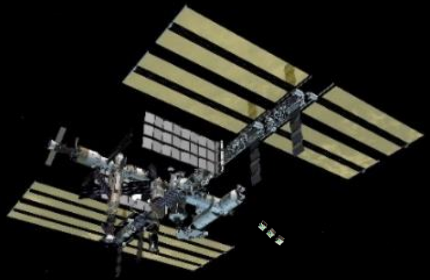


# New Perspectives & Options on Orbital Debris <u>for Cubesats</u>

Cubesat Developers Workshop
Cal Poly San Luis Obispo
April 25-27, 2023

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# So What's Special About Cubesats + Debris?

1. Cubesats mostly hit large objects, since they have most of the area.

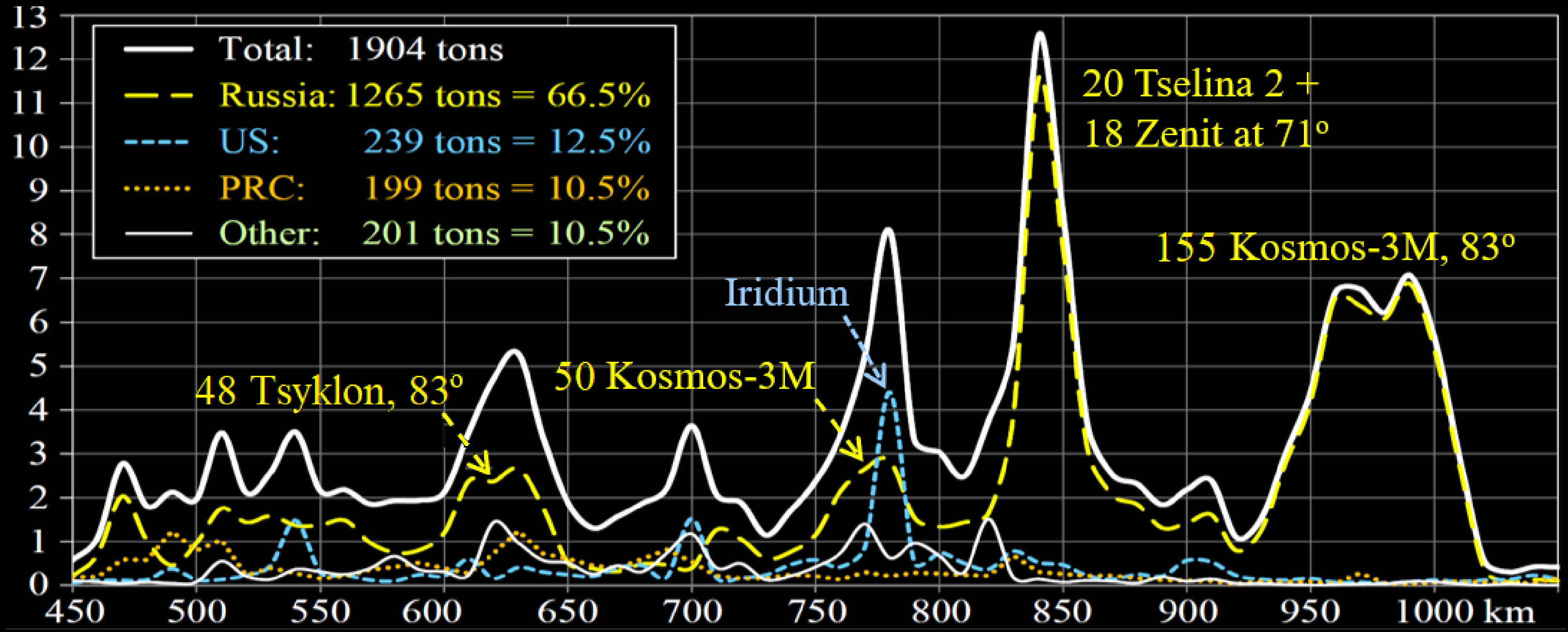
2. Compared to typical "car/car" collisions, a cubesat/car collision has:
   ~1/4 the collision cross-section, ~1/2 the total mass, and far less energy per kg.
   *Typical cubesat debris creation should be <10% that of typical large satellites!*

3. But most large expensive cubesat targets will actively avoid cubesats.
   Avoidance is a shared need, but can be done only by a maneuverable satellite.
   Cubesats have higher A/m & less stable CdA. That drives conjunction uncertainty!
   *Is it fair for cubesats to cause more frequent & larger maneuvers by $$$ assets?*

4. Eventually, LEO satellites may have to fly below other sats, or avoid them,
   ***or pay a fair share of avoidance costs imposed on other operators.***

# What Can LEO Cubesats Run Into?

Nearly all target area for Cubesats to run into is in objects of 200-9000 kg.
Much of that target area is Starlink satellites, and mostly their solar arrays.




Tons/km altitude in 2016. _Starlink has added >1000 tons, mostly near 550 km._

# An Informal Survey of Cubesat Developers

## Desired orbit life

1. Which orbit life would you prefer: ~6 months, 1 year, 2 years, or longer?
2. How much shorter life is ok, to cut ride cost 20%: <10%, ~30%, or ~50%?

## Collision avoidance

3. How can you actively avoid a collision: thrust, drag control, or neither?

## Coordinating avoidance

4. How long may it take to respond to other operators: <4 hr, 4-24, >24 hr?
5. What is your longest time between command links: <8, 8-24, >24 hours?

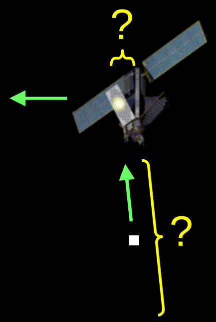
# Drag Area Variations Can Be Bad—or Good

## If you can't control drag area variations, minimize them! (typ. 1U cube)

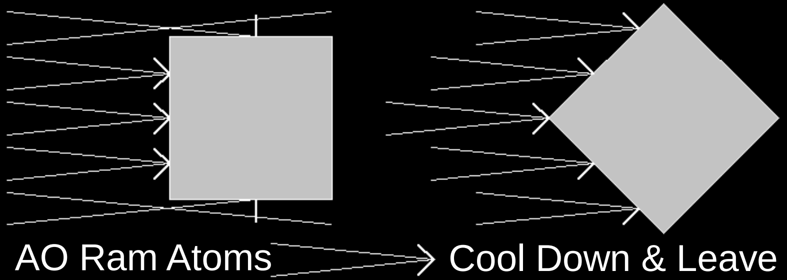
1. Conjunction uncertainties come from errors in predicting air density and drag area.
2. Cubesats are denser than most LEO assets, but still usually have higher A/m.
3. If you can't control drag area, reduce variations, to reduce others' maneuver needs.

## But if you can control drag area changes, maximize and control them!

4. 3U Doves point the camera down, but yaw to adjust ram drag area, if not imaging.
5. If you match orbit decay before a conjunction, air density changes have no effect.
6. If you can't match decay, use min or max drag earlier, to increase miss distance.



Prediction Errors



Drag in Free Molecular Flow


Dove Sats

# Observations and Recommendations

1. Delays in gov’t regs suggest they want the users to manage LEO. Do it!

2. One way is for LEO users to feel the external costs of their decisions.

3. One clear external cost is a fair share of others’ forced avoidance costs.

4. A useful avoidance option for cubesats is control of attitude & drag area.

5. Fly low! SpaceX should subsidize cubesat launches below Starlink:

   Now: <420 km (<ISS), to be <330 km before most Gen 2 Starlinks launch.

   3 yrs: <330 km (~1 month life!), once many Gen 2 Starlinks are in orbit.

   (Average satellite & debris orbit life at Alt=200-800km both scale with **~Alt$^{8}$**.)

# Additional Details

# Useful Links on Orbital Debris

A blog site for feedback:
tetherjoe.blogspot.com

## Analyses

E. Ostrom, Governing the Commons: The Evolution of Institutions for Collective Action, Cambridge U. Press, 1990.
D. Shoup, The High Cost of Free Parking, Updated Edition; Paperback, 800 pages, Routledge, 2011.
D. Kessler +1, www.castor2.ca/07_News/headline_010216_files/Kessler_Collision_Frequency_1978.pdf.
NASA Orbital Debris Program Office: LEGEND, Quarterly News, etc: https://orbitaldebris.jsc.nasa.gov/
AMOS Optical Conference, 2006-22 papers downloadable at https://amostech.com/amos-technical-papers/
IAC Debris Symposium A6, 2006-22: https://iafastro.directory/iac/archive/. See IAC-10.A6.2.10, Ailor et al on cost.
My 2014 cost paper, www.star-tech-inc.com/papers/Potential_Future_Costs_of_Orbital_Debris_in_LEO.pdf
Differential drag control of Planet's Dove 3U cubesats: https://arxiv.org/pdf/1806.01218.pdf, 2018.

## Engineering tools

DoD tracking: www.space-track.org, www.space-track.org/documentation#/faq, https://aerospace.org/cords
ORDEM, DAS, ORSAT, and other NASA tools: see https://orbitaldebris.jsc.nasa.gov/
MASTER & other ESA tools: see https://sdup.esoc.esa.int/, www.esa.int/Safety_Security/Space_Debris
LeoLabs commercial space radars & tools: see https://leolabs.space/

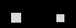
## Debris solutions?

Laser ablation: arxiv.org/ftp/arxiv/papers/1110/1110.3835.pdf, photonicassociates.com/Phipps_Acta2copy.pdf
Nudging by light pressure: ntrs.nasa.gov/api/citations/20150000244/downloads/20150000244.pdf
Wholesale LEO debris deorbit: www.star-tech-inc.com/papers/EDDE_2019_IAC_Submitted_Paper_Oct07.pdf
Satellite servicing + debris deorbit: https://astroscale.com/, spacenews.com/tag/space-debris-removal/

# Useful Terminology for Debris in Low Earth Orbit (“LEO”)

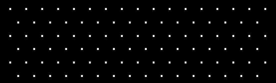
**“Cars” (~10,000)**

Intact objects, mostly dead, 0.1-2.5 tons typical; ~2% of lethal objects
Cars are >99% of the mass & target area of debris-creating impacts.
*~8%/yr car/car impacts will make most accidental hubcaps & shrapnel.*



**“Hubcaps” (~10,000)**

Tracked fragments, mostly 10-30 cm & 0.1-1kg; ~2% of lethal objects
Hubcaps are ~1/2 of LEO catalog, but only ~10% may shred most cars.
*Fengyun/A-sat & Cosmos/Iridium hubcaps are far lighter than predicted!*



**“Shrapnel” (500,000?)**

Lethal now-untracked fragments, >1 cm, ~1 gm; ~96% of lethal objects
Mostly too heavy to shield from; but much might be tracked & avoided.
*1-2cm shrapnel can shred a cubesat. Even ~1mm “hail” can disable it.*

*At 15 km/sec, an object may shred up to ~3000X its mass (~1 kg cubesat ➔ car), or disable ~1,000,000X its mass without a clear clue (~1 gm shrapnel ➔ satellite).*

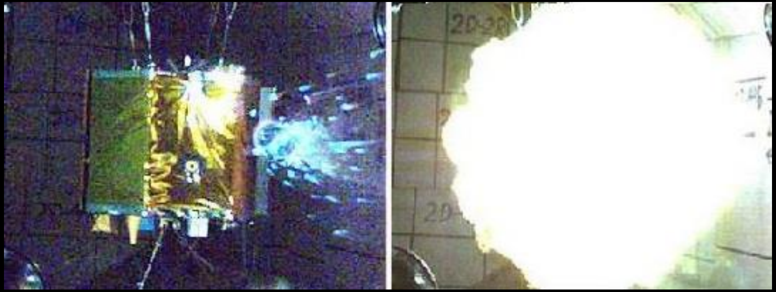
# How Hypervelocity Collisions Create Orbital Debris

## Key observables

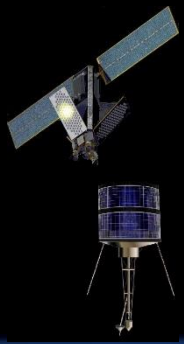
1. Most orbital impacts occur at 5-15 km/sec. Even metals splash at those speeds.
2. Ground tests show that a cloud of small debris expands at collision-like speeds.
3. But collisions in LEO create 2 trackable clouds that slowly diverge from each orbit.

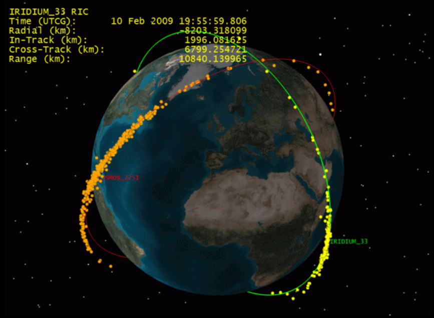
## And an explanation

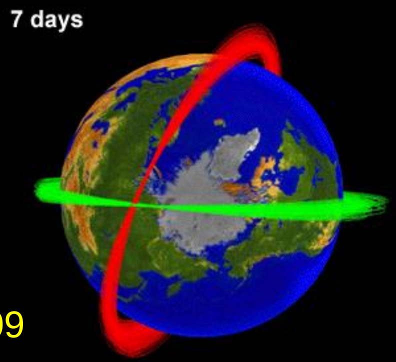
4. Collisions have offsets & different object sizes. Most mass misses the direct paths!
5. What does impact makes a “hypervelocity hailstorm” that shreds much of the rest.
6. Most hypervelocity hail that misses the rest leaves LEO, or is too small to be seen.



DebriSat test, 2014






Cosmos/Iridium collision, 2009

# Who Should Pay to Reduce Debris Costs?

## Who is responsible for new and old debris?

1. All LEO debris costs come directly both to & from LEO users, but at different rates.
2. Future new debris costs result from adding new objects to an existing population.
3. OST signers accept responsibility both for their objects and their entities' actions.

## Two key (but very unpleasant!) questions about responsibility for debris:

*4. Will debris regulation be delayed until most users clearly want regulation?*

*5. If LEO users don't pay for their new debris costs, why should anyone else?*

## What can cubesat developers do to minimize contributing to debris costs?

***6. Fly lower, to shorten lives of your cubesat and debris it makes (Life = ~$Alt^8$).***

***7. Be able to adjust drag area to proactively avoid most close conjunctions.***

# What Might Reduce Future Debris Costs <u>Most</u>?

## Options for individual operators

→ 1. Use lower orbits, to reduce impact rates, satellite life, <u>and</u> shrapnel life.
2. Move or re-orient satellites to reduce risks from predicted conjunctions.
3. Armor future satellites, to reduce the lethality of untracked shrapnel.
4. Reduce average satellite costs <u>and</u> accept more losses from impacts.

## Options requiring better tracking + better orbit predictions

→ 5. Nudge dead objects to avoid impact, using lasers or “smart barnacles.”
→ 6. Track and predict the orbits of more shrapnel, well enough to avoid it.

## Options involving wholesale debris removal (expensive!)

7. Capture & deboost large debris, <u>or</u> collect & recycle it for use in orbit.
8. Use laser ablation or space tugs to deorbit shrapnel & hubcaps (& cars?).

↑ *My bets on the 3 best options.*

# Bet 1: Payoffs of Flying Satellites in Lower Orbits

1. Altitude greatly drives orbit life of passive objects: **Life = $\sim Alt^8$**
2. Debris that they create also has an average orbit **Life = $\sim Alt^8$**
3. Higher drag reduces debris loiter time near your satellite altitude.
4. There are fewer satellites for your shrapnel to disable (**for now!**).
5. You also get less radiation, <u>but</u> more AO erosion & reboost needs.

*Up to ~800 km, shrapnel creation * life scales with* **$\sim N^2 * Alt^{16}$**

An extreme case:

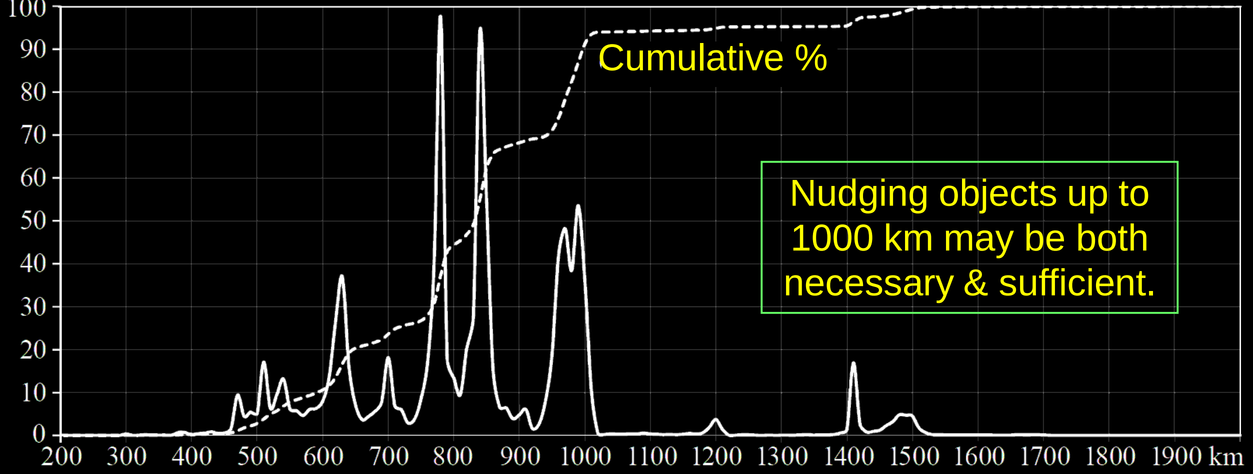
ESA's GOCE ran a "Red Queen Race"

(Run as fast as you can, just to stay in one place.)

# Bet 2: Payoffs of Nudging to Prevent Car/Car Collisions

1. Required ΔV is tiny: a 1 km/day shift needs just 4 mm/sec along-track ΔV!
2. Nudging can be done by “smart barnacles,” light pressure, or laser ablation.
3. Ablation can allow >20,000X more impulse/photon—if it is focused enough.
4. Deorbiting needs ~50,000X higher ΔV than a 4 mm/sec avoidance nudge.
5. Better conjunction predictions reduce how much & often we must nudge.

Likely >1 Gram Shrapnel Created by Impact per Year per Km Alt, 2016




Servicer despins debris & attaches a “smart barnacle” to nudge it later.

Laser pulse

But all workable debris fixes can serve as A-sats!

# Details on Nudging by “Smart Barnacles”

## “Barnacles” are attached hi-rel nanosats with thrusters

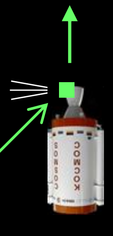
1. New long-lived satellites can each launch with a barnacle.
2. Satellite servicers take similar barnacles to existing objects.
3. On command, barnacles thrust to avoid close conjunctions.

## Key requirements on barnacles

4. GNSS + laser retroreflectors, to reduce orbit uncertainties
5. Propellant for many nudges (but avoid or use tumbling!)
6. Enough reliability & radiation tolerance for the intended life

## Some complications

7. Attitude affects comlinks, GNSS, ranging, power, & nudges.
8. Nudges can affect attitude & hence drag—perhaps usefully.
9. Operators must preclude or detect hacking of barnacle ops.



Servicer despins debris & attaches a “smart barnacle” to nudge it later.

# Details on Remote Nudging by Lasers

## Nudging by light pressure

1. Continuous vs pulsed lasers give more photons per $.
2. Local target heating will limit maximum nudge/pass.
3. We need many lasers **+** very good orbit predictions.

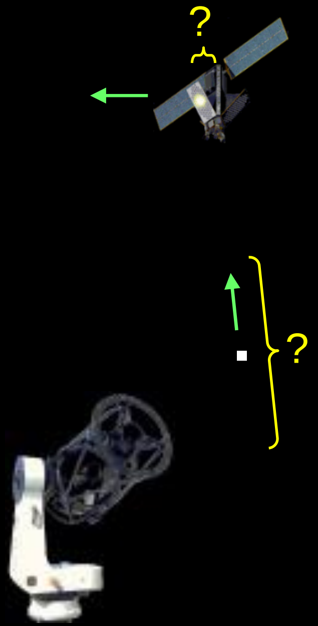
## Nudging by pulsed laser ablation

4. Ablation can give >20,000X more impulse per photon!
5. But we need ~20kW pulses, ~8m mirrors + great AO.
6. UV lasers in LEO can be far smaller, but cost is TBD.
7. Offset pulses can affect attitude motion & future drag.

## Two key questions

8. Might lasers be used until most cars have barnacles?
9. Do such lasers "damage" objects? (1972 convention!)

# Bet 3: Payoffs of Better Tracking, Predicting, & Avoiding




## Radar & telescopes can complement each other

1. Radar range & range rate data are far better than 2D direction data.
2. Telescopes give far better 2D direction data (in clear twilight skies!).
3. Telescopes cost far less but need far more sites for good coverage.

## Uncertainty in hubcap & shrapnel conjunctions is due to drag

4. Fragments have higher A/m than cars; that drives orbit uncertainty.
5. Good fragment fixes occur less often, so uncertainty grows longer.
6. Telescopic updates can radically reduce along-track uncertainties.
7. To avoid more fragments, get more fixes & infer drag $C_D A$ variation.

LeoLabs, Costa Rica

## Reducing conjunction uncertainty reduces satellite ops costs

8. Reducing uncertainty lets maneuvers be smaller and less frequent.
9. It also lets us track & avoid shrapnel that we can't even track now.

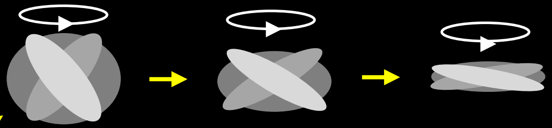
# Details on Making Better Fragment Conjunction Predictions

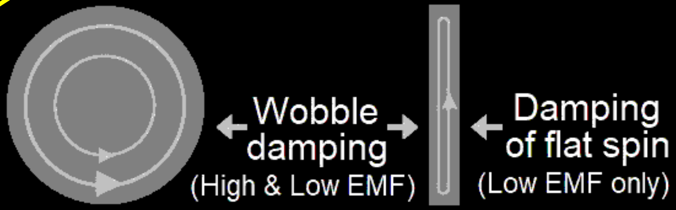
## Why do this?

Most worrisome conjunctions involve fragment + intact.
Fragments have higher A/m, and that drives uncertainty.

## Why is this feasible?

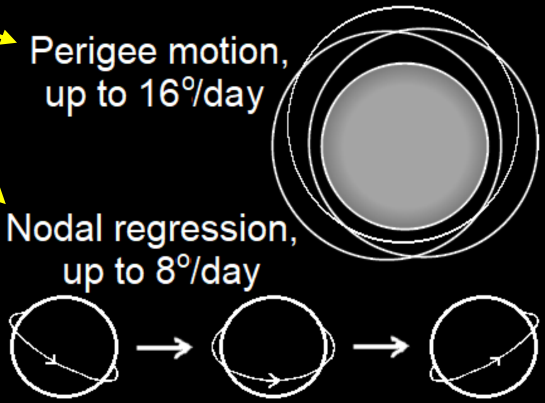
1. Most impact fragments tumble fast when created.
2. Eddy currents in metal damp tumble into flat spin.
3. Spin axis drifts slower than perigee & orbit plane.
4. So the effective drag area will vary predictably.






## How can we do this?

5. Analyze long-tracked collision fragments first.
6. Plot actual drag history vs fits assuming fixed $C_DA$.
7. Assume edge-on attitude at perigee when drag low.
8. Iterate the spin axis so predicted drag fits TLE history.
9. Use ensemble fits to revise full 3D air density history.



# Governing Our Orbital Commons

Countering the pessimism of Garret Hardin's "tragedy of the commons," empirical data* shows that commons are usually sustainable, if they have:

1. Clear boundaries of the commons, and who is allowed to use it
2. Rules on usage that fit that commons, local conditions, technologies, etc.
3. Ways for most users to participate in occasional revisions to the rules
4. Monitoring of conditions and behavior that is accountable to the users
5. Graduated sanctions decided by other users or officials accountable to them
6. Quick and easy access to local arenas, to resolve most conflicts at low cost
7. Acceptance by higher authority of users' rights to their own governance, and
8. In parts of larger commons, distinct layers of nested organizations and roles.

* Governing the Commons, 1990, by Elinor Ostrom (2009 Nobel prize in economics)

# "The High Cost of Free Parking" (book title)

## A few details about the book

1. A long harangue by UCLA prof Don Shoup on crazy parking patterns near UCLA.
2. For example, at times, >1/3 of drivers are cruising to find free on-street parking.
3. He argued for smart meters that can adjust street parking prices with congestion.
4. Drivers can then pay more for a convenient street spot, or less for a garage spot.
5. To sell this, commit ≥half of new parking fees to local improvements like garages.

## Potential relevance to "parking fees in congested orbits"

6. Approval of orbit use by US operators is by FCC approval of radio transmitters.
7. FCC allows 25 years free parking (sometimes only 5), but no penalty after that.
8. Huge constellations will need reliable avoidance, prompt removal, + penalties.
9. FCC regulates only US radio use, but that includes foreign access to US markets.

# Why Charge "Parking Fees" for Orbit Use?

## Why charge fees for "parking," rather than launch or something else?

1. We want reliable avoidance & deorbit—but 23 of 95 original Iridiums are >720 km.
2. Debris risks start when objects stop avoiding impact, but are left parked in orbit.
3. Charging a fee for leaving passive objects in congested orbits is easy to justify.
4. Scaling fees with predicted future costs to others provides the most efficient signal.
5. Constellation builders often go bankrupt, but parking fees also apply to later owners.

## Pros & cons of parking fees scaled to predicted external debris costs:

+ Even low initial parking fees encourage choices that will reduce debris costs.
+ Debris-cost-based parking fees could eventually fund debris-reduction bounties.
+ Parking fees can adjust for observed differences from initial plans & expectations.
– We need new laws to charge fees based on actual practice, vs. plans as licensed.
– US fees penalize US companies vs. others not paying such fees, so start small!

# What Key Features Might Parking Fees Include?

## Possible principles

1. Parking fees should scale with expected new debris costs to others, but start small.
2. Parking fees encourage better LEO use, by internalizing costs imposed on others.
3. Fee calculations must be based on an understandable, fair, consensus cost model.
4. New technologies, practices, data, or analyses may require revision of cost model.
5. Parking fees can eventually pay for bounties that balance out net new debris costs.

## Possible key features of cost estimation

6. Estimated costs are the current value of predicted future costs over debris lifetime.
7. The cost model needs a consensus on future investment * vulnerability vs altitude.
8. Estimates use actual practices (average avoidance, etc.) to infer losses to others.
9. External costs can include other operators’ costs for avoiding your passive objects.

# How Can We Estimate the Future Cost of Debris?

## Key insights

1. New objects start posing collision risks once they stop actively avoiding collision.
2. The minimum cost of debris is the best mix of tolerating, avoiding, & preventing it.
3. Finding the best mix will require trial & error, so total debris costs now are higher.
4. The actual costs will evolve with technology and actual usage of LEO & GEO.

## Some concepts for an evolving debris cost model

5. Mean debris from a new object is the mean new debris it creates, times its life.
6. Estimate mean new debris from altitude, mass, size, & “non-avoiding” orbit life.
7. Costs require a consensus guess at future investment * vulnerability vs altitude.
8. Mean debris cost is the current value of future mean costs, using likely practices.
9. Countries & companies may accept a cost model, but dispute inputs until proven.

# Should We Pay Bounties for Reducing Debris Costs?

## Key ideas that could define bounty concepts, calculations, & evolution

1. Cap bounties at the current value of predicted savings in future debris costs.
2. Bounty calculations need to handle most credible methods and anomalies.
3. Bounty calculation methods must be revised as new options & issues arise.
4. But bounties must be high enough & stable enough to attract viable options.

## How about alternatives to bounty payments?

- Cap & trade: can be efficient, but grandfathering often rewards bad practices
- Prizes: effective if a real market exists; less if it assumes future regulations
- Contracts: $/object, $/year, or cost-plus are less efficient than $/Δ debris cost
- Government-funded development: often biased toward less creative options
- Potemkin: any plan that looks real but doesn't make substantial progress

# What Key Features Might Debris Bounties Include?

1. Maximum bounties can be capped at present value of discounted future savings.
2. Bounties paid by the USG can be capped at the predicted value to USG agencies.
3. Bounties can rise as other countries add $; then their operators can earn those $.
4. Bounties pay for reducing net external debris costs; anomalies reduce the bounty.
5. Nudging just reduces small chances of collisions; pay bounties for those changes.
6. Operators must post plans (& bonds?) & be regulated & supervised per the OST.
7. Before touching foreign objects, operators must insure to indemnify launch states.
8. Cataloging shrapnel may merit a small bounty, if it allows affordable avoidance.

*We don't know our best options now! Deorbiting LEO mass may not even be needed, if we can nudge large debris, or track & avoid most shrapnel.*

# Debris and the 1972 UN Liability Convention

## Items in 1972 UN Convention on International Liability for Space Objects

1. It defines just country to country liability; domestic liability is a domestic choice.
2. Damages from reentry pose full liability; in space, only “if at fault” (undefined!).
3. Damaging another state’s space object may make you share its future liabilities.
4. If A launches B’s payload from C’s site, all 3 have full “launching state” liability.
5. Selling or re-registering objects doesn’t seem to transfer “launching state liability.”
6. The convention does also let states agree to separately re-indemnify each other, to better allocate any costs each state may incur under this Liability Convention.

## Some implications

7. About half of new LEO shrapnel may be from collisions of 2 dead Russian “cars.”
8. Light pressure nudging may be a benign way to reduce near-term collision rates.

# Current US Regulation of Orbital Debris

## Federal Communications Commission ("FCC")

1. Regulates all non-government use of radio transmitters in & over the US.
2. Before launch, it must approve # of satellites, orbit, & radio transmission usage.
3. Requires deorbit within 25 years (& now 5!) after mission, but can't enforce (yet).

## Federal Aviation Administration ("FAA")

4. Regulates launches (& intact reentries) by all US entities, in or outside the US.

## Department of State

5. Regulates export for foreign launch of space hardware, services, & tech data.
6. Governs US interpretation of UN Outer Space Treaty & Liability Convention:
    a. US agrees to "authorize & continuously supervise" space acts of its entities. (Does it?)
    b. Launching state(s) are liable for damage on earth; in space only "if at fault" (undefined!).
    c. Changes in the location or condition of a space object do not affect its ownership.
    d. If you damage another space object, you may share its liability for later damage.

# Evolution of LEO Debris Practices

## The US has set most debris precedents, both good & bad

1. In 1963 we put 480,000,000 tiny dipoles in MEO. Some are still up:
2. We launched all of the 283 longest-lived tracked objects still in LEO.
3. Those 283 are: 33 satellites, 16 rockets, & 234 fragments (80% from 1 explosion!).
4. Since 1978, when we predicted debris cascading, the US has led most work on it.
5. The US invests the most in LEO & gains the most by leading with better practices.

## USSR/Russian practices

6. The USSR used low orbits early on, but left more mass in long-lived orbit by 1970.
7. In 2016, >2/3 of the world’s total passive mass left in LEO was owned by Russia.
8. Most of that is at 920-1000 km, & may make most accidental long-lived shrapnel.

## Starlink and Starship

9. These will drive future debris. But flying future Starlinks <350 km is a good sign.