Space Transport Development Using Orbital Debris

NIAC Phase I Review Presentation
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Project Objectives and Payoffs

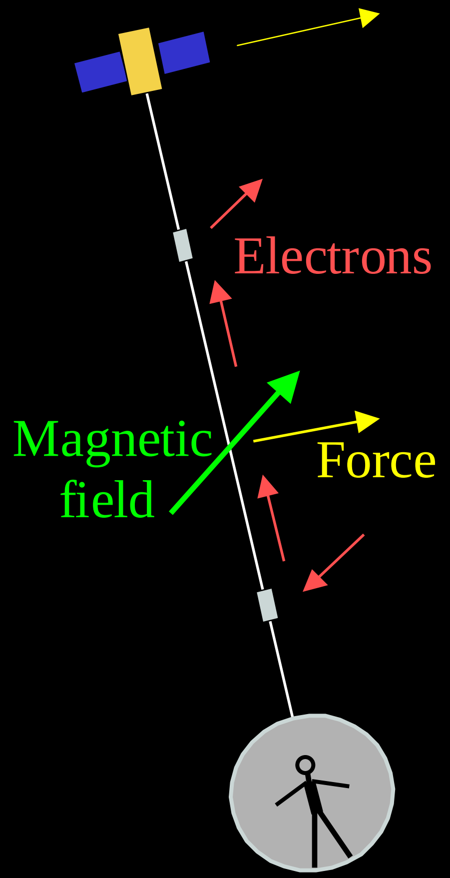
1. Reduce the creation of collision-generated debris, by relocating the ~1500 objects that account for nearly all the mass & area of debris in low orbit.

2. Reduce the direct risk of collision between debris & operating spacecraft, by clearing many smaller objects out of the most popular altitude bands.

3. Collect ballast for high-deltaV “sling” facilities.

4. Prove out tethered capture, to ***justify*** such slings.

Intro to Orbiting Tether Concepts



Momentum transfer

- Tension transfers momentum & energy
- DeltaVs up to ~4 km/s are feasible now

Electrodynamic effects

- Current in magnetic field causes force
- Connect to plasma to close current loop

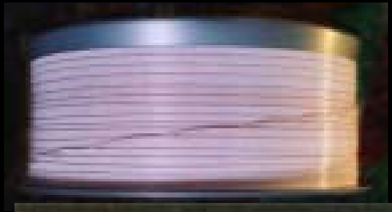
Tethered platforms

- Artificial gravity w/low Coriolis effects
- Allows isolation and remote access

Tethers Are Ready for Real Jobs!

SEDS-1, March 1993

- Deployed 20 km braided Spectra tether
- Slung 26 kg mass into controlled reentry



PMG, June 1993

- Hollow cathodes emit well & collect poorly

SEDS-2, March--April 1994

- Tether was seen by many around the world
- Impact risks are real (cut after 3.8 days!)

TiPS, June 1996--

- Libration damped out over several months
- 2 mm x 4 km tether is intact after 6.3 years!

NIAC Phase I Tasks and Findings

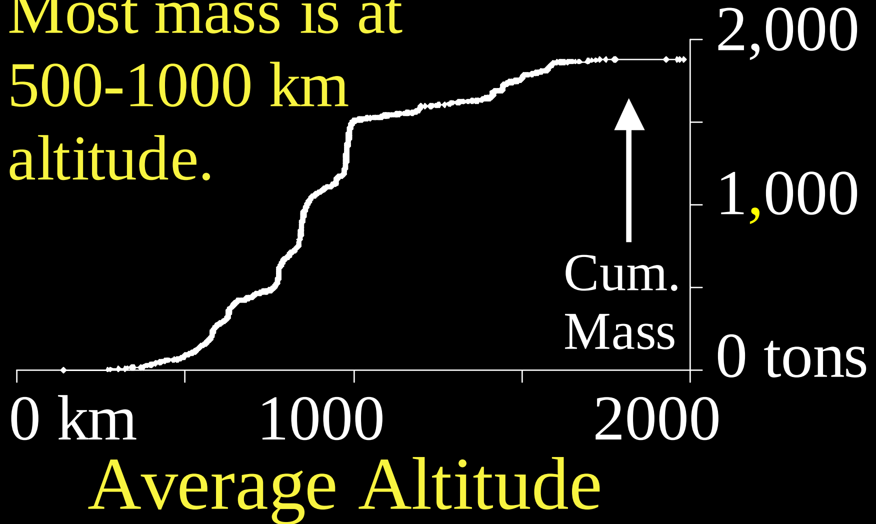
1. Study LEO debris population and triage options
    - Debris is very clustered in inclination & altitude
    - Of ~2,000 tons in LEO, 98% is 1500 objects >100 kg

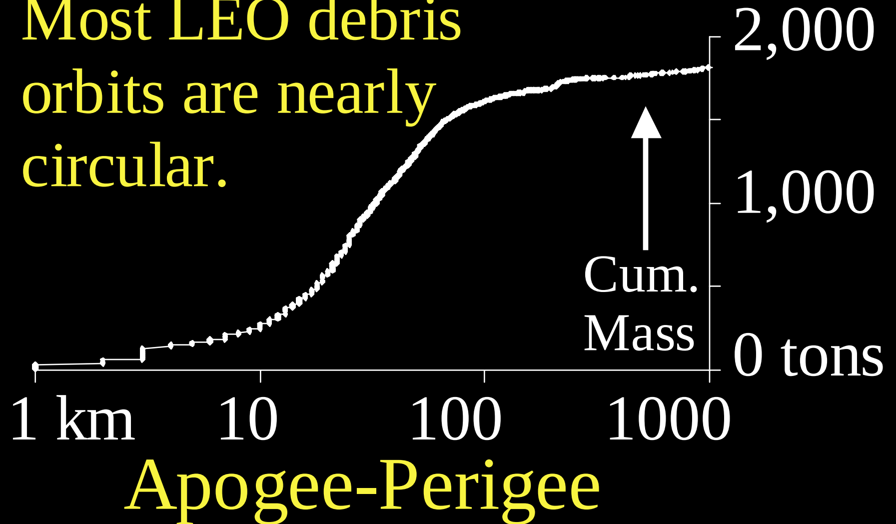
2. Explore capture concepts, and make and test models
    - Spinning net & two-dog capture both seem promising

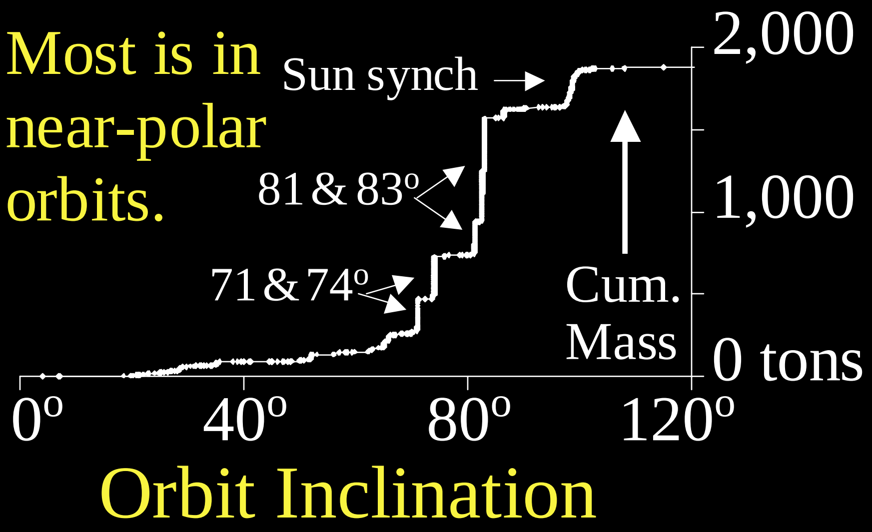
3. Study rendezvous, capture, disposal, and contingencies
    - It is hard for 100-kg tethers to deorbit objects >500 kg

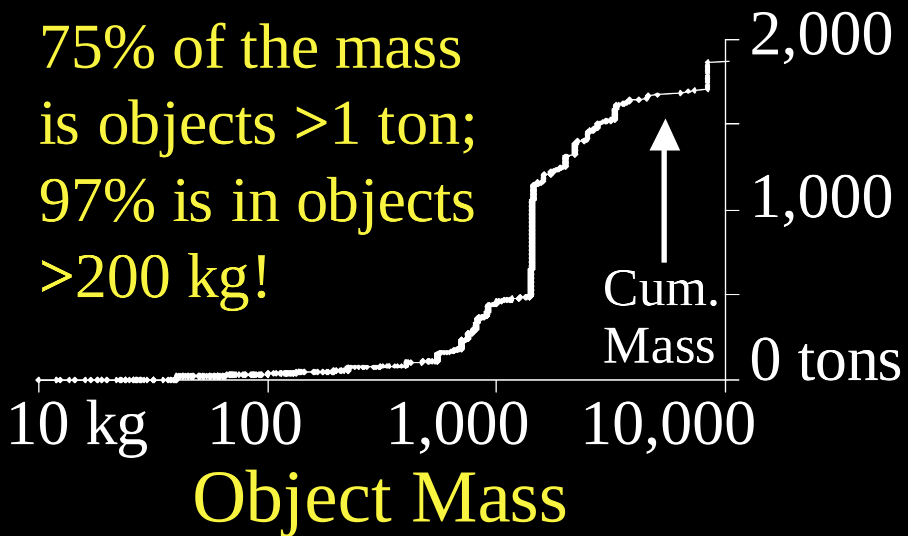
4. Flesh out system architecture & estimate performance
    - 12 shepherds might relocate most debris in ~5 years
    - Heavy debris can serve as ballast for “sling” tethers

Data on Debris Mass in LEO

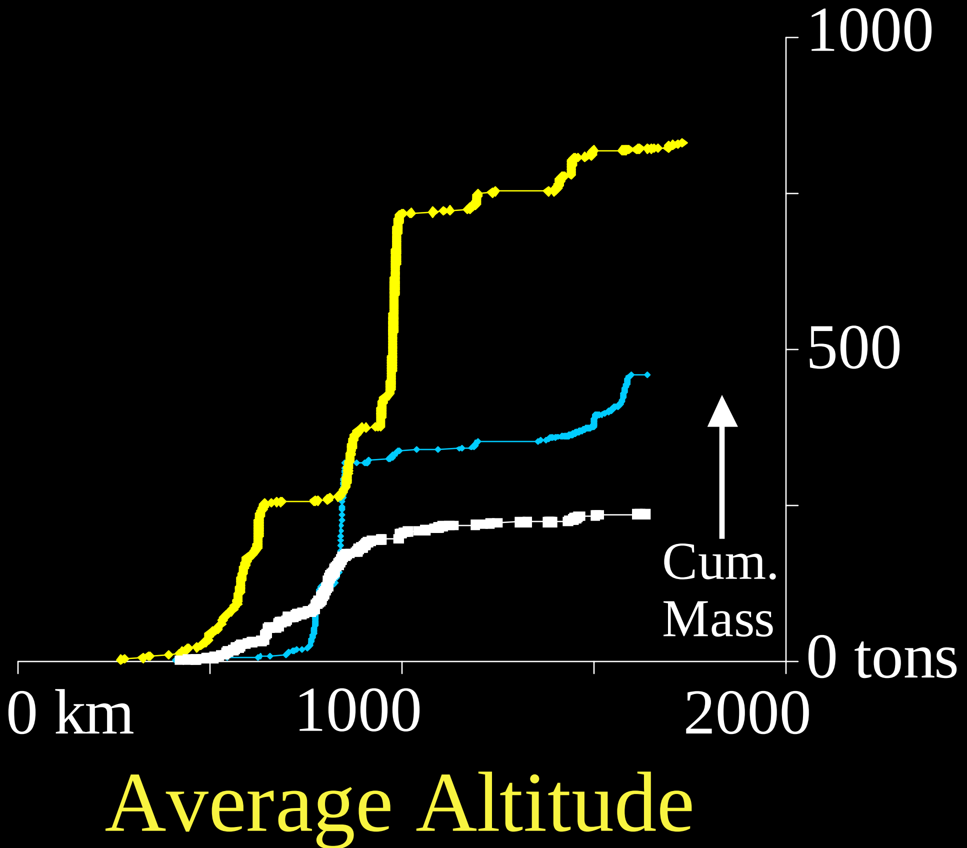

Most mass is at 500-1000 km altitude.

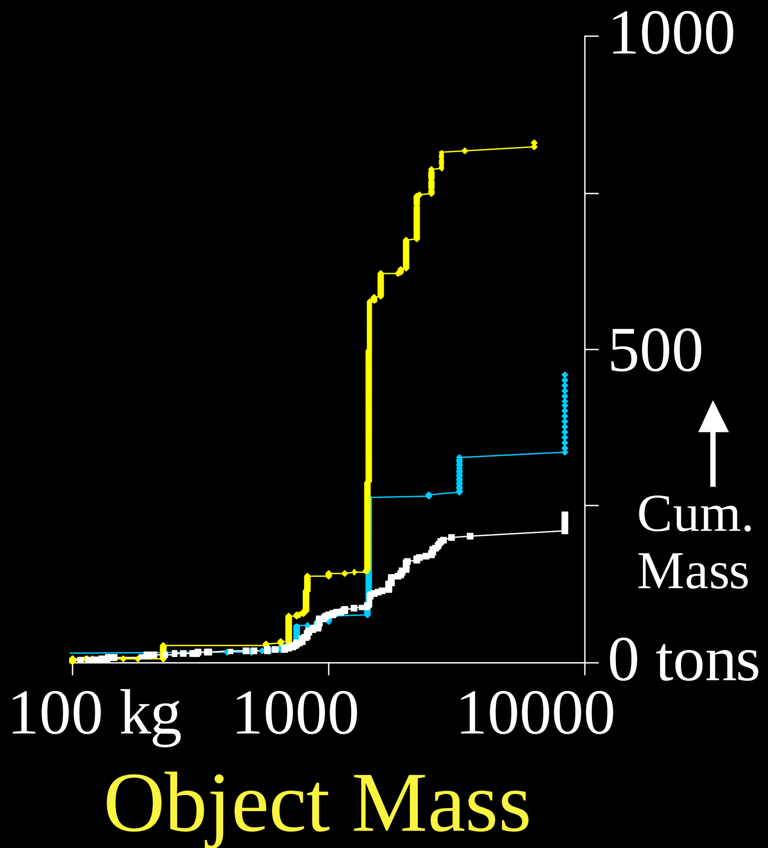

Most LEO debris orbits are nearly circular.


Most is in near-polar orbits.


75% of the mass is objects >1 ton; 97% is in objects >200 kg!

Data on 3 LEO Debris Clusters





Debris mass estimates provided by NASA JSC Orbital Debris Office.

71-75^o Inclination: 98% CIS
81-83^o Inclination: 99% CIS
96-102^o: US, CIS, other

Other Relevant Details

1. LEO debris has 200 acre-years exposure (LDEF $<$ 0.1).
2. Most collisions involve large debris, since they are most of the "target area". The collision rates are enhanced if $i_1 + i_2 \approx 180^o$, as occurs with 81-83^o and sun-synch orbits.
3. Debris is clustered in inclination and altitude, but the ascending nodes and apsidal phases are nearly random.
4. The ownership and identity of large debris are known.
5. Intact spacecraft and stages all have launch support hardpoints that are accessible once they separate.

Key Unknowns About Debris

1. Debris tumble rates
   - Neither NASA nor DOD records tumble rate data
   - But eddy currents can de-spin aluminum in weeks
   - And amateur-class videos can detect tumble rates

2. Response of US and other debris owners
   - Are the treaty implications ***actually*** clear?
   - Is a debris shepherd liable for anything it touches?

3. What can we do about GTO and GEO debris?
   - ED tethers cannot easily reach those high orbits
   - DeltaVs are low enough for ion-engine shepherds

Possible Triage Strategy

1. Objects under ~500 kg
    - Drop objects that will burn up into orbits below ISS
    - Drop other objects into controlled-location reentries
2. Heavier objects near useful inclinations
    - Capture them as they approach nodal coincidence
    - Deliver to active ballast assemblers (near 500 km?)
    - Or put them in lower-risk temporary storage orbits
3. Other heavy (or dangerous) objects
    - Release into controlled reentry (hard to do!)
    - Or deliver to larger tethers that ***can*** deorbit them
    - Or put them in lower-debris-density storage orbits

1989 Tethered Capture Contest

First Prize: Darryll Pines and Siegfried Zerweckh

Second Prize Design (of 4 designs entered)

Contest Rules

Open to all MIT.

Soft/light grabber (don’t break egg).

No practice tries.

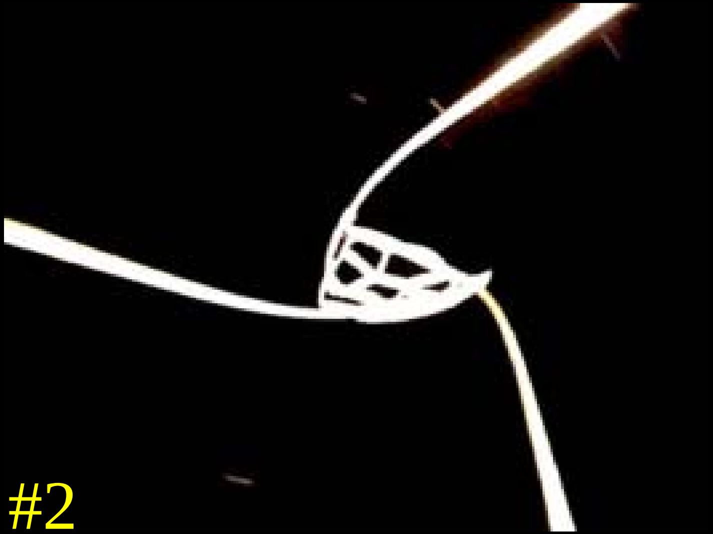
Lift “ET” 3 times.

Score = total time.

Prize = $300!

Spinning Nets for Passive Capture

#1



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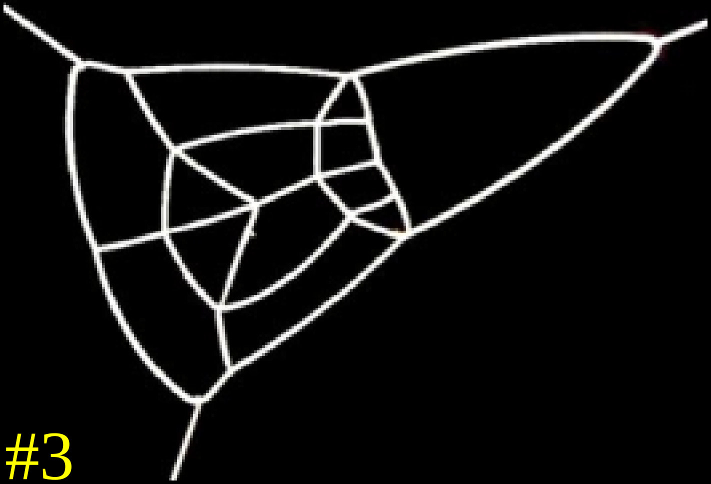
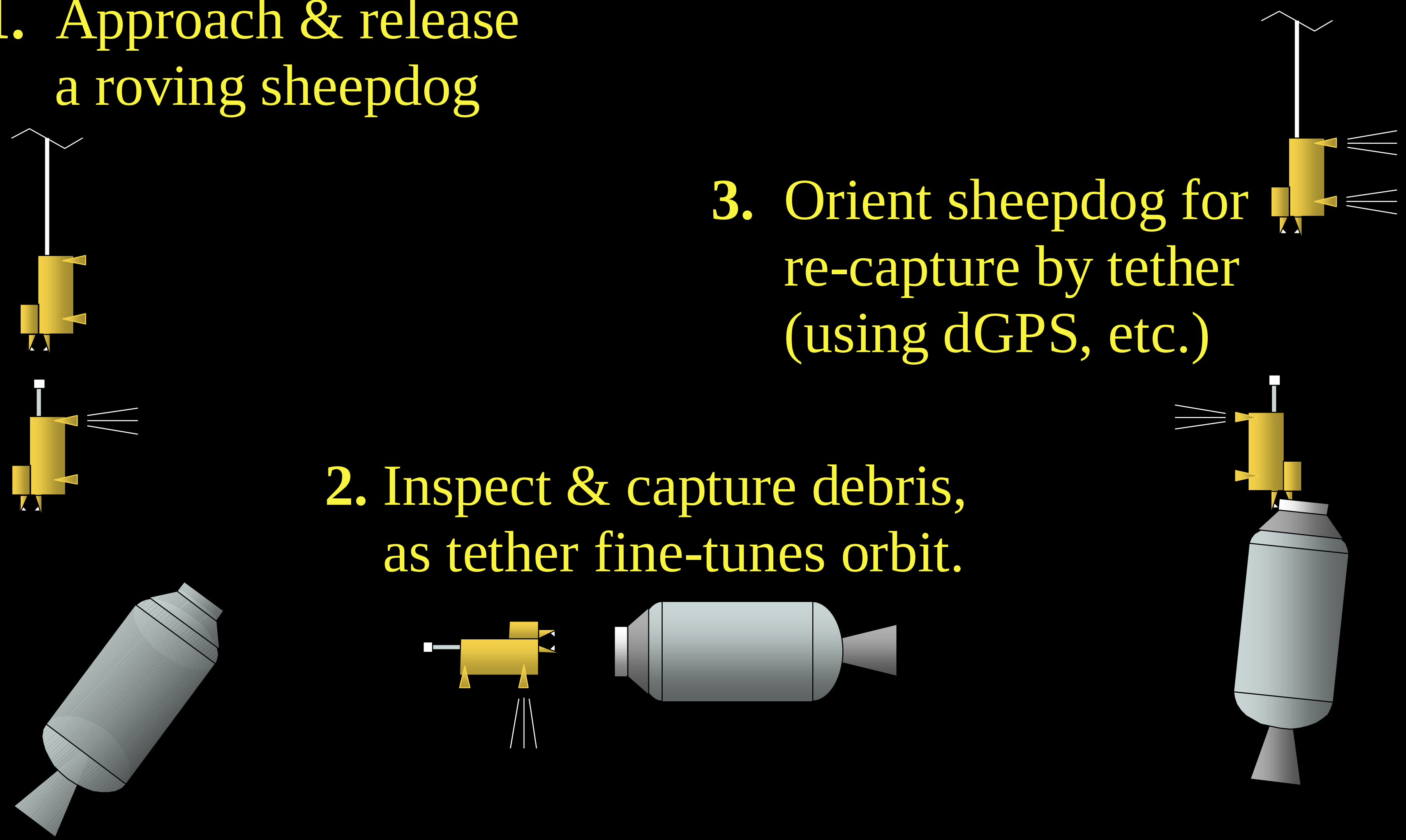


#3

Contrast-enhanced frames from video of net spin-up. Net was made from bead-chain for high inertia/drag. Flight net would use a fine mesh of high-strength fiber.

Cooperative "Two Dog" Capture

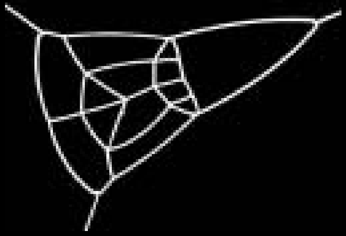


1. Approach & release a roving sheepdog

2. Inspect & capture debris, as tether fine-tunes orbit.

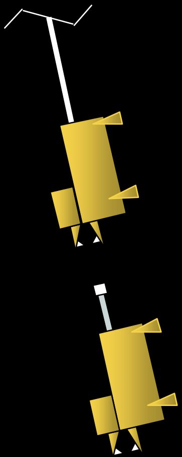
3. Orient sheepdog for re-capture by tether (using dGPS, etc.)

Capture Hardware Issues



Basket-catch in net (spinning at ~2 rpm)

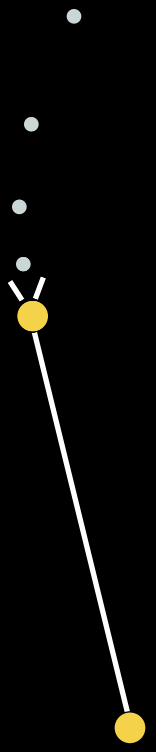
- Approach sideways, to slip net under debris
- Net rotates ~60^o by time debris falls into mesh
- Nets are light: <50 g for house-size catch area
- Nets can complicate later debris use as ballast
- Nets can foul on shepherd, disabling one end



Cooperative “two dog” capture

- Sheepdog can survey debris before “biting” it
- Sheepdog also usable w/GTO and GEO debris
- Sensors & ops common w/high-deltaV slings
- Hardware must capture and release under load

Is Tethered Rendezvous Feasible?



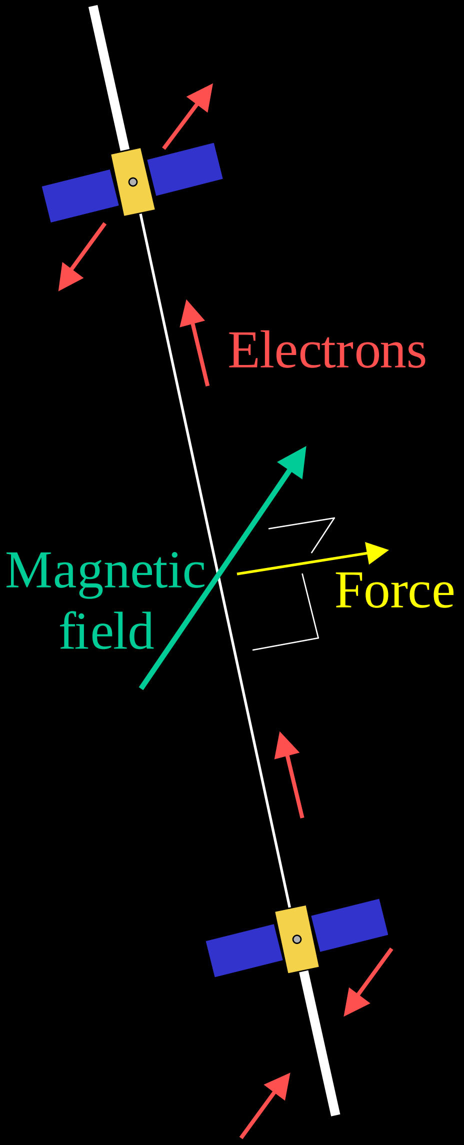
What could prevent rendezvous?

- Inaccurate relative-navigation sensor data
- Or poor prediction of the tether dynamics
- Or large disturbances (drag variations, etc.)
- Or insufficient control authority or accuracy

What must we do to ***ensure*** rendezvous?

1. Use adequate sensors, models, & strategies
2. And reduce disturbances and control errors
3. And ensure control forces are large enough

ED Maneuvering Constraints



Tether force direction

- Push/pull requires 2 collectors & emitters
- Force is normal to both field and tether
- Tether direction has dynamic constraints

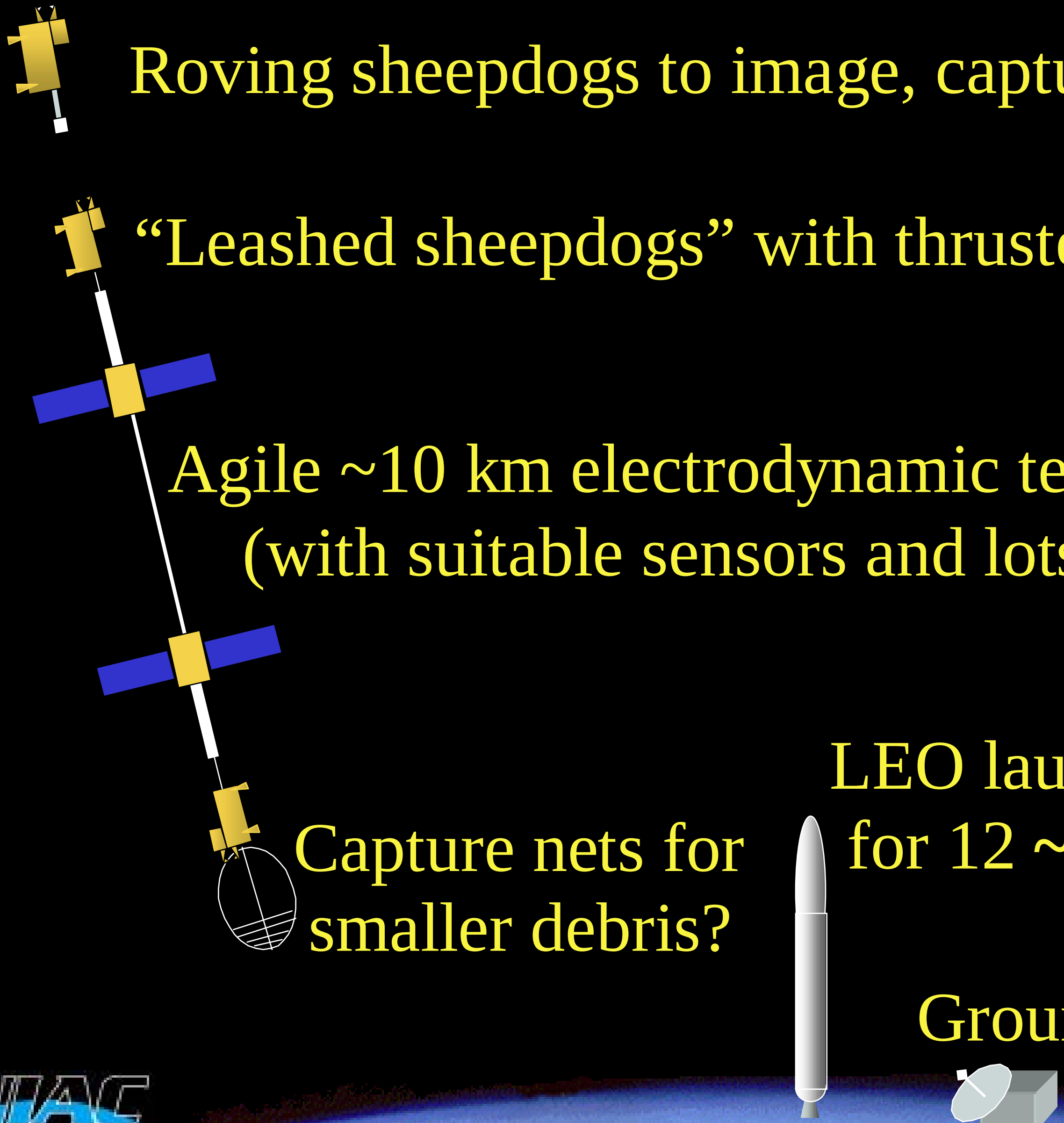
Tether dynamics

- IP & OOP libration & bending stimulated
- Control is tricky except at low current

Plasma density

- Large electron collection areas needed
- Narrow tapes collect better than wide ones
- Service altitude varies over solar cycle

Elements in Architecture



Roving sheepdogs to image, capture, & orient debris

“Leashed sheepdogs” with thrusters & reelable leash

Agile ~10 km electrodynamic tether “shepherds”
(with suitable sensors and lots of software!)

Capture nets for
smaller debris?

LEO launches (***any*** orbit)
for 12 ~100 kg payloads.

Ground station

Possible Scenario for Program

1. Design, build, launch, & test one to prove concept
2. Refine design & build ~12 more debris shepherds
3. Launch as secondaries on ***any*** LEO launches
4. Climb high near solar max; stay low otherwise
5. Estimate ~2 weeks per rendezvous + relocation
6. Reassign shepherds as others fail or needs vary

Throughput: ~25 objects/year per shepherd, or 1500 heavy objects in 5 years, using 12 shepherds!

“Compared to What?”

What limits orbit change rate of tether?

- Mainly, weak magnetic field + resistivity of aluminum
- Also power system mass (for “deadhead” maneuvering)
- And low plasma density (depends on alt & solar cycle)
- In 5 years a tether might relocate ~1500X its own mass

Could high-Isp electric thrusters be competitive?

- They need an Isp >50,000 sec. for similar system mass
- Very high power/thrust is needed to allow such an Isp
- And they must weigh less than their 1-3 ton “payloads”

Are there other alternatives?

- None we know of seem both plausible and competitive

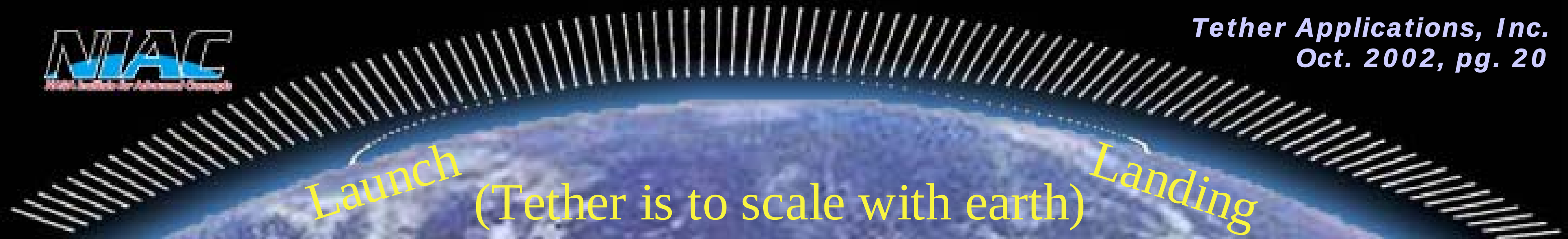
Suborbital Capture by Sling

Scenario taken from 1991 TAI study for NASA HQ

Launcher & sling shown every 10 seconds, launch to landing.
Sling is 290 km long and needs a ballast mass ~30X payload.
Payload handoff is 1.2 km/s suborbital, near 130 km altitude.
Launch and landing sites can be within the continental US.

Update for NIAC study

Larger deltaVs seem feasible: 2+2 km/s (sub+superorbital).
>1000 tons of orbital debris may be usable as ballast mass.



(Tether is to scale with earth)

Surprises About Launch Sites

Low-inclination slings allow once-around launches

- Capture and carry launch vehicle with payload.
- Release launch vehicle at nadir 1 orbit after capture.
- Glide east to launch site (~26° earth spin in 1 orbit).

Near-polar slings allow two-launch-port shuttle ops

- Launch north from southern port; land at north port.
- N+0.5 days later, launch southward & return home.
- Required cross-range scales with Abs(DegIncl-90).

(Other inclinations have more complex constraints.)

Surprises About Sling Operations

Sub-orbital capture can be fail-operational

- Missions to GEO or beyond still need 2 km/s after a successful 4 km/s suborbital-to-superorbital sling.

- If suborbital capture fails, use that propellant to reach orbit and dock with sling; then refuel and go.

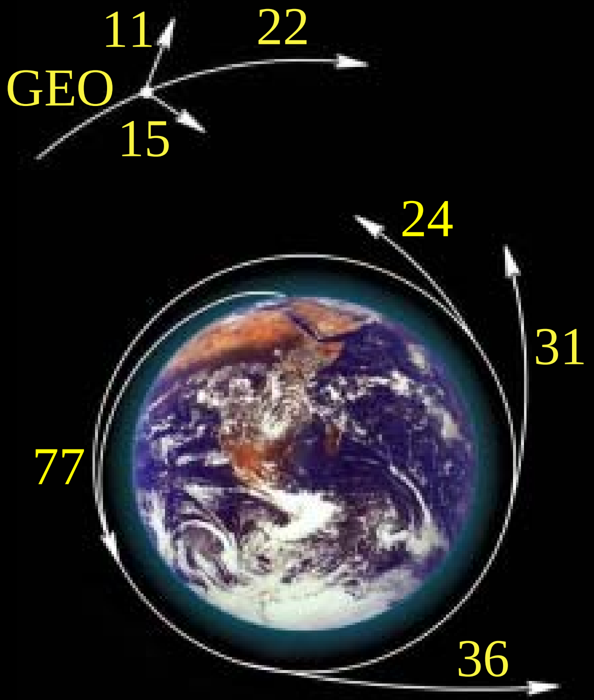
Component masses and throughput

- Reboost power supply will outweigh sling tether, if net mass flow outwards exceeds ~1 payload/day.

Earth-GEO-Moon-Mars DeltaVs

Hohmann deltaVs in units of 100 m/s, from 400 km circular equatorial orbits. Full deltaV is sum of start & finish #s.

Orbiting slings with 1-3 km/s tip speeds can provide most or all of these deltaVs!



Conclusions from Phase I Study

Debris

1. Most of the mass is in intact objects weighing 1-3 tons.
2. Most debris mass is near-polar, at 500-1000 km altitude.
3. Intact objects all have unintentional “capture features.”
4. Key unknowns include debris tumble rates and politics.

Rendezvous and capture

1. Good sensors, actuators, and software are essential.
2. 12 shepherds might handle most large debris in 5 years.

High-deltaV slings

1. Slings could use much of the heavy debris as ballast.
2. Such slings could provide up to 2+2 km/s deltaVs.

Possible Phase II Tasks

Debris

- Find tumble rates and typical interfaces & appendages.
- Identify and study possible problems (technical & other).

Rendezvous and capture

- Analyze sensor options and control concepts in detail.
- Test and refine capture/release hardware concepts.
- Analyze survey, capture, de-spin, and other operations.

Architecture and development scenario

- Flesh out shepherd, sheepdog, ballast, & sling concepts.
- Refine throughput estimates for shepherds and slings.
- Estimate key technology needs, schedule, & ROM cost.

Some References

Orbital Debris

NASA JSC: http://www.orbitaldebris.jsc.nasa.gov/ (site is currently down)
JSC Newsletter http://sn-callisto.jsc.nasa.gov/newsletter/news_index.html
Aerospace Corp: http://www.aero.org/cords/
Europe: http://www.etamax.de/debrisweb/
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Book: Orbital Debris : a Technical Assessment, National Academy Press, 1995.

Space Tethers: General Info

Tether Guidebook: www.tetherapplications.com (click on “Review Papers”)
NASA Tether Handbook: http://cfa-www.harvard.edu/~spgroup/handbook.htm

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Stuart, D.G., “A Guidance Algorithm for Cooperative Tether-Mediated Orbital Rendezvous,” MIT Sc.D. thesis, Feb. 1987.

Carroll, J. “Preliminary Design of a 1 Km/Sec Tether Transport Facility,” report to NASA HQ on contract NASW-4461, March 1991, Tether Applications.

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