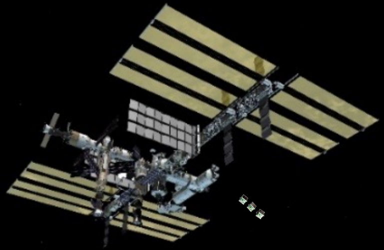
New Options for Orbital Debris?



Commercial Space Telecon
NASA Space Portal
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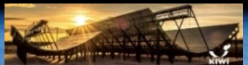


Useful Terminology for Debris in LEO

"Cars"
(~8,000)

Intact objects, mostly dead, 0.2-2.5 tons typical; <2% of lethal objects
Cars are 99% of mass & 98% of target area for debris-creating impacts.
~7%/yr car/car impacts will make most accidental hubcaps & shrapnel.

"Hubcaps"
(~12,000)

Tracked fragments, mostly 10-30 cm & 0.1-1kg; <3% 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 modeled!

"Shrapnel"
(500,000?)

Lethal now-untracked fragments, >1 cm; ~1 gm: >95% of lethal objects
Mostly too heavy to shield from; but many might be tracked & avoided.
"No-see-em" shrapnel is the direct threat to assets, and will remain so!

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

How Hypervelocity Impact Tests Can Mislead Us

Gun tests can mislead us about shielding effectiveness

1. Max gun speeds are ~7 km/s; in LEO, most are 7-15 km/s.
2. But most tests shoot spheres, not typical shrapnel shapes. **Fixable.**

Gun tests can mislead us about fragment mass spectrum

3. Max gun speeds are ~7 km/s; in LEO, most are 7-15 km/s.
4. We can't test car/car impacts, which make most fragments.
5. Most gun tests aim at CG, but LEO impacts have offsets. **Fixable.**

Even A-sats can mislead us, about fragment # and mass

6. Most LEO impacts have large offsets, but A-sats aim at CG. **Fixable?**
7. A-sats may be smaller & denser than most "cars" in LEO. **Fixable?**

Are LEGEND's Long-Term Debris Projections Accurate?

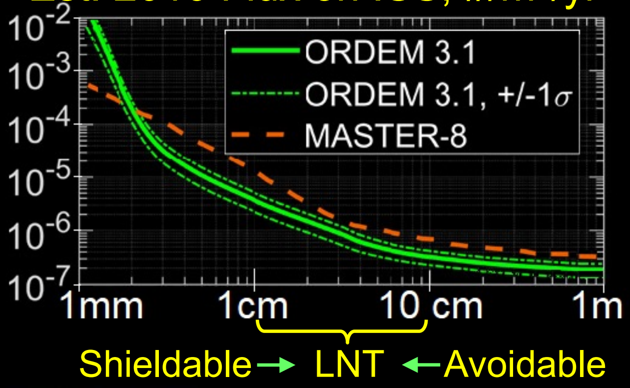
My concern about LEGEND's projections of an exponential debris cascade:

1. Its collision fragment model fits ground tests before 2001, + one 1985 A-sat test.
2. I estimated A/m of Fengyun and Cosmos/Iridium hubcaps from 2009-2010 TLEs.
3. Masses of these hubcaps are well below LEGEND's "SSBM" breakup estimates.
4. If tracked fragments are lighter, then fewer make fragments, and for fewer years.
5. LEGEND predicts ~half of hubcap/car impacts shred the car. Might it be far less?
6. Car/car collision rates are quadratic. Will that persist?

Can we shrink the "Lethal Non-Trackable" (LNT) gap?

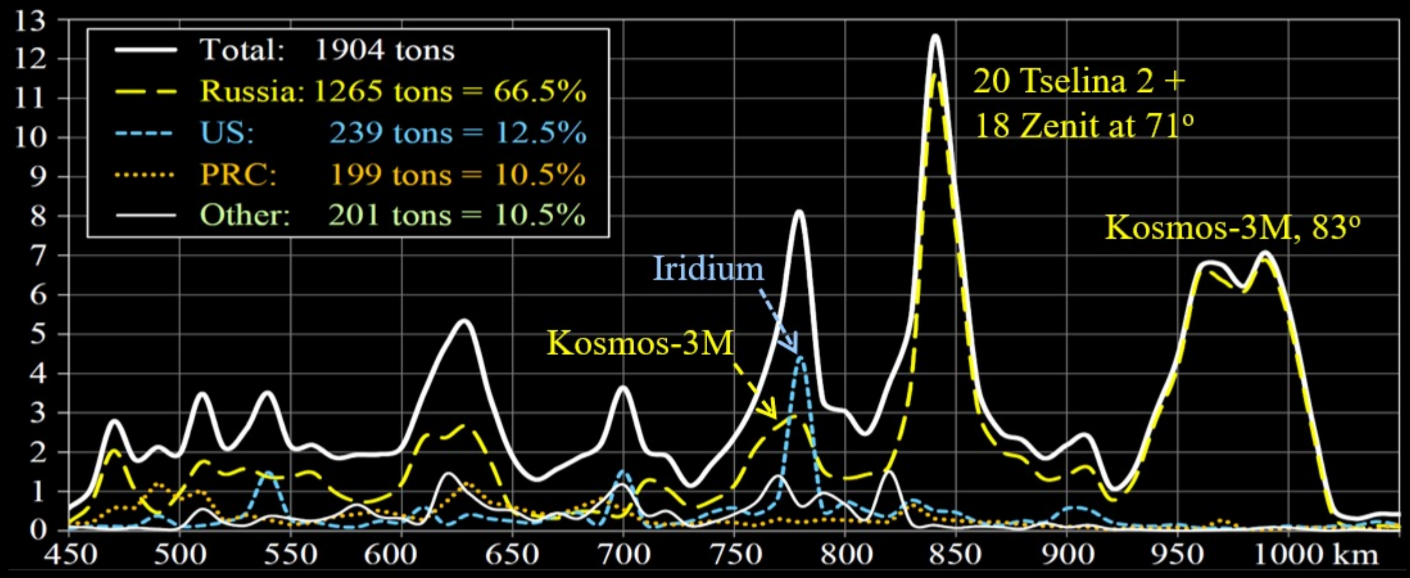
7. Most impact tests of shields have used spherical bullets.
8. For equal lethality, most shrapnel is larger & more visible.
9. Shrink the LNT gap to greatly reduce future debris costs!

Est. 2016 Flux on ISS, $\#/m^2/yr$



Why Does Orbital Debris Really Matter?

We focus on an eventual hubcap/car collision cascade making more & more hubcaps.
We should focus on shrapnel, & the car/car collisions (~7%/year) that make most of it!



Tons/km altitude, in 2016

To paraphrase Winston Churchill:

Orbital debris is a technical riddle, wrapped in an economic mystery, inside a diplomatic enigma.

(And it is probably best worked in that order!)

What Might Reduce Future Debris Costs Most?

Options for individual operators

→ 1. Use lower orbits, to reduce impact rates, satellite life, <u>and</u> shrapnel life.
2. Re-orient satellites on occasion, to reduce risk from known 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

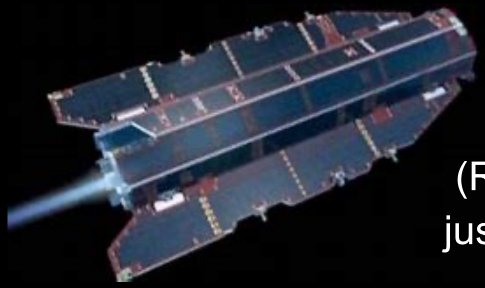
7. Capture & deboost large debris, <u>or</u> collect & recycle it for use in orbit.
8. Use laser ablation or space tugs to deorbit shrapnel & hubcaps (& cars?).

↑ *My bets on the 3 most useful options.*

Bet 1: Payoffs of Flying Satellites in Lower Orbits

1. Higher drag cuts debris transit time through your satellite altitude.
2. Your satellites decay faster, once they stop boosting: **Life = ~Alt^8.**
3. Any fragments that your satellites create <u>also</u> last only with **~Alt^8.**
4. There are fewer satellites for your shrapnel to disable (**for now!**).
5. You also see less radiation, <u>but</u> more AO erosion & reboost needs.

*Punchline: <800 km, shrapnel creation * life scales with* ***~ N^2 * Alt^{16}***



An extreme case:

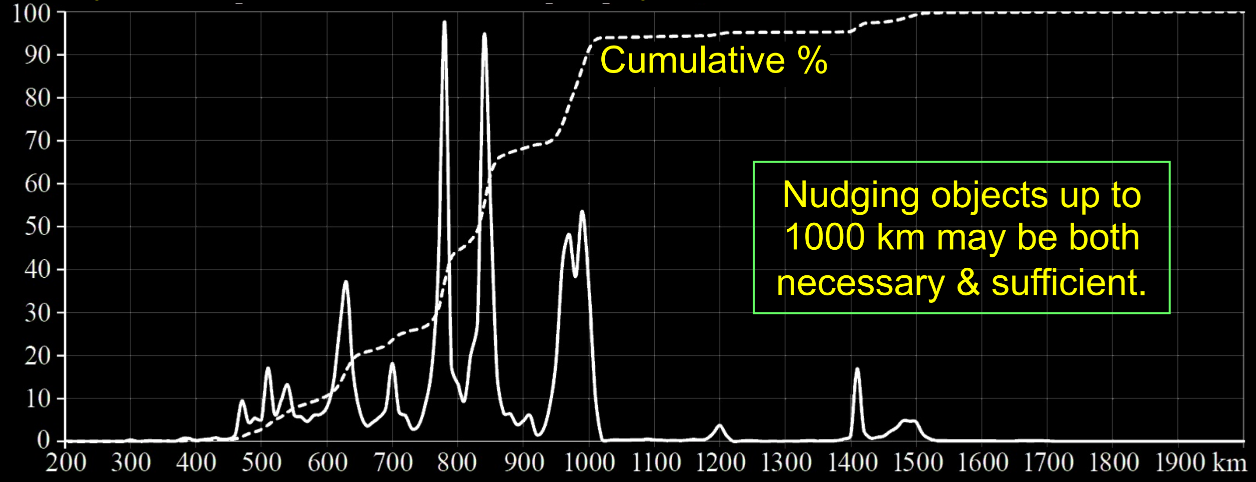
ESA's GOCE ran a "Red Queen Race"

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

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

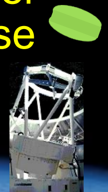
1. Required ΔV is tiny: a 1 km/day shift needs just 4 mm/s along-track ΔV!
2. Nudging can be done by “smart barnacles,” light pressure, or laser ablation.
3. Ablation can allow >20,000X more impulse/photon—if it is focused enough.
4. Deorbiting needs ~50,000X higher ΔV than a 4 mm/sec avoidance nudge.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

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



Servicers despin debris & attach “smart barnacle” to nudge it later.

Laser pulse



All workable debris fixes can serve as A-sats!

Details on Nudging by Smart Barnacles

"Barnacles" are attached hi-rel nanosats with thrusters

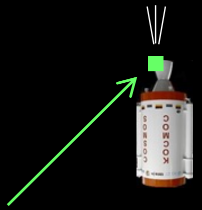
1. New long-lived satellites can each launch with a barnacle.
2. Satellite servicers take similar barnacles to existing objects.
3. On command, barnacles thrust to avoid close conjunctions.

Key barnacle features

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. Can operators preclude or detect hacking of barnacle use?



Servicers deliver "smart barnacles" to allow infrequent nudges of debris.

Details on Nudging by Lasers

Nudging by pulsed laser ablation

1. Ablation can give >20,000X more impulse per photon.
2. But the lasers need ~8m mirrors + near-perfect AO.
3. UV lasers in LEO can be far smaller, but cost is TBD.
4. Offset pulses can affect attitude motion & future drag.

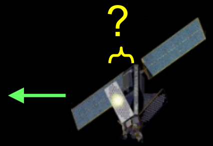
Nudging by light pressure

5. Continuous lasers can deliver far more photons per $.
6. Local target heating will limit maximum nudge/pass.
7. We need <u>many</u> lasers **+** <u>very</u> good orbit predictions

8. Two key questions

8. Might lasers be used <u>until</u> most cars have barnacles?
9. Does ablation “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 fragment conjunctions is driven by fragment drag

4. Fragments have higher A/m than satellites; that drives uncertainty.
5. Good fragment fixes occur less often, so uncertainty grows longer.
6. Telescope updates can radically reduce conjunction 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.

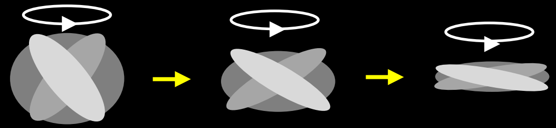
How to Make Better & Longer Fragment Orbit Predictions

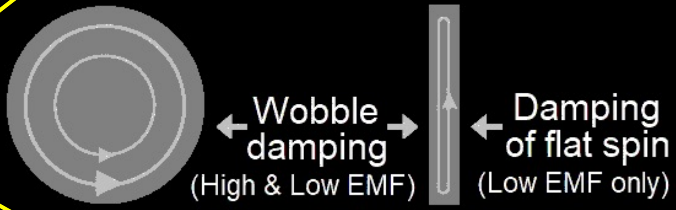
Why do this?

Fragments have higher A/m than cars & drive uncertainty.

Why can we do this?

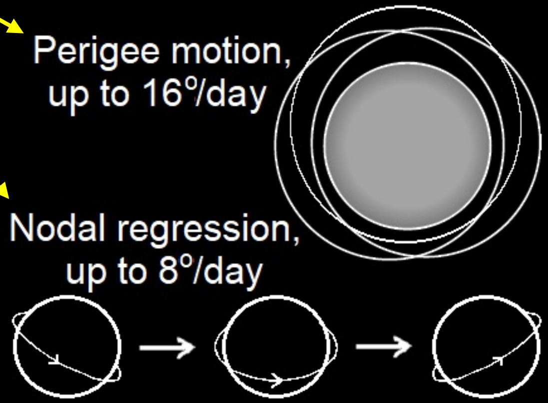
1. Most impact fragments tumble fast when created.
2. Eddy currents in metal damp tumble into flat spin.
3. Spin axis varies less than perigee & orbit plane.
4. So the effective drag area will vary predictably.





How can we do this?

5. Analyze long-tracked collision fragments first.
6. Plot actual drag history vs fits assuming fixed $C_D A$.
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.



How Can We Estimate the Future Cost of Debris?

Key insights

1. The minimum cost of debris is the best mix of avoiding, removing, & tolerating it.
2. Finding the best mix involves trial & error, so total debris costs now are higher.
3. Estimated costs must evolve with technology and actual usage of LEO & GEO.
4. Good costing allows insight into internal and external costs of different practices.

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, & avoidance over 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.

Who Should Pay to Reduce Debris Costs?

Who is responsible for new and old debris?

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

A key (but very unpleasant) question about debris:

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

And how about LEO vs GEO issues?

5. GEO has similar issues, but both the users and the best fixes are mostly different.
6. Even if debris runaway ends all use of LEO, most GEO sats can still traverse LEO.
7. Orbit users may accept "debris fees" if they efficiently clean up their orbit regime.

Why Charge "Parking Fees" for Orbit Use?

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

1. Debris costs vary greatly with design, orbit, & use. Launch fees don't capture that.
2. Parking fees that scale with expected externalities send the most efficient signal.
3. Parking fees, with rebates for avoidance & deorbit, are easy to explain and justify.
4. We want reliable avoidance & deorbit, but 22 of 95 old Iridiums are still >720 km.
5. Constellation builders can go bankrupt, but parking fees can apply to later owners.

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

+ Even very low initial fees will encourage choices that reduce future debris costs.
+ Debris-cost-based parking fees might eventually fund debris-reduction bounties.
+ Parking fees can adjust for observed differences vs initial plans & expectations.

– We need new laws to charge fees on observed practices, 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 a fair, understandable, consensus cost model.
4. New data, analyses, practices, or objections may require revision of model details.
5. Parking fees can eventually pay for bounties that balance out net new debris costs.

Possible key features

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 might include prices charged to maneuver to avoid others' objects.

Why Use Bounties to Reduce Debris Costs?

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

Key factors that may drive bounty concepts, calculations, & evolution

1. Cap bounties at the current value of "reductions in net 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.

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. Operators must post plans (& bonds?) & be regulated & supervised per the OST.
6. Before touching foreign objects, operators must insure to indemnify launch states.
7. Cataloging shrapnel may merit a small bounty, if it allows affordable avoidance.

We don't know our best options yet! Removing mass from LEO may not 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 concern.
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 change launching state liability.
6. The convention also lets states agree to separately re-indemnify each other, to better re-apportion costs any 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 the best near-term way to reduce collision rates.

How to Govern 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. Clarity in the boundary 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 modifying those rules
4. Monitors that audit conditions and behavior, and are accountable to the users
5. Graduated sanctions assessed by other users, or officials accountable to them
6. Rapid access to local arenas to resolve most conflicts at low cost
7. Government acceptance of the users' right to their own governance, and
8. In parts of larger systems, distinct layers of nested organizations and roles.

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

Key Conclusions and Possible Early Steps

Key conclusions

1. A key gap in debris studies has been estimating the likely cost of debris.
2. We don't yet know the costs of inaction, or our best options, or payoffs.
3. Users of LEO (& GEO) need to feel the external costs of their choices.
4. The easiest way to lower future LEO debris costs is to use lower orbits.

How should we start, if parking fees & bounties may make sense?

5. Evaluate options & payoffs of nudging dead objects to avoid impacts.
6. Estimate potential costs & savings from better tracking & predictions.
7. Infer $C_D A$ variations to allow better and longer debris orbit predictions.
8. Start work on consensus models of likely debris costs, for LEO & GEO.
9. Develop and refine parking fee and bounty concepts, and alternatives.

Useful Links on Orbital Debris

A blog site for feedback:
tetherjoe.blogspot.com

Analyses

Kessler & Cour-Palais, 1978, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/JA083iA06p02637
NASA Breakup Model, 21 refs: https://ntrs.nasa.gov/api/citations/20170002906/downloads/20170002906.pdf
NASA Orbital Debris Program Office: LEGEND, Quarterly News, etc: https://orbitaldebris.jsc.nasa.gov/
AMOS Optical Conference, 2006-21 papers downloadable at https://amostech.com/amos-technical-papers/
IAC Debris Symposium A6, 2006-21: 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

Engineering tools

DoD tracking: www.space-track.org, www.space-track.org/documentation#/faq, https://aerospace.org/cords
LeoLabs commercial space radars & tools: see https://leolabs.space/
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

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/,
and find "undertaker" in https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3491&context=smallsat