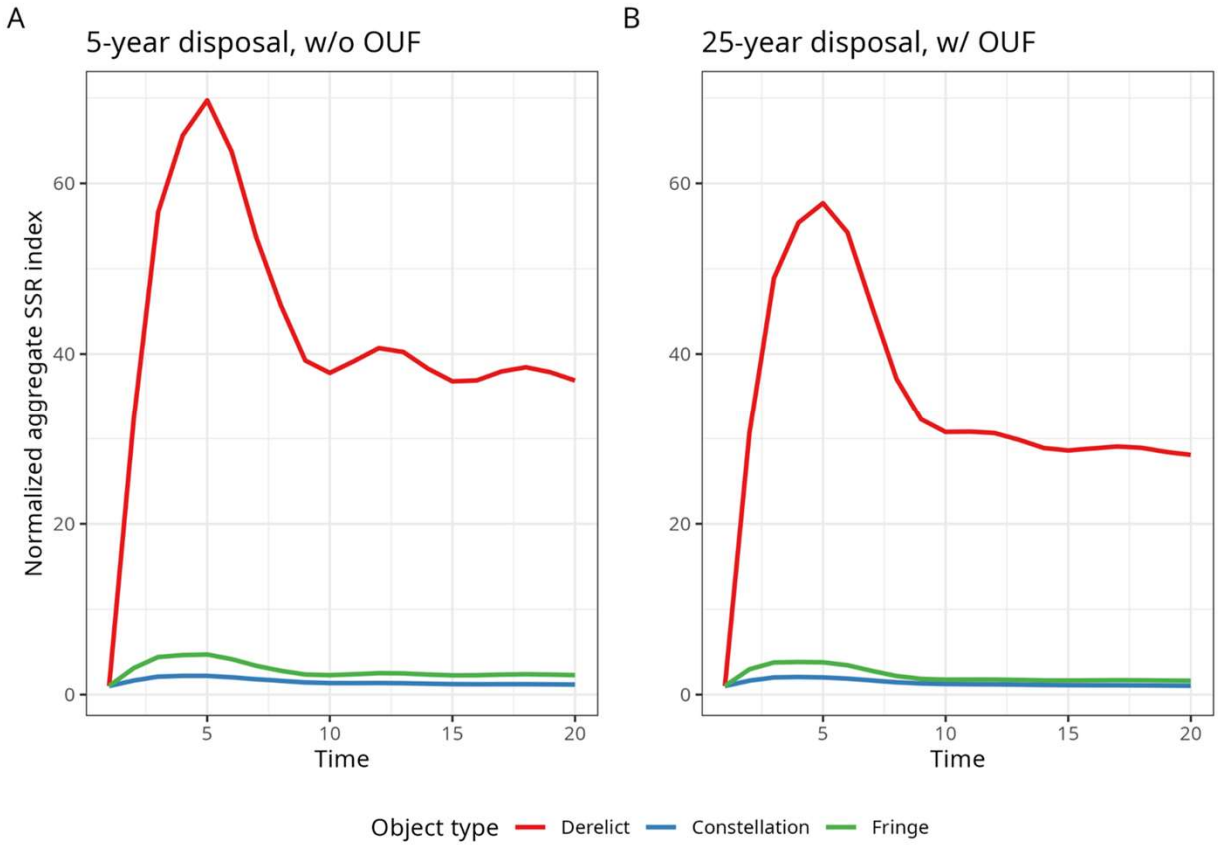
25 year PMD w/ OUF



5-year PMD vs 25-year w/ OUF (SSR)

Model is uncalibrated – illustrative only

- Take with salt
- *In principle*, OUF can replicate stricter disposal timeline



5-year PMD vs 25-year w/ OUF (Economic welfare)

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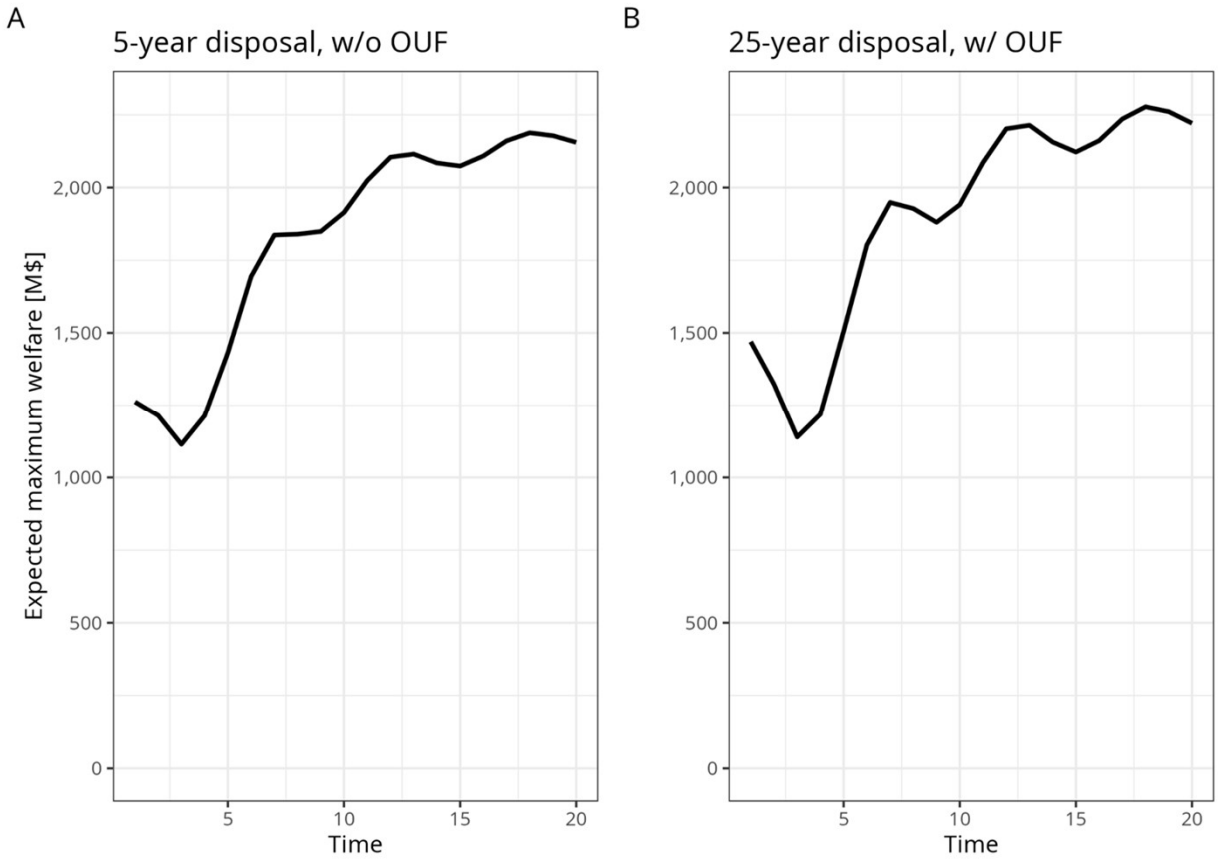
- Take with salt
- *In principle*, OUF can replicate stricter disposal timeline



Future R&D directions

Some directions for improvements:

- Improved economic parameter calibration
- Models of launch capacity and prices
- More detailed models of operator behavior
- Models of constellation behavior
- Models of non-commercial demand for satellite services