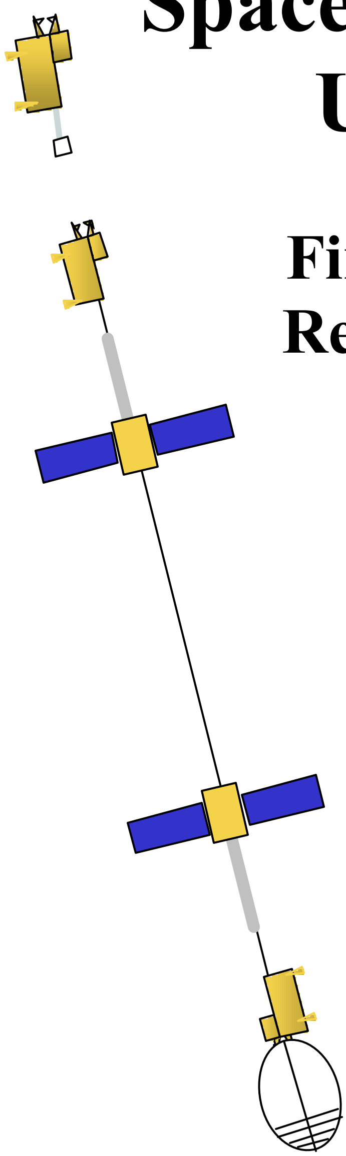
Space Transport Development Using Orbital Debris



Final Report on NIAC Phase I Research Grant No. 07600-087

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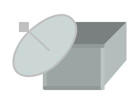

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One-page Project Summary

About 1500 objects weighing >100 kg each account for over 98% of the 1900 tons of debris now in low earth orbit. These objects also have nearly all the total cross-sectional area, so the main future source of small debris (which is both more common and harder to see and avoid) may be collisions of existing small debris with these large objects. Our concept is to reduce the future rate of such collisions by moving most of the large objects to lower-risk orbits.

We propose using a fleet of ~12 agile ElectroDynamic Delivery Express (EDDE) tethers to capture the large pieces of debris and drag them into short-lived orbits. Debris capture involves two steps. First the EDDE "debris shepherd" maneuvers close to an object and releases a small "sheepdog" that can approach, inspect, and (under ground control) "bite" the debris at a suitable structural detail. Then it orients the debris so its own tail faces the shepherd, and provides navigation aids so the shepherd can return and capture the sheepdog's tail. Now the shepherd can drag the debris into a short-lived orbit, where the sheepdog can release it. As an alternative, the shepherd can deliver the debris to a "ballast tether" that can later become the ballast mass for ambitious tether slings that can capture suborbital payloads.

These concepts and their connection to each other may allow revolutionary improvements in safety and in low-cost access to space. If successful, the work we propose could lead to a future NASA program because of:

1. NASA's international leadership in development of debris-mitigation policies,
2. The vulnerability of current and future NASA spacecraft to debris, and
3. NASA's ongoing work on both space tether concepts and launch vehicles.

Our Phase I effort focused on these areas and had these key findings;

1. The large debris objects are clustered in inclination & altitude, and are accessible to EDDE.
2. The capture concept should work, IF the debris has capture features and spins slowly enough.
3. About 12 shepherds weighing 100 kg each might be able to relocate most debris in ~5 years.

<u>Possible steps in a development scenario for debris-shepherds and high-deltaV slings</u>

1. Determine what might be capturable and how to do the captures (NIAC Phase II, year 1).
2. Develop detailed shepherd architecture and operating scenarios (NIAC Phase II, year 2).
3. Develop adequate ED tether dynamics simulation capabilities (NASA MXER effort).
4. Develop suitable ED and strength tethers and capture hardware (NASA MXER effort).
5. Select a suitable inspector-type satellite as a "sheepdog" and adapt and enhance as required.
6. Complete development of EDDE (solar arrays and array steering, integration, etc.)
7. Flight-test EDDE or another suitable precursor with a sheepdog (preferably by 2008).
8. Refine system design concepts based on what is learned from the flight experiment
9. Launch shepherds and sheepdogs to deboost LEO debris near solar max (2010-2014?).
10. If slings do indeed look feasible, assemble ballast and other components and operate slings.
11. Build a safe-abort payload carrier to allow intact-abort with suborbital payloads.
12. Eventually, develop an RLV optimized to launch payloads for suborbital capture by sling.

Chapter 1: Debris Analysis and Triage Options

Task 1. Analyze debris population and triage options
1.1 Characterize LEO debris population for accessibility, risks, and potential resources
1.2 Merge with other data on mass, geometry, special issues for satellites, rocket bodies, etc.
1.3 Study triage options and criteria (eg., deorbit, deboost, move to storage orbit, or ignore)

Introduction
Many plots and tables in papers on orbital debris treat each piece of trackable debris equally. (The tracking threshold varies with altitude but is roughly 10 cm in low orbit.) A perspective that "debris is debris is debris" is appropriate for most studies, since they usually focus on the risks of debris collision with the ISS, shuttle, or high-value satellites. Collisions with any trackable debris, large or small, has serious enough consequences that avoidance maneuvers are necessary. Thus each piece of tracked debris imposes a similar avoidance requirement, independent of size.

The perspective in this report is a longer-term perspective, with a different focus. Most of the current inventory of debris in orbit is due to explosions of spent stages, unnecessary release of untethered lens covers and other hardware, and similar causes. These sources are becoming less important as most organizations active in space have adopted at least basic policies to reduce the generation of such debris. It appears that in the future, new debris in orbit will be due less to these causes than to collisions between existing objects. At high altitude, debris is cleaned out by drag so slowly that we already have a slow-motion chain-reaction, in which debris objects are generated faster than they are removed. This chain reaction has a long enough time-scale that we may have many decades in which to act. But the earlier we act, the less work will be required.

Working satellites are only ~3% of the tracked objects in LEO (low earth orbit). Such satellites are larger than average tracked objects, but they still have only a very small fraction of the total area. So most collisions are not debris/satellite, but rather debris/debris. More specifically, most collisions will probably be between one of the many small objects (since there are many such objects) with one of the large objects (since they have most of the total cross-sectional area). The collision rate should scale roughly with the product of debris object count and total debris area. But if two "targets" have the same size and one is more massive, it will probably generate more debris. Hence another approximation is that the generation of small debris should scale roughly with the product of debris object count and total debris mass. A further subtlety is that very small bullets will be fragmented enough by the first wall in a satellite or stage to be stopped at the second wall, reducing the release of new free debris, while larger bullets will also rupture the second wall, and still larger ones will disintegrate the whole target.

Reducing the collision rate requires either reducing the number of small bullets or the target area or mass. If the main cost is maneuvering to the objects and capturing them, then one should focus on large "targets," since there are fewer of them. But if the main cost is dragging objects down to short-lived orbits, one should concentrate on "large bullets," since their total mass is low but their effects can be large. The approach we propose is to focus primarily on the large targets. We do this largely because they may actually have salvage value.

Statistics of orbital debris in LEO

When we wrote our Phase I proposal, we included a plot of debris vs inclination in low earth orbit. We did not have mass data, but we had data on average radar cross-section (RCS), which is usually close to physical area, so we plotted total RCS vs inclination. That plot is shown below:

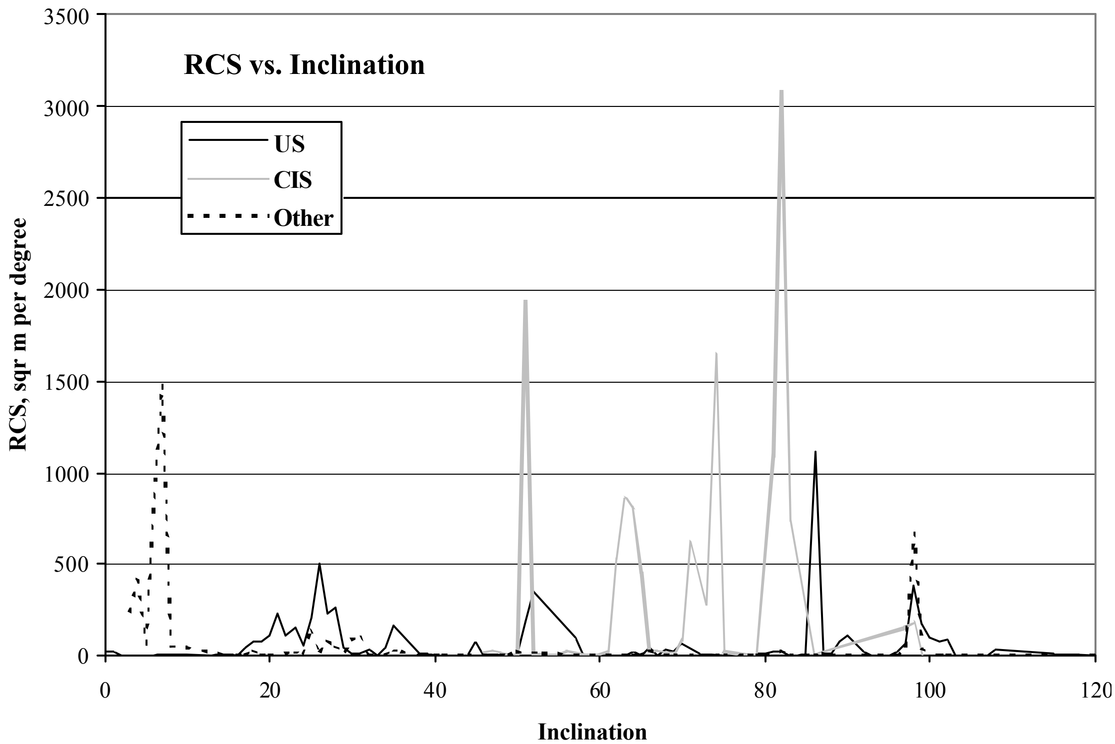


Figure 1. Total Radar Cross-section (m2) vs Inclination for Objects in Low Earth Orbit

Figure 1 shows very clearly that most debris is clustered in a few orbit inclinations, and that each country prefers a different combination of inclinations. Note that the high aspect ratios of some of the peaks make it hard to quantitatively compare their areas. In our later plots, done during the Phase I effort, we decided to plot cumulative data. Then the total amount in a certain inclination band, and the relative amounts in two bands, can be estimated more easily and accurately.

When our study started, we contacted Nick Johnson of the Orbital Debris office at NASA JSC. He has provided us with both lots of data, advice, questions, and challenges during the effort, all of which have been useful. He provided an orbit element catalog of all 8431 tracked objects in earth orbit. We spent half a day with him at JSC the day before the NIAC review meeting in June, discussing debris issues and our concepts. He then sent us his latest mass estimates for all 2181 objects >5 kg in LEO. Later, when our interest broadened to include objects near GEO, and the possibility of doing captures using concepts similar to those developed during our Phase I effort, he also sent his mass estimates for them as well. Our cumulative mass plots of this database are shown in Figure 2 on the next page. Because so much of the mass is clustered in 3 few narrow inclination bands (70-74°, 81-83°, and 96-103°), we plot key data for those clusters in Figure 3.

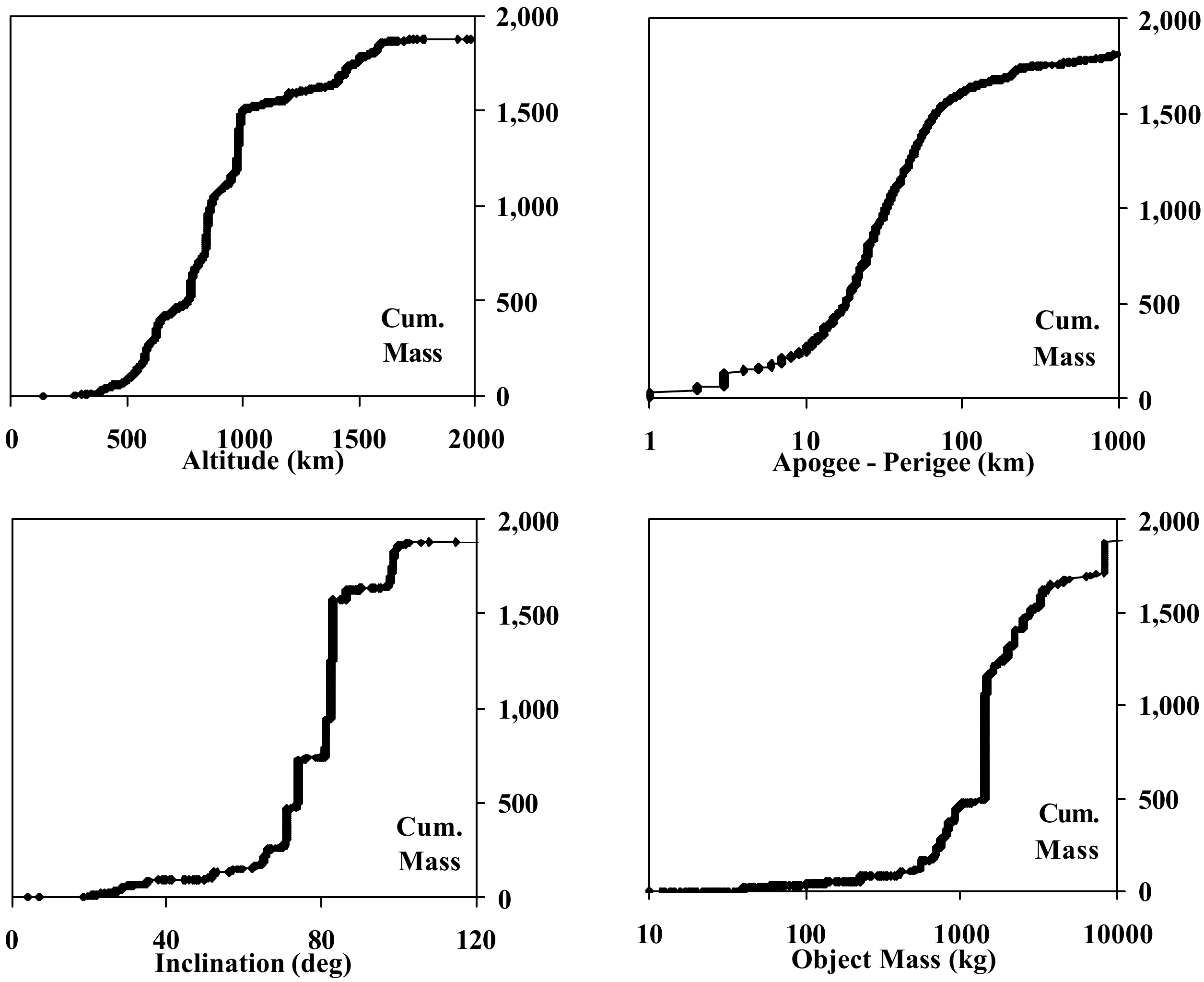


Figure 2. Key characteristics of >5 kg debris objects in low earth orbit

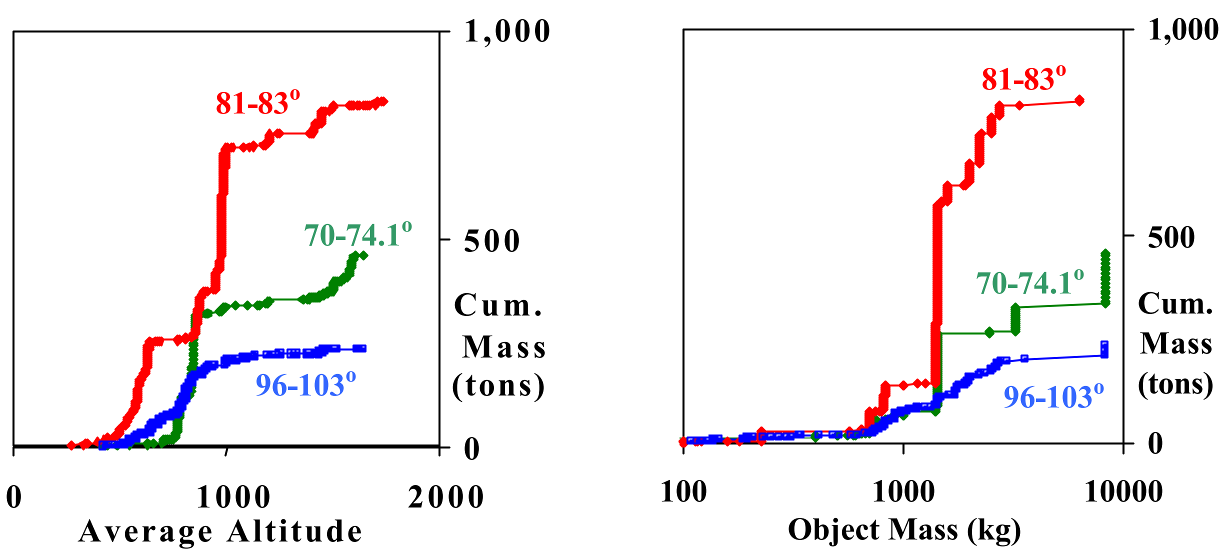


Figure 3. Key characteristics of the 3 largest inclination clusters of debris in low earth orbit.

Observations and conclusions on LEO debris statistics

1. High-mass objects are tightly clustered in inclination. Almost half are between 81-83°, and most of the rest are near 71° or 74° or sun-synch orbits (96-103°, mostly 97-100°).

2. Most LEO objects are between 500 and 1010 km. The most congested regions are 950-1010 km (292 objects totaling 340 metric tons) and 830-860 km (67 objects totaling 240 metric tons). These two bands may create most of the potential debris-mass-generation risk from two massive non-maneuverable objects running into each other. That risk varies with the square of debris density, so moving just 200 objects to less crowded orbits may cut by nearly half the risk of catastrophic growth in the LEO debris population.

3. About 79% of the mass (and 90% of the objects that are easy to capture and most worth moving) are Russian. The US depends more on access to LEO than Russia does, and has more resources, so the US has appropriately taken a lead in facing up to this problem.

4. The objects most worth relocating all have known design, and most of them are members of one of a small number of basic types (upper stages, Cosmos satellites, etc.). NASA JSC has provided us with pictures of 3 of the most common types. During Phase II we plan to track down pictures and/or drawings of many other common types as well.

Risks from uncontrolled reentry

In addition to collecting and studying data on debris itself, we needed to also understand the risks to people on the ground from uncontrolled debris reentry, and how those risks might grow if we started dragging large debris objects down and releasing them into either somewhat-controlled reentry trajectories or short-lived orbits that would end in uncontrolled reentries.

Reentry analyses and simulations showed two competing effects. One is that since most LEO debris objects are in near-polar orbits, the ground tracks are more crowded at high latitudes than at bw latitudes. So one might expect more reentries there. Competing with that is that for objects in near-circular orbits (as most orbits are just before reentry), the 21 km high equatorial bulge of the earth and its atmosphere (compared to the poles) should cause more reentries per km of ground track near the equator than near the poles. Simulations showed roughly sinusoidal 2:1 variation between equator and pole. We also expected a weak asymmetry between north and south, due to combined J2 and J3 perturbations which make nominally circular polar orbits (in standard TLE form) actually have a 15 km higher altitude over the southern poles than the northern pole. However, the rate at which the atmosphere circularizes orbits near the end of orbit life is faster than offset apsidal recession effects, so this asymmetry turns out to be small.

The other side of this risk analysis depends on the distribution of world population. We found an online world population database with $1^o x 1^o$ resolution, which is detailed enough for preliminary reentry risk studies. We were already aware that of the asymmetry between populations in the northern and southern hemisphere, but the size of the difference still surprised us. As a good approximation, half the world's population lives from 23N to 45N, a fourth north of that, and the remaining fourth is split evenly between 0N-23N and 0S-90S.

We used the above analyses and databases to quantify risks due to random or controlled reentries from different orbits. Discussions, analyses, and manipulation of these databases in Excel and in several analytical programs we wrote in Pascal have led us to these main conclusions:

1. The risk more than scales with mass, since light objects are more likely to burn up completely.
2. Over 90% of the mass of debris in LEO is in 1,200 objects weighing >500 kg.
3. The risk per object varies by about a factor of two with orbit inclination
   (Equatorial orbits have the lowest risk, and mid-inclinations have the highest risk).

Orbital debris that survives reentry transitions from mostly horizontal to mostly vertical motion about the time it decelerates below Mach 1. By the time it reaches the ground, it is likely to be falling nearly vertically. The debris impact is likely to be considerably less dangerous than a similar mass of aircraft crashing, both because of the vertical impact and because flammables are almost certain to have been burned away during reentry. However, reentry of objects containing large amounts of radioactive material may cause more serious problems.

If we assume that the "lethal impact area" on the ground is of order $20m^2$ per ton of original satellite mass, then the lethal impact area on the ground from all ~2000 tons of LEO orbital debris is about 40,000 m^2. The average human population density of the earth (land and sea, all latitudes) is about 1 person per 80,000 m^2. The exact numbers in this rough analysis are subject to dispute, and to refinement due to covariation of population density and reentry patterns, but it seems reasonable to say that random reentry of all debris now in low earth orbit is more likely to result in either 0 or 1 human fatalities than a larger number.

Rather surprisingly, the cumulative risk to the ISS crew may actually exceed this—if one assumes no avoidance maneuvers by the ISS, and an exposure time sufficient to allow all that debris to "rain" through ISS altitude. Neither side of this comparison is entirely reasonable, but the comparison is probably still roughly fair. It suggests the following perspective: we should try to avoid doing things that significantly increase the risk on the ground, but we should focus more on reducing the risk in orbit. If we change the perspective from people to property damage, the contrast between high risks in orbit and low risks on the ground is probably much stronger.

Triage options: debris deboost, reentry, storage, and recycling

With the above perspective on debris risks, we did a study of "triage" options: what (if anything) should be done with different classes of objects. Our triage analysis led us to these conclusions:

1. Release into short-lived orbits below ISS light objects that will burn up during reentry

For objects that will burn up during reentry, uncontrolled reentry is acceptable, so it is enough to drag them down to a low enough orbit altitude that their orbit life is short. The debris shepherd can easily climb back up from altitudes at least moderately below ISS altitude (which is planned to vary from ~350 to 470 km over the solar cycle), so it is feasible to drag objects to orbits below ISS before releasing them. Then they cannot pose any risk to the ISS. They could be a small risk to shuttle, Soyuz, or Progress vehicles going to or from ISS, but mission plans for these vehicles can easily be adjusted to avoid possible close approaches.

Dragging light objects down below ISS is easy to do, but it solves only a very small part of the LEO debris problem, because tracked objects light enough to burn up completely are a very small fraction of the debris area and mass (despite being most of the trackable objects).

2. Sling moderately heavier objects into controlled reentry trajectories

Our reentry simulations suggest that we should be able to sling objects from ~200x300 km orbits into <90x300 km reentry trajectories, while boosting the debris shepherd into an orbit with low enough drag (average altitude >350 km) that the shepherd can climb to its next assignment.

The problem with this concept is that it gets difficult at about the point it gets worthwhile. It is hard to induce enough orbit change in objects much heavier than the shepherd, because the shepherd orbit change ends up being far larger than that of the payload. Our analyses suggest that the shepherd mass for other purposes need not exceed ~100 kg, so this strategy will not work with the objects >500 kg that constitute nearly all of the debris mass and area.

3. Capture two objects at opposite ends of tether, and use light one to help deorbit heavy one

Another option is to capture a fairly light object (100-500 kg), and then a heavy one (500-1500 kg) at the other end of the tether. Then the shepherd drags itself down to ~160 km, and uses the inertia of the light object to help sling the heavy object onto a controlled reentry trajectory, with perigee below 90 km. Then half an orbit later, at a new, higher apogee, the lighter object is slung into another reentry trajectory. This also boosts the tether perigee so the tether's thrust can overcome drag (which requires an average altitude >350 km).

This concept requires two good reentry locations half an orbit apart (which occurs several orbits per day for most high-inclination orbits). It also requires an adequate supply of light objects in suitable orbits. There aren't enough objects in this size range, so this strategy is also limited to playing a minor role.

4. Follow strategy 3, but hang onto the second object and re-use it on the next assignment

This requires a higher apogee at the time of the sling, and a fairly heavy "light" endmass. This added mass will significantly slow down the climb to the next assignment. But this strategy may be generally applicable for all controlled reentries.

The time required for a ~100kg shepherd to drag a total mass of ~2000 kg (say 1500 kg main payload and 400 kg secondary payload) from ~1000 km to sling altitude may be ~2 weeks. The climb to the next assignment may take a comparable time with a total mass of 500 kg. This means a 100kg shepherd might controllably deorbit ~18 metric tons or 180X its own mass/year.

5. Move heavy debris objects to lower-risk storage orbits

Most heavy LEO objects are in orbits with fairly low eccentricity. There are great variations in the debris density over fairly narrow altitude ranges. For example, the region just above 1010 km is <10% as crowded as the 950-1010 km altitude band. So moving some objects just slightly upward can greatly reduce their risk of impact with other objects. This strategy has diminishing returns, because the density increases in the less crowded region.

However, if one can accumulate objects into a few assemblies as they go through nodal coincidence, and provide at least weak maneuverability to those assemblies to keep them away from other tracked but not-yet-uncollected objects at the same altitude, this strategy might be used more seriously. The task of assembling objects relocated by debris shepherd is common with the next option. Possible assembly procedures for both are discussed in Chapter 6.

6. Collect heavy debris objects to serve as ballast for high-deltaV sling facilities

To operate a fleet of orbital debris shepherds, we will clearly have to master any problems associated with tethered capture. This will do much to demonstrate the feasibility of massive high-deltaV tether "sling" facilities. Such slings can be used to capture objects and throw them into significantly higher or lower orbits. Most of the mass required for such facilities is simply ballast. This reduces the amount of facility altitude change resulting from each sling maneuver. It appears possible to use heavy pieces of orbital debris in suitable orbits as the ballast. So if we can actually operate a fleet of debris shepherds, then it is possible that the best thing to do with much of the orbital debris they can capture and relocate is to collect it so it can be used as the ballast mass for such a sling. Remember that the sling's feasibility may be largely demonstrated by successful operation of the debris shepherds.

Thus our triage analysis ended with a focus shift away from deorbit (controlled or not) towards on-orbit recycling of suitable objects into useful components of a system whose feasibility might itself be thoroughly established by successful operation of a fleet of "debris shepherds."

Recycling debris into sling facility ballast

Ambitious tether slings can provide deltaVs up to at least 2 km/sec above or below the sling orbit, which may be circular or eccentric. And they can provide twice that for launch payloads that can use both deltaVs, such as GEO comsats. Such deltaVs dwarf the differences in launch deltaV between equatorial and polar orbits, which are <500 m/s. Thus one can put far larger payloads into near-polar orbits with a sling than one can into equatorial orbits without a sling.

There are many more LEO objects in high-inclination orbits than low-inclination orbits, despite the higher cost. In fact only 14% of the mass is in inclinations <70^{o}, and 1% in inclinations

>100^{o}. Most of the mass is Russian objects, but even excluding them, there are more US, European, and other non-Russian LEO objects in near-polar orbits than low-inclination orbits. Hence polar orbits are more popular than lower inclinations, despite their higher launch cost. Hence one or more slings in high-inclination orbits that have already proven popular might be able to serve much of the LEO market. A scenario for how to develop the needed technology for high-deltaV slings and how to collect debris into a few ballast assemblies is discussed as part of the development scenario presented in chapter 5.

The concept of recycling debris into sling ballast is far more complicated and less final than the other scenarios above, but throughput may be higher, because smaller altitude changes are needed, and the shepherd need not drag around a reusable "reaction mass" payload. And that strategy may be more valuable, because it helps enable ambitious tether slings, the feasibility of which is partly established if one can actually shepherd space debris as proposed here.

Moving a typical 1500kg object to a collection facility with nearly the same orbit inclination and ascending node should take about the same time as dragging it down to a very short-lived orbit, which requires more altitude change but no plane change. Thus the marginal cost of dragging debris to a "recycling center," compared to just dragging it into a short-lived orbit below ISS, may be negligible. Even if there are technical and/or political constraints on what can be collected and recycled, there may be enough mass in the objects that meet those constraints that triage option #6 might be the primary one.

<u>What objects are worth collecting into a few massive "ballast assemblies"?</u>
Rendezvous requires matching all 6 orbit elements of a ~100 kg debris shepherd with those of a typical ~1500 kg target. After that object is captured, delivering it to a ballast facility requires doing the same with a 16X larger mass. This reduces the orbit-change rate by about a factor of 16. The shepherd can cause fast decay, but climbing and inclination and node changes are much slower, since they require power and not just low tether resistance. For now let us assume 3 collection facilities, at 72^{o}, 82^{o}, and 99^{o} inclination. Over 80% of the mass in LEO is within 2^{o} of these 3 inclinations. If each ballast assembly collects the debris in one narrow inclination band, then the typical inclination change that the shepherd plus debris must make is of order 1^{o}.

Dealing with ascending nodes isn't as easy, since the nodes are very nearly randomly distributed. Earth's oblateness causes the nodes to regress at a rate that varies with inclination and altitude. For these 3 different inclinations, it takes 3 to 7 years for other objects to pass through the orbit plane of the collection facility, if the altitude difference is 300 km. There is more debris above 750 km than below it, and decay is faster than climbing, so it appears better to put a collection facility below 500 km than >1000 km, if the goal is to collect as many objects as possible during a ~5 year near-solar-max campaign. Low altitude imposes a requirement for orbit reboost on the collection facility, but at 500 km altitude, this can be done with a few-kW electrodynamic tether. (And that tether can also adjust the assembly orbit slightly to prevent a potential collision, if there is enough advance notice.) In addition, radar sensitivity is better at low altitude, so we will have more data on what objects we may need to actively avoid.

There are other constraints on what is collectable, that relate to the object itself. Nuclear reactor cores should probably be left in high orbit. Objects with large unfired pyro devices or unvented propellant might better be deorbited, along with objects whose surfaces are flaking (or may do so if exposed to large fluxes of atomic oxygen). Finally, the entity that launched the object may want it left alone or deorbited rather than collected, for security or other reasons. Obviously, if Russia has a blanket objection to collection, that would radically reduce the collectable mass. But 90 of the 230 metric tons of objects in sun-synch orbit are US objects, and another 40 tons are non-Russian, so it may still be worth having a sun-synch collection facility even if Russia objects to collection of their objects. If this collection ends up being the only one, a large electrodynamic tether could later move the collection to a lower inclination where it might be more useful.

Debris spin rates and torques

Our work on Task 2 early in the project focused on expendable capture nets, but the possibility of recycling much of the debris mass into sling ballast mass made us take a look at some of the problems that nets might cause. They include fouling on "ballast assembly hardware" (whatever that looks like), and possible net degradation and generation of fine debris, due to potentially high cumulative atomic oxygen exposure of the ballast mass.

This led us to look for alternatives. The most attractive one we have found is a "two-dog capture" concept. This breaks tethered capture up into two stages: capture of a passive object by a free-flying agile "sheepdog," followed by cooperative capture of a now stable and cooperative sheepdog/debris combination by a tethered sheepdog at the tip of the tether. This concept is discussed in far more detail in Chapter 2. It is mentioned here because the practicality of that scenario depends on the tumble rates of typical large pieces of debris. High tumble rates will complicate a "bite" type capture of some structural detail on the debris. High tumble rates will also increase propellant usage by the free sheepdog, which needs to de-spin the debris and orient its tail towards the tether, to provide needed cooperative guidance data and to allow capture.

Our interest in the two-dog capture concept hence led to an interest in learning about typical attitude rates of large pieces of orbital debris in LEO. The remainder of Chapter 1 is concerned with this subject.

We didn't know what the actual attitude dynamics might be, so we checked with Nick Johnson. He said that NASA does not have any database on the attitude dynamics of orbital debris, but said that the military might. He also suggested we talk with Paul Maley, who works in another group at JSC and is active in the Amateur Satellite Observers group. Paul said that that group's interest was mainly in fast spinning objects (~1 rev/sec), which are somewhat rare. He said that Zenit mission scenarios apparently put the orbiting stage into a fast tumble, near 1 rev/sec, but that that rate does not last. He said it was hard to make general statements, because there seems to be no long-term stability in the dynamics. Some objects spin up and down several times. We also called Jim Barnds at the Naval Research Lab. Jim said that some of the radar observations of some debris objects are "fairly dense data sets" but that the data are not analyzed to determine the period of any regular variability in radar cross-section. He said that such analysis could be done. Others have said that the Air Force Maui Optical Site (AMOS) could be tasked to do the same thing.

These approaches are possible, but they may be overkill, because the objects of most interest are large and close enough that under good viewing conditions, they can easily be observed with amateur-class video equipment. The videos can later be digitized to determine the amplitude and period of any regular variations in brightness. Paul Maley cautioned us that we may need two passes to conclusively determine that an object is not spinning, because some combinations of lighting and viewing angles do not cause significant variations in observed brightness.

Our proposed Phase II effort includes obtaining data on spin-rate statistics for the most popular object classes, either by persuading one of the existing observing groups to derive it from their observation data, or by collecting and analyzing video data ourselves. Our consultant Mike MacDoran collected good video imagery of SEDS-2 during over a dozen twilight passes. At the altitudes of interest (mostly 600-1000 km), most good passes will allow 2-5 minutes viewing with elevation angles >45^{o}. This should be enough to determine whether an object is spinning several rpm (which could pose real capture problems) vs under 1 rpm (which should make it far easier to capture). Note that we do not need at this stage a thorough study. A sampling across the most popular classes should be enough to tell us roughly what fraction of the objects may have high enough spin-rates to cause problems. (And we plan to do some man-in-the-loop virtual-reality capture simulations to determine what spin-rates are likely to cause problems.)

Analysis of torques acting on orbital debris

Rather than trying to find enough spinrate data to be statistically useful, we decided to do an analysis of typical torques and potential spinrates of dead satellites and rocket bodies in LEO. What we learned from this preliminary analysis was both surprising and encouraging.

Most torques fall into one of 3 categories: "random" spin torques, spin-down-only torques, and orienting torques. By "random" we mean that the torque can spin an object either up or down. The main candidate we have found is propellant venting. Newer vehicles often intentionally burn or vent propellants before their batteries die, but older-design vehicles and many satellites often contain fluids when they become inactive. The large exposed tank area of rocket stages makes it seem likely that those tanks will eventually be perforated by small debris or micrometeoroids. Several small holes can be seen in the Delta second stage tankset that landed in Texas several years ago. (It is now on display outside the Aerospace Corp. in Los Angeles.) This mechanism might explain Maley's observation that some Russian stages have been seen to spin up and down several times over several years. But note that some analysts in this field seem skeptical that impact-induced tank venting might explain more than a small fraction of the observed effects. (Minimal holes in tanks with low vapor pressure might never go "over center" into a spin.)

Another form of random spin torque is some form of "windmill" acting on solar pressure or aerodynamic torques. The Magellan mission to Venus canted its solar arrays to cause an aerodynamic windmill torque to determine accommodation coefficients. Windmill torques will probably be very small except on objects explicitly designed for them.

The second category of attitude torques consists of passive energy-absorbers that can only despin objects. The two largest such torques are likely to be large-loop-area eddy currents in aluminum alloy structures, and magnetic hysteresis in magnetically soft material such as Permalloy. Nick Johnson of NASA JSC has said that JSC has composition data on most LEO objects, and that most include large amounts of aluminum. Eddy current torques due to rotation in the earth's magnetic field are proportional to the conductivity and area of the current loop and its rotation rate across field lines. Most objects in LEO are in high-inclination orbit. During one orbit, the magnetic fieldlines rotate two full cycles. So the "spin-down" torques imposed by eddy currents or magnetic hysteresis are towards a 2X/orbit slow tumble, not towards inertial or LVLH frames.

Typical 1/e decay times for a hollow aluminum alloy sphere several meters in diameter should be of order a week, so even objects with only modest amounts of aluminum should spin down within a few years at most, as long as the aluminum allows large-area low-resistance current loops to flow, and no sustained larger torques cause spin-up of the object. By contrast, the density/conductivity ratio for stainless steel is ~75X larger than for typical aerospace aluminum alloys, so vehicles with stainless steel tanks may take many years to spin down. With the Delta 2nd stage, most of the eddy-current damping will probably come from the cylindrical aluminum electronics-bay and "mini-skirt" truss near the front of the stage, rather than from the larger and heavier stainless steel tankset.

We do not know how common or important magnetically soft materials are. They are used to shield sensors that are sensitive to magnetic fields, so they seem more likely to be on satellites than in rocket stages. They may provide a non-trivial part of the damping on satellites not made of aluminum. Magnetic hysteresis torques are independent of rate, so they can cause objects to spin down and stop, rather than causing a viscous-type exponential decay as eddy currents do.

The third category of torques tries to orient an object in some preferred attitude. In this category are gravity gradient effects, offset solar pressure and aerodynamic forces, and permanent magnetic moments in ferromagnetic materials. These torques do not spin objects up or down, but they can torque the spin axis of a spinning object. This in turn may cause changes in eddy current or hysteretic damping. And once eddy current or hysteretic damping reduces the spinrate to ~2X/orbit, gravity gradient effects on very prolate or oblate objects may be able to capture the attitude dynamics and cause the object to librate about the local vertical, rather than continuing to spin. If the body also has retained fluids or loose objects, energy absorption between them and the structure can occur in the presence of such spin-rate-varying torques

Overall, we suspect that most spent stages and satellites will spin slowly if it all, since a few spin-up episodes triggered by fluid venting are likely to be followed by years of spin-down, and perhaps even gravity-gradient capture. If this is true, then capture of debris objects by free-flying "sheepdogs," and re-orientation to allow tethered capture may not involve serious problems. But, as noted earlier, we plan to collect data on actual debris spin-rates during Phase II, and also on what spin-rate threshold appears likely to cause capture problems, based on man-in-the-loop capture simulations. (Note that objects spinning too fast to capture with the "two-dog" technique should still be capturable with the spinning-net capture concept discussed in Chapter 2.)

The analysis and conclusions to this point have been driven mainly by debris statistics and orbit mechanics. The remainder of the report focuses on how to design and operate debris shepherds, collection facilities, and slings capable of doing the things discussed above.

Key conclusions from our work on debris

Our key conclusions from our study of debris issues relevant to debris removal are as follows:

1. Most debris is tightly clustered in inclination, especially the large objects.
2. Elements of those clusters are themselves clustered in altitude and type.
3. Almost all the mass is in ~1,500 large objects of known type and history.
4. Removing these objects from crowded regions would reduce future debris generation.

Chapter 2: Capture Concepts

Task 2. Explore capture concepts, and make and test prototypes
2.1 Study existing capture-hardware designs (spider net, frog's tongue, jaw, harpoon, etc.)
2.2 Develop prototype scaled capture hardware and make scale models of typical targets
2.3 Do capture tests (in air and in vacuum) and iterate the designs based on the test results.

Introduction: free-fall docking and tethered capture

There is considerable experience with rendezvous and docking in orbit, from the first attempts (all successful) by Gemini VI and VII, through Apollo, Skylab, Apollo-Soyuz, Mir, shuttle/Mir, and now shuttle, Soyuz, and Progress docking with the ISS. Most dockings are crew-controlled, except that most Progress dockings have been automated. (The disastrous collision with Mir occurred during a manually-controlled approach.) There have also been successful captures of passive but stable objects such as LDEF and some other shuttle payloads. And recently, Japan's Engineering Test Satellite 7 (ETS-VII) captured a companion satellite several times, using both remote-controlled operation and autonomous control.

Despite the considerable track record, even rendezvous and docking in free-fall remains a considerable challenge, even with cooperative targets. To our knowledge, the only attempts made to capture objects not specifically designed for capture were the successful captures of Palapa and Westar in 1984. The unintentional capture feature they used was the nozzle of the solid-rocket motor. The recovery of Palapa and Westar involved extensive crew training and customized hardware built just for those targets. And some of that hardware did not fit, since the satellite configuration was apparently not exactly as documented. (The crew was able to find a work-around.) There was a similar problem on another 1984 shuttle mission to service the Solar Max satellite. Solar Max had a protruding pin designed to be captured by a jaw-like device called a "TPAD." But a button-like clamp on the satellite insulation prevented the TPAD from engaging far enough to close and lock on the pin. Again, the crew found a workaround.

We go into this detail here for two reasons. One is to indicate that we are not entirely naïve about potential difficulties associated with even free-fall capture of objects not designed for capture, especially if their attitude rates may be non-trivial. The other is a comparably important detail, that we should try not to depend on the configuration to be as documented (especially 10-30 years after launch, and especially when there is no space-suited crew on-board!).

There is yet another difficulty. We want one or a few types of capture hardware to capture a wide range of hardware types, not just one, and we want it to last 50-100 operations, not just one. So this is well beyond typical practice, and a suitable topic for a NIAC effort. We should also note the one thing that makes this task a little bit easier than typical captures: we don't have to worry very much about damaging the object we are trying to capture, unless we can hit it hard enough to create new debris or damage our hardware.

Now we must superimpose on these issues the unconventional difficulty of capturing an object in free fall with a tethered object. The trajectory of the tether tip is roughly cycloidal, whether the tether is hanging, swinging, or spinning. But superimposed on that are bobbing motions and transverse bending modes of the tether, plus air drag (more on the tether than on the tether tip), and other factors. It is not at all a surprise that the biggest credibility issue that most ambitious space tether concepts have is questions about the feasibility of accurate tethered rendezvous ***plus*** prompt tethered capture at the cusp of the approach path.

On the other hand, we should point out that in 1989 two MIT students developed an "industrial-grade Velcro" capture design concept for a tethered-capture contest put together by the PI and Prof. Andy von Flotow of MIT. Contestants were required to capture a swinging and nodding nose cone (modified in any way believable as a fixed or deployable modification of the nose of the shuttle external tank), using a tethered probe controlled from two stories above. As a surrogate of a shuttle safety test, the probes were held in several orientations and dropped 1 foot onto a raw egg on a marble floor. None of the designs broke the egg. To emphasize reliability, the contest score was the total time required for the first 3 captures, from "ok to drop probe" until the "tank" support lines went slack; and to focus on ease of use, no on-site practice was allowed beforehand. Two frames from the video of the winning design are shown below in Figure 4:

Figure 4. 1989 MIT Tethered-Capture Contest (Darryll Pines and Siegfried Zerweckh's design)

With the above discussion of free-fall and tethered-capture work on cooperative targets as background material, we can now address the evolution of our capture design concepts during this study.

Issues that may drive capture hardware design

The large number of objects in each of a modest number of different types suggests that by the time this flies, several different capture hardware designs may be justified, or perhaps several sizes of one design. Depending on the triage strategy selected and the debris cluster serviced, a debris shepherd may need to capture of order 100 objects during a 5-year campaign. This suggests that reusable designs can weigh 100X as much as an expendable one without incurring a net penalty. Note that "expendable" capture probes cannot be released into congested orbits after a miss, without creating a significant debris risk of their own. They need to be retracted or slung into short-lived orbits.

Handing off an object from a shepherd to a collection facility may be easier if the shepherd leaves something attached to the object during the transfer. For example, this may allow handoff to be done by crossing tethers that have complementary Velcro-like features. If the collection facility is to be below 500 km altitude rather than >1010 km, the capture hardware and Velcro features must both be resistant to long-term erosion by atomic oxygen.

Another issue that constrains capture hardware design is that it is difficult to ensure that capture is both reliable and safe. We need to focus on safety, since we can easily make many capture attempts at one-orbit intervals for each object captured, without significantly extending a mission time that is typically 2 weeks per object collected.

We have found two rendezvous strategies that each allow repeated passes at one-orbit intervals, with similar approach dynamics and lighting each time so one can learn from experience. If typical assignments take 2 weeks, then even if we need an average of 4 capture attempts/object before capture, the time required for those multiple attempts will reduce throughput by <2%. In addition, the ability to make frequent passes allows preliminary "strafing runs" to photograph the target with high resolution. The shepherd might gradually "tip toe" in towards capture. Imagery from several preliminary passes could be used to predict the target's attitude during future passes, and to quantify and compensate for any bias errors in the endgame guidance strategy.

Another issue is a trade between development and operational costs. If we were trying to capture only a few objects, we would assume man-in-the-loop control during the endgame. If we were trying to capture millions of objects, it would clearly make sense to automate capture.

We are between these cases. We want to capture roughly 1,500 objects in 5 years (about 1/day), and perhaps to hand objects off to collection facilities at a somewhat lower rate. Even with an average of 4 attempts per capture, this might add up to only ~1 full-time job during a 5-year campaign. Maintaining ground stations to provide low-latency communications during capture attempts may imply several other jobs, but the direct workload for man-in-the-loop capture control appears quite modest. Note that imagery from early imaging passes does not require immediate downlink, so the system needs low-latency comlinks for part of only a few orbits/day.

A thrown-web capture concept

Based on the above considerations, our initial focus was on an expendable capture scheme that left something attached to the debris, to assist handoff of objects that are to be assembled in one place, and a reusable scheme for objects that are to be deorbited or relocated without being collected into a ballast mass assembly. One expendable concept we considered was a large capture web with hook-tipped radial extensions. If the net can be both deployed and thrown against the object, then the extensions will wrap around the object and several would probably foul on the capture web. This concept is shown in Figure 5 on the next page, to scale with 3 common spent stages:

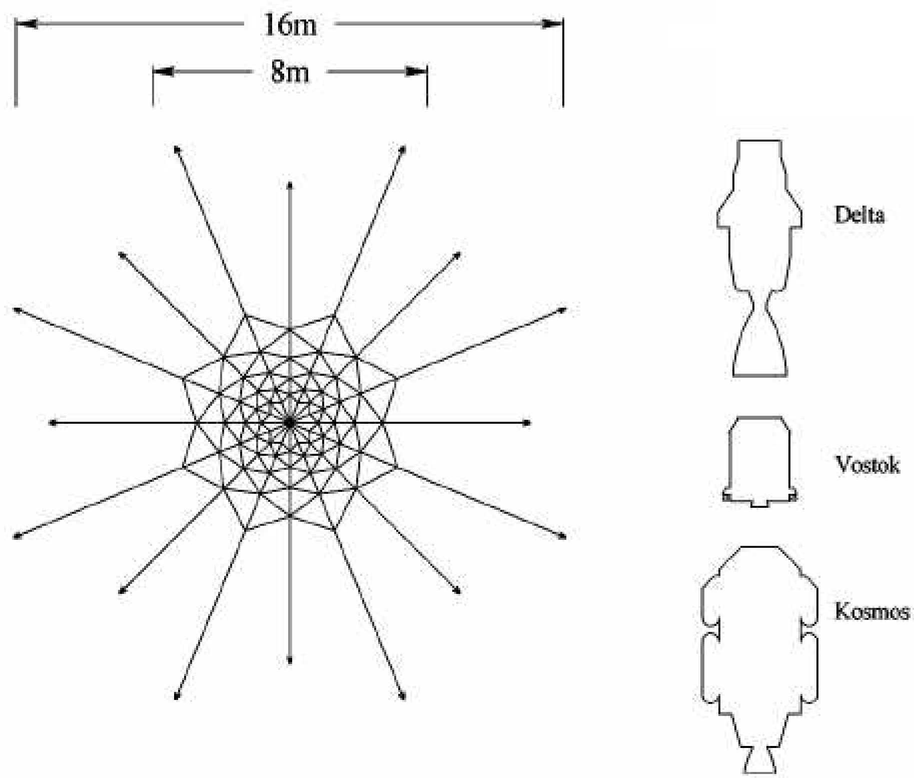


Figure 5. ~100-gram thrown-web, to scale with spent stages (from June poster presentation)

The thrown-web concept requires that the web hit the target at some speed rather than just being draped over it. This complicates reuse, and can create a serious debris problem if webs must be released after failed capture attempts, to keep the net from recoiling and fouling on the tether tip. This could limit this concept to low altitudes, where webs can be slung into short-lived orbits. These problems led us to keep looking for other design concepts.

Spin-stabilized capture nets

A first look at system performance had suggested that each assignment might take several weeks. If so, then, so even several missed capture tries at one-orbit intervals would reduce throughput only a few percent. This led us to wonder about concepts that might allow multiple capture attempts but might not be reusable after a capture. We considered lariots that can wrap around the payload or an appendage, schemes involving UV-curing or other adhesives (which we are skeptical of but think deserve a chance), and inflatable probes that might be inserted into gaps in the payload structure. These concepts may be feasible, but we were not excited by any of them, since we saw potential problems like outgassing of adhesives, deflation of inflatable probes, etc.

But thinking about a spinning lariot led us to consider spinning nets, as an alternative to thrown nets. We considered hanging a “macramé basket” net from the end of the “shepherd” tether, and slowly spinning up the support to pull the basket open. By then we knew that typical targets were of order 3 meters across, and that we might have approach trajectory errors of several meters, due to the poor binocular depth perception available with a near-end-on approach trajectory. So we considered nets with typical dimensions of ~10 meters, suspended on lines of similar length. The payload would approach from the side (which would improve binocular depth perception) and fall into the basket. Spinning simple loops of bead chain suggested that the full-size net at the end of the shepherd tether would need to spin at ~2 rpm. This is slow enough that the payload could enter between support lines and fall into the basket while the net rotates only ~90^o.

The net and suspension geometry shown below allow large entry and capture zones. The images are from a video of net spin-up by a variable-speed drill. The net and lines are made from bead-chain. This has a high enough ratio of inertia to drag to make vacuum testing unnecessary. We also tried catching an empty 2-liter plastic bottle, but the bottle always slipped through the coarse mesh. The actual net would have a finer mesh, using lines thinner than the suspension lines. We used a coarse mesh since we had only one chain type, and we wanted a representative ratio of suspension to net mass.

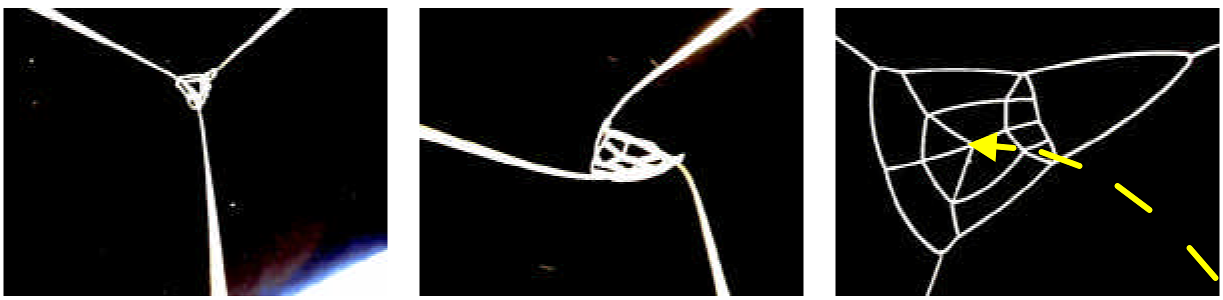


Figure 6. Net spin-up viewed from support, with desired payload trajectory shown in frame 3.

We did some tests with the above bead-chain model in which we intentionally fouled the net by either inverting it or passing it through one of the openings. Hanging it or jiggling the lines did not clear the fouling, but spinning up the lines usually did, especially if we jiggled the spinning support a bit. (But this did not always work.). We also did a simple dimensional analysis that said that stiffness vs gravity effects should stay the same if we scaled the net dimensions with the inverse square root of the acceleration, using the same lines as in the full scale net. The logic is that if you double the length of a cantilever beam holding its own weight against gravity, you double the weight and the moment arm, so you need to reduce gravity to ¼ the value to have the same bend angle and hence a scaled geometry. This suggests a 1-gee net should behave about the same if it is 2m across, with 2m suspension lines. Tests with wound, folded, or twisted-bunch Spectra lines only 2m long in 1 gee showed that they deployed readily under their own weight.

We think a ~10 meter flight net made of Spectra should weigh ~50 grams, including suspension lines, one-shot "rip-stop" type post-capture energy absorbers, and a very small and light storage spool (attached to the center of the net, to prevent generation of loose debris). The force available to deploy such a net without throwing it is very limited: the very low tether-tip acceleration, times the very low net mass. We can make the net of cleaned Spectra, which doesn't stick to itself very much. If deployment stops part-way, we can start to spin the assembly up, so centrifugal force helps pry the lines and then the net off the core.

New issues and perspectives

During the middle two months of the Phase I effort, we stepped back and took another look at our basic agenda for capture. This led to a change in perspective, and a change in the focus of the work during the rest of the contract.

Non-cooperative tethered capture seemed more plausible to us if it involved real-time man-in-the-loop feedback, based on images taken at the end of the tether and low-latency data and command links. There were orbit dynamics and sunlight viewing constraints on where we could make the most suitable rendezvous attempts at one-orbit intervals, without inducing lots of undesired dynamics in the tether. After considerable study, it appeared that the anti-nodes of the orbit had significant advantages for rendezvous. Since most of the debris is in inclinations of 70-100^{o}, this meant we would need ground stations at high latitude for low-latency com-links. And for some orbits and times of year, only the southern anti-node pass would be in the sun. It looked expensive to require low-latency high-bandwidth comlinks between a control station and debris shepherds, if these comlinks were sometimes required when a shepherd was near the north pole, and at other times when it was near the south pole.

As we started thinking in more detail about capturing objects using webs or nets, several more issues came into view. One was that our strawman design documented in the first status report suggests that each "debris shepherd" might be able to capture and relocate >100 large debris objects during a ~5-year mission. That led us to worry about the possibility of a missed capture in which a net caught the edge of the payload and then snapped free. In this case the net would recoil onto the tethered endmass and foul on it. That could prevent that end of the tether from doing any more captures (and possibly even any more imaging). We weren't sure whether we could prevent this, so we decided we wanted to have at least one capture option that didn't involve a large net or other flexible structure.

Another issue was the recognition that capturing objects with nets could generate large amounts of fine loose debris, from flaking paint or degraded multiplayer insulation (MLI) released every time the net shifted and rubbed on a surface. Analysis of tiny craters in LDEF and other objects has apparently shown that many of the fine impactors are paint and similar materials flaked off other objects in low earth orbit. We do not want to add to this problem, so we started looking at capture concepts that could grab some strong and non-brittle feature on the debris, and not touch other surfaces on the debris object.

In addition, the net itself would eventually become a source of debris, if it were made of a strong lightweight polymer like Spectra, which is sensitive to atomic oxygen, and were used to capture objects that later become ballast mass for a long-lived sling facility in fairly low earth orbit.

Yet another issue was that if we were going to capture >100 objects with one-shot nets, the combined mass of those nets could become a non-trivial part of the shepherd mass. This would increase launch costs, and slow shepherds down as they maneuvered from one assignment to the next one. We realized that reusable capture hardware could weigh at least 50-100X more than expendable capture hardware, while handicapping overall system performance less.

These issues led us to wonder whether we could find a limited number of high-strength non-brittle features on most debris objects, and capture them with one or a few different types of reusable capture hardware. This in turn led us to consider the implications of being able to capture and relocate passive space objects without damaging or fouling on the object. One could then also capture failed LEO satellites without damaging them. Then they might be repaired at the ISS or a follow-on facility and then returned to their operational orbits (typically in higher-inclination orbit). A debris shepherd that can operate at 1000 km near solar max can operate through the full solar cycle at significantly lower altitudes, so debris shepherds might also serve as satellite ferry vehicles in the "off season." In this case one must clearly avoid damaging the satellite or its appendages. A whip antenna may be the best target (if present). Then we wondered whether new satellite designs might include one or more intentional capture features. The simplest and lightest is probably a whip antenna modified to increase visibility. For example it might have low-grade optical retroreflectors embossed in its surface, or a better retroreflector at the end. This capture feature should be positioned for easy access when the satellite is stabilized passively, eg. by gravity gradient.

About then we happened to read a discussion on the webpage of the new startup Orbital Recovery Corp (www.orbitalrecovery.com). This company wants to rendezvous and dock with GEO comsats that are electrically functional but running out of station-keeping and attitude-control propellant, and provide stationkeeping and attitude control for additional years of revenue service. Their website noted that they wanted to design a satellite that could grab onto the marman clamp or other launch-support interface that is present on all comsats.

We thought about this and then realized that both satellites and spent stages ***always*** have some such interface, which is used during launch and accessible after the satellite and stage separate. This interface may not be the only capture feature, and it may not be the best one, but it is likely to be the most standardized, rugged, and best-documented feature on the exterior of most stages and satellites. This interface also seems to usually be accessible after appendages are deployed in orbit, based on most satellite designs we have seen. (And most stages don't have deployable appendages.) This may perhaps be the case because it might simplify assembly and testing on the ground.) In any case, the satellite/stage interface appears to be a good candidate capture feature for further study.

On the way to Atlanta for the October meeting, I stopped off at the World Space Congress to attend the three days worth of sessions on orbital debris, and I also spent a day at NASA JSC. Based on discussions with personnel there and at the conference, and on inspections of photos of several common types of satellites and rocket stages, it seems very likely that most large space objects might have at least one fairly good and conveniently accessible capture feature. During the Phase II effort we plan to learn far more about this. We want to get drawings of the most common capturable features, make models, and try capturing them with candidate "jaws" or other capture hardware. We may also sponsor a student contest, to get ideas for alternative capture hardware designs that might not occur to us. We may also pay the winners an additional bonus later, if they can refine their designs to better meet our needs.

The main problem we have found with the concept of grabbing one of a few specific structural features on the debris is that that none of those features might face the tether when it comes by for rendezvous (the first time, and possibly even for many passes in a row, on a bad day). This led to a significant effort to learn about the probable attitude dynamics of orbital debris, as discussed at the end of chapter 1. It also led to the "two-dog capture" concept discussed below. This concept eliminates "bad attitude" as a potential cause of a missed capture.

A two-stage cooperative "two dog" capture strategy

We liked the idea of capturing specific features and not touching any other part of the object, because it might also allow a "debris shepherd" tether to play a key role in satellite servicing, by capturing failed satellites and dragging them to ISS orbit. But we didn't want to make tethered capture more difficult than necessary, by making operations depend on a suitable debris attitude.

We eventually realized that we might be able to reduce the difficulty of tethered capture if we broke the operation up into two parts:

1. Take your time to capture the debris object with a small free-flying "sheepdog."
2. Then orient the sheepdog so it can be captured by a sheepdog at the end of the tether.

This concept is shown below:

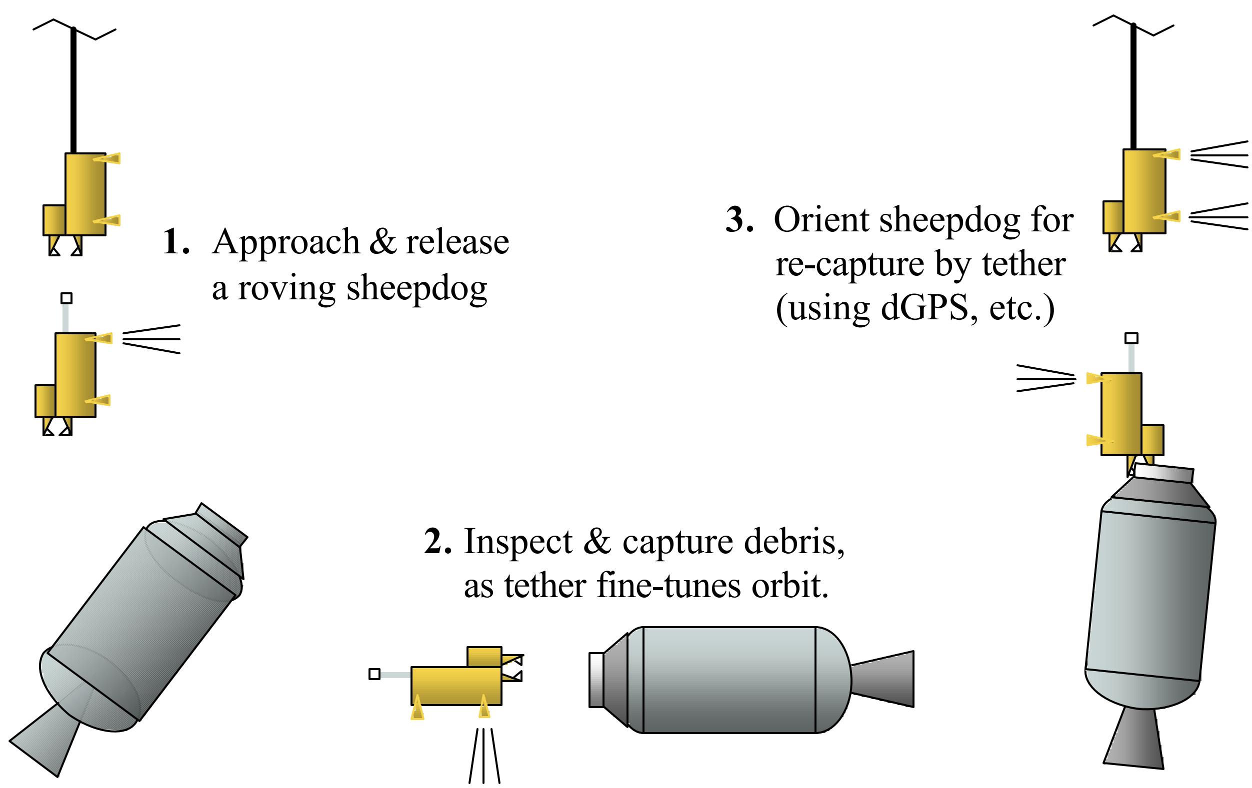


Figure 7. Two-stage Cooperative "Two-Dog" Capture of Passive Objects by Tether

Advantages of the two-dog capture concept

We soon realized that this concept also had four powerful advantages. First, the sheepdog can fly around the debris object and image it in great detail before capturing it. The total exposure area-time product of all large debris in LEO is roughly 200 acre-years (not a typical aerospace unit, but a good one to provide a feel for the areas and times involved). This is >2000X larger than the exposure area-time product for LDEF (the Long Duration Exposure Facility), which has been the basis of most debris impact studies to date. The launch date and orbit history of all large objects is known, so collecting good close-up images of even a modest subset of objects of different ages in different orbits could prove invaluable at determining the past, present, and probable future trends in untrackable debris (mm to several cm). Such a photo-survey would also be quite useful to the shepherd operations, since it would verify the current configuration and capturability of the intended capture features. Finally, if the sheepdog has a hyperspectral sensor, it could also do in-situ surface contamination and degradation surveys on a wide variety of materials that have been used but whose actual long-duration performance in LEO is not well known. This could prove very valuable for most LEO spacecraft developers and users.

The second advantage is that debris capture by the free-flying sheepdog can be scheduled for a daytime pass over a convenient ground-station, allowing direct low-latency low-risk com-links. This makes man-in-the-loop control more affordable, and eliminates any need for remote ground stations and low-latency links from the control station to the remote facility. By contrast, the best free-return trajectories that allow repeated tether capture attempts at one-orbit intervals appear to require that tethered-capture be done near the northernmost or southernmost point of the orbit. This could impose significant costs for ground station operation and reliable low-latency com links to a low-support-cost control station at lower latitude.

The third major advantage of this two-stage "two-dog" strategy is that the roving sheepdog can provide not just a properly-oriented capture feature, but also a suite of guidance aids, including dGPS, ranging transponders, and so forth. This provides the tether with better guidance data than is available from the tether's long-baseline binocular imaging capability, and allows a more accurate approach. (This should eliminate any need for "man in the loop" control for this phase of the operation, and the expensive high-latitude low-latency ground stations which that implies). A more accurate approach may allow use of a small intentional capture feature on the sheepdog, and tethered capture hardware that is simpler than might otherwise be feasible.

The fourth major advantage of this concept is that it does allow capture and relocation of ***any*** object in LEO that is not spinning too fast to be captured by an untethered sheepdog. Capturing failed satellites could be uniquely useful to NASA, and in particular to NASA Goddard. Unlike either commercial or military LEO satellite operators, who usually launch several satellites of a given type, GSFC satellites are usually unique. If one fails, it is usually not a matter of launching the next one off the production line a bit earlier, but of starting a process of soul (and budget) searching, to determine whether they can and should build a copy of the failed satellite (which should in itself be a source of worry), or expedite work on a next generation, or some alternative. Being able to get to, safely capture, and drag a failed satellite to ISS within a matter of months, where it can be inspected and repaired, and then returned to its operational orbit within months, should be of great interest to NASA Goddard—especially since many failures do not involve unique sensors, but ordinary items like fuses, batteries, gyros, etc.

Since the "two dog" capture concept does not require building a specific intentional capture feature into satellites, it can even be used with satellites that have already been launched, as long as they have ***some*** accessible capture feature.

Possible cooperative-capture hardware design

Our strawman concept for a cooperative capture probe on the sheepdog is similar to the grapple fixture used on many shuttle payloads: a button or mushroom on the end of a shaft. We do not need the flying buttress structure at the base of the grapple fixture, since we do not need to react large cantilever loads. And there is no need for the shaft to be as long or stiff as on the grapple fixture. But our first-cut design uses the same diameters for the button (32mm) and shaft (16 mm). We made a crude model, and did some very informal tests with it, using one hand to accelerate it at ~0.02gee and catching it with the other (with arm fixed). This was extremely easy. Tossing it and capturing the button at the peak of a one-gee kiss trajectory was only slightly harder.

The capture hardware on the shuttle "arm" that grabs the grapple fixture is large and heavy, partly because it is designed to allow a 15 inch capture zone for the manually-controlled arm, and partly because it is part of a structure that can exert large cantilevered loads on payloads once they are captured. We do not need anything like that. Our plan for this half of the hardware is to use a small jaw that clamps over the end of the button. As an alternative, it might clamp on from one side. Another variation on the "jaw" theme is for the jaw to resemble a lobster trap. That would allow the button in but requires active jaw motion for release.

We then wondered about some sort of jaw feature that would provide automatic release on overload. Our technician Randy Evans pointed out that one simple way to do that is to put a mechanical fuse in the probe, either at the button or at the base. (A released probe that stays in the jaw can later be released into a shortlived orbit by the tether, and another "tail" or capture probe can be deployed by the sheepdog if needed.)

Tentative sheepdog requirements

We want the sheepdog to be light, but it needs enough electrical power for a good comlink to the ground (and to provide flash lighting periodically during eclipse so it can image the debris). It probably needs several m/s deltaV capability for each photo survey and capture. It will also need some additional propellant to despin, orient, and stabilize the debris for tether capture. The deltaV to do this ~100 times is significant. Our tentative plan for thrusters is small resistojets (<0.1 newton) that use steam as propellant. Even modest-performance steam resistojets should give an Isp near 100 seconds. This is considerably better than cold gas, and the tank can be far lighter. If 20% of the initial sheepdog mass is water, and the average Isp as used is 100 seconds, the lifetime deltaV capability is ~220 m/s. If some sheepdogs run out of propellant prematurely, they might be replaced by new sheepdogs (of potentially revised design) delivered by another electrodynamic tether vehicle, which can dispense sheepdogs to many debris-collecting tethers. An alternative concept is to deliver ballast to a ballast assembly facility with a sheepdog still attached, and capture a new sheepdog released by the ballast facility to take on the next mission. This "dog swap" operation raises the possibility of refueling sheepdogs at the ballast facility. Water may be one of the easier propellants to deal with in transfer operations. It is also a good propellant for secondary-payload-class flight tests, for safety reasons.

Overall, the sheepdog will require at least the following features:

- Thrusters in many directions, with pulse T/W of ~1 milligee and deltaV ~200 m/s
- Solar arrays and batteries to power avionics, resistojets, and comlinks to ground
- Strong jaws (several kinds on different faces?) to grab and release debris many times
- Wide-angle cameras facing in several directions, and telephoto cameras for photosurveys
- Snag-free exterior with soft bumpers, to tolerate soft impacts without damage
- Features to assist tethered rendezvous (eg dGPS or RF ranging transponders)
- Cooperative tethered capture probe (preferably similar to high-deltaV-capable designs)
- Launch support interface

Note that the "tethered sheepdog" has many similar requirements on it, and might use many of the same components and much of the same software. Possible differences include:

- A short reel, to allow end-game axial position adjustments for tethered capture,
- Possibly larger thrusters (since there is less time to cancel transverse errors),
- Possibly more specialized "jaws" than the free-flying sheepdog,
- Possibly a supply of spinning capture nets, if they turn out to be useful in some cases.

Note that both the debris shepherd and its free-flying sheepdog can probably use commercial (non-rad-hard) electronics, because most of the time will be spent climbing to the debris altitudes and dragging objects back to lower altitudes. About 80% of the mass of LEO debris is below 1000 km, with large subsets near 800 and 950 km. To keep the total doses over a ~5 year mission low enough for most commercial electronics, shielding equivalent to ~4mm of aluminum appears enough (and this might include incidental structure, batteries, etc.). Note that by ~2010, it is possible that most commercial electronics will be more tolerant against total ionizing dosage than currently. However, the gradual reductions in critical charge as device features shrink may make the electronics more susceptible to single-event upset. This may require error detection and correction in memory, and perhaps other protection features as well.

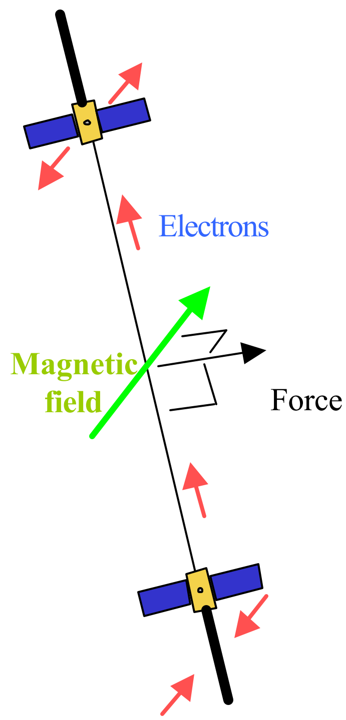
<u>Conclusions from our work on capture concepts</u>

We think the "two-dog" capture concept is very attractive, despite the fact that it depends on two unknowns (the details of capture feature geometry, and low enough spin-rates to allow capture). We plan to focus the first year of our proposed Phase II effort on resolving those issues, so that we can decide whether and how to refine our shepherd design concepts assuming the use of two-dog captures, or whether to change to a spinning-net capture or some other form of capture.

Chapter 3: Rendezvous, Relocation, & Contingencies

Task 3. Investigate rendezvous, capture, disposal, and contingency strategies

3.1 Develop strawman rendezvous and capture strategies that minimize use of expendables
3.2 Determine required accuracy of guidance data during approach and capture
3.3 Identify and analyze guidance sensor options (eg, binocular imaging from ends of tether)
3.4 Identify and analyze likely contingency modes and their implications



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 are stimulated.
- Control is tricky except at low tether current.

Plasma density
- Large electron collection areas are needed.
- Narrow tapes collect better than wide ones.
- The service altitude varies over solar cycle.

Figure 8. Electrodynamic tether maneuvering constraints displayed graphically.

Rendezvous and capture strategies

Figure 8 shows the basic problem with electrodynamic maneuvering. The force is always normal to both the field and the tether. At any given time you can apply a force in only two directions, 180^{o} apart. More flexible control comes from using the variations in field direction around the orbit and control of the tether attitude dynamics to provide forces in desired directions.

We have found two different capture strategies that allow repeated close passes once per orbit, without expenditure of propellant. Most tether capture concepts proposed to date involve capture with the tether near vertical (whether the tether is spinning, librating, or hanging). Doing this makes it hard to match orbit periods, as required for free repeat passes every orbit. Our concepts involve capture with the tether temporarily horizontal. We have done simulations of both cases. In one case, the shepherd stays within 40 km of the target all through each orbit, while in the other it moves over 100 km away. The option that stays closer allows far better binocular optical depth perception and better maneuvering, so we plan to focus on that.

Range estimation using binocular imaging

Our preliminary analysis suggests that binocular vision from both ends of the tether can provide more than adequate data to drop a sheepdog off close enough to a target. We can usually arrange to make those passes near the end of a daylit period, when the target has been illuminated for over an hour. We can also arrange to approach the target mostly from the sunlit side, with the target in front of a starfield rather than the lit earth. The more interesting question appears to be how low an imager performance we can tolerate. Note that typical cameras used for starfield imaging have narrow fields of view, and attitude rates must be very low (sometimes <0.1°/second) to detect the typical 6th magnitude or dimmer stars that are often the brightest stars reliably present in narrow fields of view. Going to a wider-angle view sacrifices angular resolution, but also reduces the need for sensitivity.

A startracker appears far more than sensitive enough to see most targets from any required range. Upper stages are usually light colored, but satellites are often darker. If we assume that a typical >500 kg satellite viewed from the lit side is typically at least 1/10 as bright as a $1m^2$ front-lit white surface, then a 3rd magnitude threshold allows target detection to at least 160 km. Typical orbit phase errors in the orbit catalog are a few seconds or less, so one should be able to detect the target well before getting close enough that catalog errors could lead to collision. By the time that the target is within 10 km, it will be brighter than Venus at its brightest.

In our proposal we discussed using electrodynamic tethers as short as 2 km. Since there is far more heavy debris than we thought, and longer tethers allow better electron collection and hence efficient operation to higher altitudes, we have increased the baseline tether length to 10 km. This obviously gives far better depth perception than a 2km baseline does. For example, at the maximum distance of 40 km between two close passes (with our preferred formation-flying scheme), a 10km baseline and 0.3 milliradian RMS error per view should allow range estimation with an RMS error ~70m (and transverse position errors ~10m RMS), when the tether is nearly broadside to the target. By 300 seconds before closest approach, the RMS range error should be ~7m and transverse error ~3m. We can use electrodynamic forces for most maneuvers, especially during the first pass that drops off the sheepdog. During subsequent runs we can also actively damp transverse tether dynamics, to improve the predictability of the shepherd's dynamics. But as we approach capture, there is not enough flexibility in the electrodynamic control authority, and thrust is needed to adjust the trajectory of the tether tip doing the capture.

The major perturbing forces on the shepherd are likely to be gravity gradient effects and any residual transverse tether dynamics. We will be able to model and predict the effects of these forces quite well, especially after some practice. The other main perturbing forces at 600-1000 km altitude, near solar max, appear to be aerodynamic drag, and parasitic electrodynamic current loops involving ram-ion collection and balancing electron collection elsewhere. Solar pressure and differential orbit perturbations appear to be less. A preliminary estimate of the typical net combined unpredictable component of these forces is a few millinewtons, mostly due to variations in twist of a flat tape tether. (This can affect both tether drag and ram-ion current collection.) These will affect the whole tether length, so the forces will cause displacements and tether bends, only a small part of which will need to be reacted by the tethered sheepdog doing the capture. So the maneuvering force required will be likely to be <1 millinewton.

Another driver of maneuvering propellant requirements is errors in estimated target position. The earlier any expected position errors can be corrected, the less propellant is required. But one should "undercorrect" to keep from spending propellant just to chase sensor noise. If we have a 5 kg tethered sheepdog, plus 1 kg of tether that is close-coupled enough on this time-scale, then 1 millinewton thrust for 300 seconds can cause a 7.5m displacement.

Other guidance sensor options besides binocular vision

Binocular vision appears far more than adequate for the uncooperative approaches that simply need to drop off a sheepdog near the debris object. ("Near" could be 1 km or more if necessary!) Improved binocular vision may conceivably be good enough for a spinning-net capture, due to the transverse approach. However, the desired cusp-like approach for the second stage of a two-dog cooperative capture needs much better guidance. But this appears easy to do, since the two dogs can each have a copy of the same model GPS receiver, and the roving sheepdog can send its solutions to the tethered sheepdog so it can maneuver appropriately.

One trick with differential GPS (or more accurately, relative GPS) is that the tethered sheepdog should derive its solutions using only satellites received by both it and the other sheepdog. This ensures that as much as possible of the navigation error components are common-mode, and the errors are as small as possible. The exact values of these errors will depend on the type of GPS receiver used. By the time this flies, improved hardware and software may allow good enough solutions for end-game guidance, and not just early approach.

Contingency plans

We have briefly investigated the following possible contingencies:

- Shepherds becoming disabled and stranded in orbit
- Shepherds colliding with each other, with targets, or with any other space objects
- Objects colliding with collection facilities
- Loss of reboost capability of collection facilities
- Any other mishap that can generate debris at ISS altitudes.

A shepherd needs a nearly complete control system at each end. The controls need to work together for full performance. But if one end is disabled, the shepherd can still "limp home" using one control system and electron emitter. This feature can be used to deorbit an injured shepherd before it fails entirely. (We can also design the endmasses to burn up during reentry.)

Traffic control is needed whenever two or more tethers are at overlapping altitudes, because the risk of collision can greatly exceed the risk of collision of all other space objects with each other. (If at least one is librating or spinning, the average collision cross-section can exceed 50 km^2, and the mean time before collision can be as short as 2 weeks if both are in near-circular orbit.) On the other hand, the consequences of tether/tether collision on the debris population can be quite minor. Only about 0.2 gram of fine debris will be generated (most of which will deorbit immediately), and with proper design we should be able to maintain enough control of the 4 tether pieces for them to detect their state and deorbit themselves within a few days.

Similarly, the risk of shepherds colliding with random other objects (few of which are working satellites) can be large, because the effective collision cross-section is the tether length by the several-kilometer sum of widths of all objects it can collide with. Most of the risk is associated with the larger objects, due to their cumulative width, and these objects are tracked and hence easily avoidable.

Another issue is unintended collision with a target due to guidance errors. We envision using several imaging passes at successively closer range before the first capture attempt, to allow determination and correction of any bias errors before the capture attempts. We plan to have real-time video downlinks and command uplinks during capture attempts, and we can program in an automatic abort maneuver in case of loss of communication during critical phases. Finally, if we decide to do captures with some intentional transverse motion, we may also want to use a second camera view 25-100m from the capture endmass to improve endgame depth perception.

Chapter 4: Shepherd Architecture and Performance

Task 4. Flesh out a strawman architecture and system design and estimate its performance
4.1 Develop strawman vehicle design and estimate orbit change rates with and without payload
4.2 Develop operational concept and target selection strategy, and estimate system throughput
4.3 Make rough estimate of effects of system on debris trends and collision risks
4.4 Flesh out a development scenario and identify potential issues and applications

Key features of the architecture

This chapter describes our work on the debris shepherd concept. We have done enough work on sub-task 4.4 that we have given that sub-task a chapter of its own, Chapter 5.

In our proposal we discussed using electrodynamic tethers as short as 2 km. Since there is far more heavy debris than we thought, and longer tethers allow better electron collection and hence efficient operation to higher altitudes, we have increased the baseline tether length to 10 km.

Many of the key features of the proposed architecture have been mentioned in chapters 1-3. Controlled deorbit of heavy objects while keeping the tether itself in orbit appears difficult, but bringing objects to one of several collection facilities appears easier (even though there are more pieces in the system). Collecting rather than deorbiting debris does not totally eliminate debris risks, but it can reduce the risk of later debris generation by >90%. And it makes a huge amount of ballast mass available for more ambitious tether transport facilities in low earth orbit. The feasibility of such a system would be at least partly established by successful operation of a prototype debris shepherd, so the value of collecting debris for use as ballast mass might be determined well before the full system is built and operated.

Key pieces of the architecture are shown at left. The “EDDE” debris-shepherd is the centerpiece, but the sheepdogs and ground-station are equally important. (Potentially high costs for low-latency com-links at high latitudes helped shift our focus to the two-dog concept. One key item not shown is software. By the time this system is built, launched, and used, software will probably be the single largest cost. During Phase II we will do whatever we can to minimize its impact.

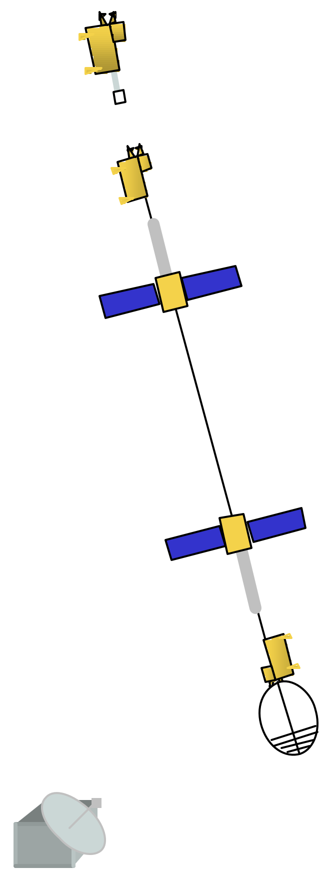


Figure 9. Key elements in the debris-shepherd architecture.

Orbit change rates with and without payload

As a rough estimate, the debris shepherd plus attached sheepdogs should be able to climb at rates exceeding 400 km/day; decay at rates exceeding 1000 km/day, and change orbit inclination or node (near polar orbit) at rates well exceeding 1^{o}/day. These values are for a shepherd without payload. When it is carrying a payload, these rates will vary inversely with the total mass, so f the shepherd is carrying 15X its own mass, it will be able to cause payload decay at roughly 65 km/day.

These orbit change rate estimates assume the plasma density is high enough at the operational altitude that the tether is not "starved." These rates would decrease significantly whenever the ambient plasma density drops below the range of 1E4-1E5/cm^3. The exact threshold depends on the operating mode. The shepherd is power-limited during climb, so it can work at top speed in lower plasma densities than it can in drag mode.

The orbit-change rates for the debris shepherd will vary with the power-to-mass ratio of the solar array. We will assume lightweight crystalline arrays on a flexible substrate. If suitable thin-film arrays can be developed, plane-change rates may increase ~30% and climb rates ~70%. Decay rates will not change significantly, because they depend more on the resistance of the aluminum conductor (and plasma density) than anything else.

Preferred payloads

The objects that may be easiest to collect and most worth collecting are those weighing >500 kg, in orbits with average altitudes of 500-1000 km, within ~2^{o} of 72^{o}, 82^{o}, or 99^{o} inclinations. That description covers 768 objects totaling 1187 metric tons. This is 2/3 of the total mass of all objects of any size in any orbit inclination at altitudes between 500 and 2000 km. Any system designed to collect most of this mass will also be able to collect or deorbit a significant number of <500kg objects at these or other inclinations. In addition, once this concept is far enough along in development that it deserves to be taken seriously by LEO satellite developers, they will have the opportunity to add to their new satellite designs intentional capture features such as modified whip antennas, and/or to design their satellites for on-orbit repair at the ISS. Related to this is the option of designing satellites for final assembly at the ISS, followed by ferrying to operational orbits (typically higher in inclination and altitude). Such maneuvers will take several months for large plane changes, but this is far faster than building and launching replacement satellites, or waiting for a secondary payload launch opportunity to a specific orbit. NASA Goddard is now very interested in flying constellations of small scientific satellites, both in LEO and in higher orbits. Some of their personnel are getting quite interested in EDDE, the ElectroDynamic Delivery Express base vehicle concept on which the debris shepherd is based. The idea of being able to recover LEO satellites for repair, and of providing modest capture features to facilitate that, may flow naturally from any serious consideration of using EDDE for satellite delivery.

A first-cut target-selection strategy

Unlike a chess game, where the implications of each move can easily change sign, removal of each piece of debris from a congested region (one "chess move") has lasting value (even if it is only probabilistic). The exact schedule and hence best available targets may vary with plasma density, so one cannot "see too far" into the future. One possible simple-minded target-selection strategy compatible with this is to provide in advance a "score" for all objects of interest, based on their mass, area, orbit, and other features that affect debris-generation potential as well as any value as ballast mass. Then when a shepherd becomes available for another assignment, one can estimate the time required to collect each of the easily accessible objects, and rank those options by score-per-day. One can then select the best-ranking options for that and other shepherds serving the same inclination and pursue each of them several assignments further, until it is clear which sequence has the best score, without having to consider all possible combinations.

The best detailed system design and sizing will depend on the orbit mechanics. If a shepherd is small, it will spend nearly all its time dragging payloads to lower orbit, while if it is large, it will spend too much time hauling its own mass to the next assignment. Right now it appears that a balanced shepherd design might use a 10km long tether weighing ~100 kg total.

Performance and system throughput

The electrodynamic current and hence the thrust and throughput of the system can be limited by controllability issues, power limitations, electron collection, or simply the electrical resistance of the aluminum tether. We think controllability will not seriously limit performance, and we think that our operational concepts will give predictable performance. We assume that thin-film solar arrays will become available at lower mass and cost than rigid crystalline cells, but using crystalline cells should decrease performance only moderately because more time is spent turning orbit energy into electric power than changing orbit plane or climbing to reach the next target. Our design should provide enough electron collection area to keep low plasma density from significantly limiting performance down to densities of ~4E4/cm^3. At lower densities, decay rates are roughly proportional to plasma density, but above that, decay rates should be limited more by the resistance of the aluminum conductor. (Climb rates are power-limited more than plasma-limited down to ~1E4/cm^3 density, but less time is spent climbing than decaying, since climbing is done without payload.)

Since the two most significant limitations on performance appear to be ohmic resistance and electron collection area, the conductor should be the single heaviest component in the shepherd, and the bare-metal electron collection area should be the dominant area in the system. In this case we can estimate performance fairly well without needing to do a detailed system design.

The plasma density appears marginal in many cases of interest. This turns out to be critical for MXER, so the upcoming NASA effort to build an accurate simulation capability for MXER should resolve any issues about what plasma densities can be expected as a function of altitude and solar cycle, at least for near-equatorial cases.

A preliminary look suggests that performance will be adequate up to at least 1000 km near solar maximum, but that away from the ~3 peak years, maneuvering rates near 1000 km will drop very rapidly. However the shepherds should still be able to reach the objects near 800 km for about a year on either side of the ~3 year peak. This has led us to baseline a 5-year campaign. Near solar minimum the debris shepherd may not be able to travel rapidly much above 600 km, so it is not clear how valuable they might be then.

If more detailed study of this plasma data and models suggests that performance will be adequate up to ~1000 km near solar max, then a fleet of ~12 vehicles weighing roughly 100 kg each may be able to collect most of the massive objects below 1000 km ~5 years, and deorbit many of the <500 kg objects. However not all of the objects in the three most populous inclination bands will pass through nodal coincidence with its collection facility during that period, especially in the 82^o inclination orbit. If one puts two collection facilities with opposed nodes in 82^o orbit, then far more of the total mass can be collected during one 5-year campaign. This mass can later be accumulated into one orbit plane by making a temporary several-degree inclination change and waiting a few years for differential nodal regression to line the nodes up.

Note that debris shepherds can be launched into any low earth orbit above ~350 km (and even slightly lower altitudes away from solar max), because they will be able to maneuver to their high-inclination operational orbits within a few months. This plus their individual mass of ~100 kg may make them very convenient secondary payloads. This in turn may allow the US to arrange for useful non-cash foreign participation, by having ESA and Russia provide free secondary-payload launches of shepherds on a space-available basis. The US might also benefit from use of real-time links through suitable ESA or Russian ground stations during some capture attempts.

Chapter 5: A Possible Development Scenario

Introduction

The last task in our proposed Phase I effort was 4.4, "*Flesh out a development scenario and identify potential issues and applications.*" This chapter does that, and also presents our detailed recommendations for future work both by us and by others. It discusses both our proposed Phase II work, and also the larger efforts that must be done by NASA and industry after that, to bring debris collection and sling technology into practice. The key steps that we envision are listed below. The rest of the chapter discusses each step in some detail.

Possible Steps in Development Scenario

1. Determine what might be capturable and how to do the captures (NIAC Phase II, year 1).
2. Develop detailed shepherd architecture and operating scenarios (NIAC Phase II, year 2).
3. Develop adequate ED tether dynamics simulation capabilities (NASA MXER effort).
4. Develop suitable ED and strength tethers and capture hardware (NASA MXER effort).
5. Select a suitable inspector-type satellite as a "sheepdog" and adapt and enhance as required.
6. Complete development of EDDE (solar arrays and array steering, integration, etc.)
7. Flight-test EDDE or another suitable precursor with a sheepdog (preferably by 2008).
8. Refine system design concepts based on what is learned from the flight experiment
9. Launch shepherds and sheepdogs to deboost LEO debris near solar max (2010-2014?).
10. If slings do indeed look feasible, assemble ballast and other components and operate slings.
11. Build a safe-abort payload carrier to allow intact-abort with suborbital payloads.
12. Eventually, develop an RLV optimized to launch payloads for suborbital capture by sling.

Note that we do not discuss TRLs (Technology Readiness Levels) here, since we will in many cases not even be able to identify the most important technologies until the second half of our proposed Phase II effort. And the relative importance of various technologies and the specific requirements on them may not be clear until near the end of the planned 2-year NASA effort on MXER. We plan to evaluate TRL levels late in our proposed Phase II effort.

Many changes from this scenario will probably be necessary once we travel far enough down the path to see the rest of the path clearly. But we think this is a good direction to start, because it builds on existing or planned efforts in a variety of areas, and provides a variety of payoffs along the way to a high-deltaV sling capability, such as debris mitigation and improved satellite inspection and servicing capabilities.

1. Determine what might be capturable and how to do the captures (NIAC Phase II, year 1).

We prefer the two-stage cooperative "two-dog" capture concept to capture of debris in a spinning net for many reasons. One strategic reason is that it makes tethered capture of debris very much like the cooperative tether captures that might be done by more ambitious high-deltaV sling facilities. It should be easier, since the tether tip accelerations can be much less, but it will allow testing of the key enabling operation for the more ambitious concepts, while at least partly paying for itself by removing debris. The problem with the two-dog capture concept is that it does require capture of debris by a free-flying "sheepdog." We don't yet know whether that will be feasible, so we plan to focus the first year of the phase II effort on determining that.

This first year effort will be divided into two key tasks: characterizing debris, and developing and testing concepts for capture. The debris characterization task will focus on 2 distinct areas. One is finding as much data as we can on the geometry of the common types of large debris in LEO, with a special focus on deployed appendages and potential unintentional capture features. The other is equally important: determining the spin-rates of a statistically useful number of objects of each of the main types. We will do this by capturing video imagery of ~100 passes of objects of interest, and post-processing the data to derive photometric curves.

This geometry and spin-rate data will feed into the second task, developing and testing concepts for capture of passive objects. We will start by developing 3D models of the most common types of objects, with enough fidelity that we can use them in "fly around" simulations of inspection and docking with a capture feature. We can also use the models to develop estimates of their brightness as a function of lighting and viewing directions, and try to estimate what spin axis and rate might give the photometric curves we have collected. Our "capture video game" will keep track of propellant usage and contact velocities and offsets as a function of debris types and spin-rate. Results of this phase of the effort will feed into design of actual capture hardware intended to work on the capture features found most useful, at the approach speeds and with the approach errors found likely. We will test and refine the capture hardware concepts as required to allow them to capture enough of the debris types to be useful.

<u>2. Develop detailed shepherd architecture and operating scenarios (NIAC Phase II, year 2).</u>
Based on our evaluation of what we can capture and what the hardware must look like to do it (agility, deltaV, capture hardware design), we plan to revisit our basic architectural concepts for debris shepherds and sheepdogs, and refine the design concepts, mission scenarios, and control concepts to fit the limitations discovered in the first year. Note that we will not address the second-stage capture (of sheepdog/debris by tethered sheepdog) in great detail, because very closely analogous operations will be under more serious study as part of the planned NASA MXER effort. But we plan to go into enough detail to make sure that our scenario resembles the MXER scenario where appropriate, and we will try to make our concepts suitable as precursor test options for MXER.

We also plan to address mission scenarios, including potential relevance to satellite servicing concepts. And we plan a significant effort on collision avoidance strategies. A dozen ~10 km tethers that spend most of their time at altitudes where most orbital debris is (600-1000 km) will need to actively maneuver to avoid both each other and also all other tracked objects. The untracked objects also present a risk, but their small size limits the risk to of order 1 cut in the whole fleet during a ~5 campaign. But since cuts are possible, we plan to require that the two halves of a cut shepherd be able to deorbit themselves promptly.

Besides addressing mission scenarios for debris shepherds, we plan to look at high-deltaV sling architectures, focused specifically on designs that could use collections of LEO debris (up to 500 tons or more) as ballast mass. This will include more detailed work on concepts for handing large pieces of debris off to the growing ballast assembly. The final area of focus in our planned Phase II effort is to refine the post-Phase II development scenario described here, based on what we have learned during the Phase II effort and on what NASA learns from its parallel effort on MXER.

3. Develop adequate ED tether dynamics simulation capabilities (NASA MXER effort).

The "Momentum Exchange/Electrodynamic Reboost" (MXER) concept was developed under NIAC funding and is making the transition to a NASA initiative at Marshall Space Flight Center. NASA's main initial effort will be to develop an accurate enough tether dynamics simulation program to determine whether something like MXER is actually feasible. We think that such a program could be quite valuable in analyzing a wide range of tether applications and hope that the effort is done well.

4. Develop suitable ED and strength tethers and capture hardware (NASA MXER effort).

In parallel with the MXER simulation effort, NASA is planning two additional efforts, one on tether design (materials, configuration, etc.) for MXER, and one on tethered capture hardware. This too could be quite useful for a range of potential applications, including the second stage of the "two-dog capture" concept discussed earlier in this report.

5. Select a suitable inspector-type satellite as a "sheepdog" and adapt and enhance as required.

We have intentionally used a vivid analogy of a "sheepdog" rather than attempting an accurate design, because we don't want to create tunnel vision too early. Even a dog may be misleading, because the capture interface may want to resemble a hand more than a jaw, and it may be at the end of a flexible structure like an arm rather than close-coupled to the body of the "sheepdog." Work on a "sheepdog" should probably begin with a thorough review of the existing inspector and satellite servicing concepts that are now under development, to see whether one of those platforms might serve as a sheepdog, or if not, whether some significant technologies from those programs might be useful. The detailed requirements on the sheepdog should become clear by the time the work described in steps 1-4 above is complete.

6. Complete development of EDDE (solar arrays and array steering, integration, etc.)

Star Corp and its subcontractor Tether Applications are about to deliver a protoflight tether for EDDE to the AFRL, as part of the deliverables on an SBIR Phase II contract with the AFRL. Included with this are the storage and deployment hardware, including passive tension control. We are also delivering a suitable flight computer, with key parts of the mission-planning code loaded into the computer. The remaining work on EDDE has to do mostly with the solar arrays and methods to orient them, integration, and other similar details that are distinct from the "tether" side of EDDE. This "balance of system" work can be done in parallel with the work described above in steps 1-5; it need not wait until those efforts are complete.

7. Flight-test EDDE or another suitable precursor with a sheepdog (preferably by 2008).

The tethers needed for operational debris shepherds may closely resemble the EDDE tether, or might involve significant changes based on analysis of data from a flight test. There is far less similarity between the EDDE tether and tether designs needed for a sling and its heavy-duty electrodynamic reboost tether. However the dynamics can be similar enough that even a secondary-payload-class EDDE mission can serve as a useful precursor not just for debris shepherds, but also for MXER and other ambitious high-deltaV sling concepts. One flight test option for EDDE would fit within the ~36 kg secondary-payload capacity available on Delta/GPS missions. Or if "EDDE-1" launches on another vehicle with more payload margin, we might test a "full-up version" approximately 10 km long, weighing about 100 kg.

We would strongly recommend having a suitable "sheepdog" ready by the time we are ready to fly EDDE-1, so that we can actually demonstrate tethered capture with a suitable cooperative target. This mission need not be purely a demonstration, because it could also deliver nanosat payloads to a wide range of orbits, and it could drop off its sheepdog to do thorough inspection of some interesting satellite in LEO: either a very old one, to look at surface degradation, or a failed one for which failure analysis might be improved by high-resolution images.

We propose that the EDDE-1 or other flight test be done by 2008, to provide time for revisions to the hardware design and operating concepts, while still allowing launch of a fleet of debris shepherds and sheepdogs before the next solar maximum. This is expected to occur about 2011.

<u>8. Refine system design concepts based on what is learned from the flight experiment.</u>
The purpose of a flight test is partly to make a decision about whether to continue development along a certain path, but also to allow corrections to that path, based on detailed feedback and analysis of the flight data. There are many potential "path corrections" that could result from the flight test, and we cannot now describe any of them in detail. But one thing that is clear is that we are likely to need several years to digest the data, refine the designs, fabricate the revised designs, and test and integrate them for launch.

<u>9. Launch shepherds and sheepdogs to deboost LEO debris near solar max (2010-2014?).</u>
As noted above, launch of a fleet of ~12 debris shepherds by ~2010 is needed if we are to make the most of the next solar maximum. We need this if we want to clear out lots of debris from the 950-1010 km altitude range. If we are 1-2 years late, we will lose much of this opportunity, but we can still clean out some of that cluster, and we can work on lower clusters as well.

Flight testing in step 7, followed by design refinement in step 8, and operational use of a fleet of ~12 debris shepherds during a ~5 year solar-max campaign in this step should be enough to determine not just whether tethered capture is feasible, but what makes it easy or hard, what dynamics simulation refinements are necessary, what capture hardware should be used, etc. This step also presents us with a key fork in the road: IF we think there is a future in slings (even if the precise details are not clear), then we should probably collect as much of the debris as we can into ballast assemblies, even if they are not in the best orbits and we don't know exactly what we will do with them. But if we don't think that slings have a future, we should concentrate instead on deboosting and/or deorbiting the bulk of the debris.

<u>10. If slings do indeed look feasible, assemble ballast and other components and operate slings.</u>
Once we have enough data to understand whether slings make sense and how much ballast mass they require, and where, we can tackle the task of assembling the ballast. "Pearls-on-a-string" ballast geometries may be simplest. Even a 500-ton assembly can be <2 km long. We think one good option for the assembly process will be a variant on our "two-dog" capture concept. We envision having the debris shepherd release the debris several km from the ballast assembly, on a slow approach trajectory, with the sheepdog still attached to the debris. As with the tethered capture by the shepherd, the sheepdog can provide navigation aids and a suitable capture target and orientation for capture by a tethered sheepdog at the end of the ballast tether. After capture, the ballast tether can reel in its tethered sheepdog, grab the debris, attach it to the ballast tether,

and deploy a few meters more of ballast tether. Missed captures should be less likely here than with the debris shepherd, since the tether tip acceleration can be far lower. But if there is a miss, the shepherd can recapture the debris and bring it back for another pass. Note that when the shepherd releases its sheepdog and attached debris, the ballast assembly can also release a sheepdog for capture by the debris shepherd. This "dog-swap" strategy also allows refueling of sheepdogs when they visit the ballast assembly, if the hardware is designed to allow that.

The details of the required work on the "other components" for a sling should be far clearer by mid-2005, when NASA's planned two-year effort on MXER simulation, tethers, and capture hardware (steps 3-4 above) is complete. The brevity of the discussion here is not intended to suggest that the effort will be simple or cheap. There will be many excruciatingly important and expensive details that will have to be gotten right to make slings work. But one key strategy (which we will follow in our sling concept work discussed in step 2) is that the slings should be able to be "grown" in a boot-strap mode. For example, the tether should have a replacement cost on the ground that is low compared to its launch cost. This makes "growth tethers" with higher payload capacity and deltaV a natural candidate for being the first suborbital capture payloads. You can afford to miss some captures, if you can deliver much larger payloads most of the time. If such a payload is captured successfully the first time, then (and only then!) will suborbital captures of more expensive payloads be likely to be taken seriously.

<u>11. Build a safe-abort payload carrier to allow intact-abort with suborbital payloads.</u>
Once a sling has a capacity to capture a payload 1-2 km/sec below orbital velocity, one can start to ask whether one should wrap payloads in some sort of safe-abort carrier and launch them to the sling, vs launching them directly to orbit. We don't know the real cross-over point, or the abort-recovery operational costs, etc. A capsule based on 40-year-old "Discoverer" designs would probably weigh nearly as much as the payload, so the sling might have to do capture at 2.5-3 km/sec below orbital velocity to show even a small net benefit. But newer technologies might reduce the weight penalty enough to allow much smaller sling deltaVs to show a net benefit despite the penalty mass of a safe-abort payload carrier. Note that development of such carriers might also be a way of testing TPS and related technologies for a later RLV program. (The necessary conservatism in programs like X-38 and CRV appears to make them a less appropriate testbed for aggressive tests of new TPS materials and related technologies.)

<u>12. Eventually, develop an RLV optimized to launch payloads for suborbital capture by sling.</u>
The longer-term answer to the question of abort protection is to design an RLV specifically for slings. It may not even be responsible to directly fund such a program until there are many debris captures, and probably even some suborbital captures. However, all new RLV-related programs will develop some new technologies that may be appropriate, so it is possible to make progress in this area without having a program specifically focused on it. It is also possible that an RLV program will be funded, but will have sufficient shrinkage in its payload-to-orbit capacity that it will end up being far more useful as a single-stage-to-sling delivery vehicle.

As mentioned earlier, many details in the above scenario may need to change as we travel along this path. But keep in mind its key feature: each new step is modest in size, but provides near-term payoffs, like improved focus on following steps, near-term operational benefits like debris removal, and a better understanding of the likelihood and nature of the long-term payoffs.

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