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SPEED: SMALL PAYLOAD EXPRESS EARTH DELIVERY

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Abstract

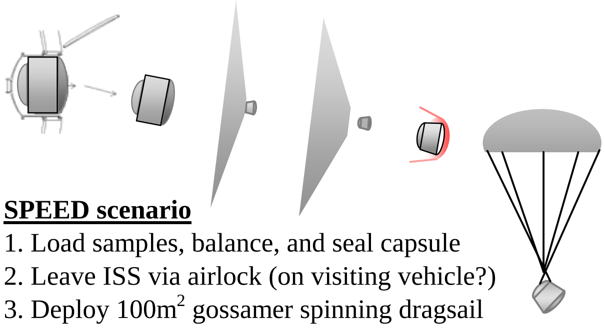
Now that the International Space Station is operational, it is time to enhance its customer base, productivity, and value. Most commercially relevant research is highly iterative. An ISS enhancement that may radically boost the productivity and value of most iterative research is regular weekly return of priority small payloads from the ISS to researchers on the ground. SPEED is a small reentry capsule with a 3.5 liter payload bay. SPEED can hold up to 2 kg of test-tubes and other small payloads. Each capsule can handle frozen, refrigerated, or unrefrigerated payloads, but only one type per flight. SPEED can be taken outside ISS on any EVA, or passed through an airlock for it and similar small deployable payloads. The most novel feature of SPEED is its passively safe deorbit system: a spinning ~10m square gossamer "dragsail". This poses fewer safety issues to the ISS and its crew than rockets or tethers, since SPEED acquires the velocity change needed for deorbit by decaying below ISS altitude. Changing the spin rate changes the drag by adjusting sail cone, yaw, and pitch angles. This allows iterative feedback control of descent time and reentry location, despite uncertainties in air density below ISS. Adjusting dragsail release altitude between 200 and 230 km allows additional range adjustment. Banking during a low-lift entry allows even later adjustment, and can also reduce peak reentry deceleration from 9 to 5 gees. The preferred recovery technique is mid-air capture near the coast of the US or other ISS partner countries, with water recovery as a backup if capture fails. Dragsails should take ~4 hours to deorbit SPEED. Overall time from capsule loading to unloading may normally be ~6 hours. Expected cost for weekly service with fully-loaded capsules is ~$50/gram + $25/cc. The paper includes discussion of applications and constraints, descriptions of the dragsail and control strategy, a comparison with some other ISS sample-return concepts, and recommendations for near-term work.

1. Introduction

Planned flight rates to and from ISS several years from now are ~10 launches/year, on Dragon, Soyuz, Progress, ATV, and HTV; plus ~5 returns/year, on Dragon plus Soyuz. There are now no plans for more frequent priority small shipments in either direction. Much attention has been paid to affordable access ***to*** space, but infrequent access ***from*** space may be the key constraint on ISS productivity and value. Return rates of ~5/year greatly limit the productivity of iterative work that could benefit from detailed sample analysis on the ground. John Charles of NASA says that more frequent return may be especially valuable for bio-astronautics research, by enabling better analysis of crew samples, and countermeasure adjustments ***during*** stays on ISS.

SPEED, the Small Payload Express Earth Delivery system, is planned to be cheap enough to let ISS raise its ~5/year priority sample return rate by a factor of ~10. This will greatly expedite iterative research, including both crew countermeasures and commercially valuable research. SPEED should also greatly enhance discovery research on ISS, since it allows timely sample analysis on new analytical equipment not yet qualified for ISS.

The SPEED operating scenario is shown below. Section 2 discusses SPEED applications, and section 3 key constraints as design drivers. Section 4 covers the dragsail concept, and section 5 dragsail control. Section 6 compares SPEED with other sample return concepts. The paper ends with conclusions and recommendations.



SPEED scenario

1. Load samples, balance, and seal capsule
2. Leave ISS via airlock (on visiting vehicle?)
3. Deploy 100m^2 gossamer spinning dragsail
4. Adjust dragsail spin-rate to modulate drag
5. Release sail ~4 hours later, near 200 km altitude
6. Reenter, deploy chute, and recover in mid-air.

2. Applications for SPEED

Limited sample return frequency has led some ISS users to focus on image return. But even that can take months: some users get their data on laptops returned by crew. Increasing sample and data return rates from ~5 to ~50/yr may be a "**difference that makes a difference.**" Far smaller rate increases may benefit ISS productivity and please traditional NASA and academic users, but may not help commercial researchers who need far faster experiment cycle times. SPEED could help ISS become a runaway success, by attracting a range of new users for purely commercial work in bio-tech, materials, and even basic biology. SPEED could even lead to enough commercial use of ISS that overflow demand creates an adequate market for Bigelow facilities.

If SPEED is indeed enabling for most commercial biotech and other commercial use of ISS, that could lead to a range of unexpected ISS improvements and launch rate increases that further enhance ISS capabilities and throughput, for both government and commercial uses.

The main NASA users and uses we expect for frequent sample and bulk data return on SPEED are:

1. Crew countermeasures development
2. ISS ops, to assess illnesses & ISS habitability
3. Materials processing research programs
4. A gravitational biology research program

The main non-NASA customers we envision for sample and bulk data return using SPEED are:

1. Some ISS NanoRacks facility users
2. Other current ISS users (US and foreign)
3. New purely commercial ventures
4. DragonLab users needing early sample return
5. Bigelow Aerospace and its future customers.

Potential SPEED and SPEED airlock applications other than sample return include:

1. Reentry testing by NASA and other entities
2. Deploying nanosats and probes from ISS
3. On-demand probe deorbit from Mars orbiters.

SPEED may also be useful as a new US capability that can be traded with ISS partners for other resources. This might even involve doing some SPEED recoveries off the coast of ISS partner countries.

3. SPEED Constraints as Design Drivers

A capsule intended to return small samples from ISS weekly has many constraints on its design and operation. The dominant one is safety. The rule for small payload operations on ISS is "First, do no harm."

More generally, one seldom has the luxury of focusing on reliability with nanosat-scale systems. Often reliability ends up in third place, behind both safety and cost. Focusing on safety and cost first may still allow reliability—but perhaps only after problems during development and flight test. If SPEED is cheap to buy, launch, test, and evaluate, and if it will be used ~weekly once operational, occasional problems on early flights may be tolerable. Much of the risk is likely to be in the dragsail and its deployment and control, so it may be very useful to image dragsail deployment, as done with Znamya and IKAROS. The small reentry capsule will have other novelties and hence risks. It may make sense to use the Aerospace Corporation's Re-Entry Breakup Recorder (REBR) as part of SPEED's payload on the first few flight tests.

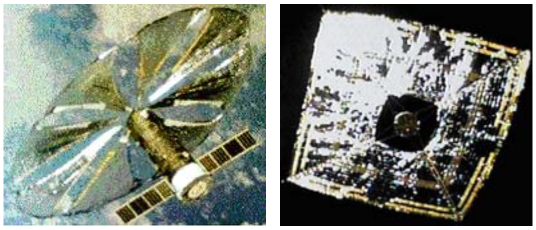
Another issue that constrains but focuses SPEED design efforts is that commercial reentry of US objects expected to survive reentry requires an FAA license. This requires safety analyses and liability insurance. If SPEED is planned as a commercial service, it should be designed partly for low licensing and insurance costs.

This issue has led us to an unusual design feature. The SPEED capsule is about the same shape as Soyuz, but it is shortened enough to make it a "slightly stable spinner." But the SPEED afterbody also looks very much like the forebody of the GE film return capsule used in the Corona program. If we use all of the limited capsule volume, the capsule CG will be near the capsule center of volume. SPEED will be bi-stable, but more likely to reenter facing backward than forward—unless it is actively oriented for reentry. But this "problem" may actually be useful, because SPEED needs active control for accurate entry. If SPEED's active controls fail, it may be better if SPEED reenters backwards and burns up. (Commercial users may also prefer this, for both liability and IP reasons.)

Safety, cost, and shock-sensitive payloads may all drive us towards mid-air recovery. Snatch loads can be kept comparable to reentry and chute-opening loads, and damage to the capsule heatshield and structure can be prevented. Recovery off the coast may be safest, and since several key bio-tech centers are on the east, west, or gulf coasts, this may expedite delivery to customers.

A final constraint is size. Reentry heat fluxes vary little with capsule size if capsule density stays the same, since changes in ballistic coefficient and nose radius cancel out. But thicker heatshields may be needed on smaller capsules, since they have thinner structure that can't absorb as much heat. This is a particular challenge with small sample return capsules, since there is little room for insulation between heatshield and payloads. Hence reentry heatsoak rather than avionics may be the main constraint on minimum SPEED size.

4. The Spinning Dragsail Concept



Flight test images of Znamya and IKAROS

The spinning dragsail is based on "spinning disk" solar sail concepts like Energia's Znamya and JAXA's IKAROS sail, both shown above. The SPEED concept was actually stimulated by the above image of Znamya. The image, taken from Mir, led Carroll to estimate the orbit life of a low-mass test solar sail starting at ISS altitude. Carroll had already studied the use of tethers for sample return. Finding that a solar sail might reenter from ISS altitude within a few hours led to study of spinning sails for deorbiting sample-return capsules.

Early SPEED dragsail designs were circular, and had narrow triangular gores with radial seams. But after seeing pictures of JAXA's IKAROS solar sail test and studying papers on it, we have changed the sail from round to square, and added 4 small corner masses as on IKAROS. The corner masses are intended to aid initial sail deployment rather than tensioning thereafter, so they can be quite light. The membrane itself provides most of the centrifugal force, so IKAROS and SPEED do not need concave edges, as do NASA's framed non-spinning "scalable square solar sails."

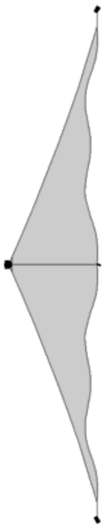
4.1 IKAROS stowage and deployment concepts

Most AIAA papers on IKAROS from 2005-2008 showed a "skewed fold" stowage/deployment concept, as shown below in a figure from AIAA 2008-2051. But the sail actually flown used a bellows-like concentric square folding geometry, as shown in AIAA 2010-2583. That design may allow easier scaling to large sail sizes, and also eliminates tight creases in some thin-film solar cells and liquid-crystal steering devices built into the sail. We plan to use a fold similar to the skewed-fold concept, since it seems suitable for 10x10m sails.

Skewed fold for IKAROS (from AIAA-2005-2051)

4.2 Dragsail shape

The actual shape of a spinning square dragsail is complex, but its key features are easy to grasp. Consider a cone "sweep angle," the complement of the average cone half-angle. In the sail at right, that sweep angle (away from a flat vertical sail) is ~20^o. Note the slight curvature in the sweep: the tip sweep is ~1/3 less than at the apex. At each point, the local sweep depends on the ratio of axial to radial forces outboard of that point. For a sail that is circumferentially slack like this, all axial and radial forces reach the apex, except for the axial force that slows down the sail itself, and not its payload.



A "coned" square sail has circumferential sweep variations, even if it has no tip masses. But there is a circumferential average sail radius and sweep, and hence a mean axial ***edge*** displacement due to the sweep. That defines the moment arm that lets drag torque the sail spin axis. If a sail were either flat or normal to the flow, there would be forces but no torques, because the force acting on the center of the "sail shadow area" would pass through the capsule. But coning displaces the sail edges to the right of the capsule. Then sail yaw or pitch can impose torques on the sail.

Another sail shape issue for a sail that can lay flat is that the sail ripples circumferentially when it is swept. The average circumferential slope has to nearly equal the average cone sweep angle. The resulting cosine loss of drag area due to circumferential rippling equals the radial cosine losses: a 20^o average cone sweep shrinks the sail from 10m to 9.4m in both directions, and hence reduces its area from 100m^2 to 88m^2. Half the drag area loss shows up as radial cosine foreshortening, and the other half as average circumferential cosine loss.

4.3 Sail yaw, needed to precess sail pitch angle

We want the dragsail to "fly like a shuttle-cock" as it goes around the earth. It can do this, but continuously pitching its spin axis down all around the orbit requires a yaw angle of order 10^o, when flying the sail for near-maximum drag. A 10^o yaw cuts drag area by <2%, so shuttle-cock sail flight is compatible with a "max early drag" strategy proposed in section 5.

Much larger yaw angles are not very effective at reducing sail drag area, because beyond 35^o yaw angle, reductions in sail sweep reduce the yaw moment arm and torque, so increasing the yaw angle cannot increase the pitch precession torques. And 35^o yaw reduces sail drag area only 17% compared to 10^o yaw, so yaw allows only limited (but still useful) control range.

But if fast spin precludes sail pitching at the orbital angular rate even with large yaw angles, one can take advantage of this and keep the sail attitude nearly stable inertially. This reduces orbit-average drag area to ~2/Pi of the drag area that occurs in sail "shuttle-cock" mode. This can be combined with large yaw angles to further decrease average sail drag area.

4.4 Thrusters for sail spin control

The required spin rate adjustments appear modest, but everything contributes to the cold-gas budget. As a first cut, assume a total 10x10m drag sail mass of 200g (=2g/m^2), and a required sail spin-rate change of order 100 rpm between 400 and 200 km. If we can vent gas from a corner of the sail, with a 7m torque arm and an Isp=50 seconds, we should need only ~12 grams of gas. It may be a challenge trying to get useful thrust from a corner of the sail, before sail deployment is complete. Several options appear viable, but we have not yet analyzed them in detail. Controlling SPEED capsule spin before sail deployment and during reentry takes far less torque than for sail control, but perhaps more gas, since that requires thrusters on the capsule itself.

4.5 Windmill torque effects

Simple calculations for plausible unintentional "windmill" details caused by asymmetrical tears in the sail indicate they should have very little effect on sail spin-rate. "Windmill drag" may be more significant. Oncoming air does not just slow the dragsail and its payload down; but also slows down the spin, because air impacts axially but leaves with a "memory" of sail spin. This may increase sail spin gas requirements by ~30%.

4.6 Developmental testing

We have already done some handling, seaming, and stowage tests using 1.4 micron Mylar. We now plan on using 1.2 micron Teonex film, which is lighter and stronger than Mylar, and far more tolerant of both UV and ionizing radiation. We already have enough Teonex for 18 full-scale 10x10m dragsails. Our main initial focus will be testing and refining our concepts for handling the film and assembling and stowing the sail.

The main drawback of a frameless spinning sail may be that realistic ground deployment tests do not seem feasible. But this is also true of most other solar sail designs. Both air and gravity can seriously affect sail behavior during deployment. But we can bound the severity of many of the potential problems by doing worst-case torture tests. For example, if worst-case static cling can be overcome by film tensions available at modest sail spin-rates, we don't have to worry about that. We also plan to measure the long-wave emittance of thin Teonex, since that limits allowable aeroheating.

If work on fabricating, stowing, and deploying a full sail suggests that we should use thicker and more robust film, the best compromise may involve a longer deorbit time as well as a heavier sail. If the sail uses 4X thicker film, the optimum sail might have ~half the area and ~2X the mass, and an 8 hour descent. Thicker films are more robust and easier to handle, but limited tests suggest 1.2 micron Teonex may be workable. It does tear easily, so a "rip-stop" reinforcing grid is needed.

5. Controlling a Spinning Dragsail

Between dragsail deployment near ISS and capsule reentry, SPEED will travel ~2.5 times around the world, or ~100,000 km. To limit continuing operating costs, we want accurate enough reentry to allow reliable and safe off-shore recovery in mid-air by a single aircraft. High-altitude opening of the parachute may allow the recovery aircraft to travel ~100 km, from the end of any reentry blackout until SPEED descends to ~10,000 feet.

For SPEED to end up within 100 km of a recovery aircraft, it must control its range and hence its orbit life within ~0.1%—despite radically larger uncertainties in air density below ISS altitude, and even sample return capsule mass uncertainties that may exceed 1%. This will clearly require iterative feedback control. We have several control options available to us, one after the other. From sail deployment to mid-air capture, range adjustment capabilities may be roughly:

±20,000 km from dragsail drag modulation
±1,000 km from dragsail release altitude changes
±50 km from roll control early in lifting entry
±100 km from recovery aircraft dash range.

In general, the main way to control drag is to control sail spin-rate. Increasing the spinrate has 3 distinct effects on sail drag:

- Increased gyro-stabilization affects yaw & pitch.
- Centrifugal force stretches out wrinkles and creases.
- Increased sail cone angles increase the drag area.

The relative importance of these effects varies during the dragsail descent. Early in the descent, when drag is low, the drag area is likely to involve primarily the first and second effects, while late in the mission, variations in the third effect are likely to be dominant.

5.1 Control overview

For any combination of ISS altitude, ambient air density at ISS altitude, capsule mass, and dragsail area, there is a minimum time required to spiral down from ISS to reentry. Descent time can always be increased by decreasing dragsail area normal to the airflow.

The key to SPEED ops planning is to get the capsule loaded and ejected, and the dragsail deployed, early enough to accommodate all uncertainties thereafter, especially any plausible decreases in air density. To retain this margin as SPEED spirals down toward reentry, the top-level control strategy is to fly with maximum sail drag until remaining uncertainties are small enough to allow easing off on the braking.

A very good analogy to dragsail control is bringing a car to a stop at a stop-sign, on a road with icy patches. To ensure you can stop at the right place despite ice you may not even be able to see initially, you should start braking early, and "overbrake" at first. Once you are close enough to the stop-sign to see what ice remains, you can ease off on the braking to stop where you want. The key is to always reserve enough braking margin to handle all remaining uncertainties.

A key challenge is that atmospheric density can vary by a factor of up to ~4 around the orbit, due to the atmosphere's diurnal bulge and oblateness, and typical low but non-zero eccentricity values for ISS. But if we stay in max-drag mode around most of the first orbit, we can use GPS or ISS-ranging data to infer that drag and use it to refine our estimates of the drag at lower altitude during the remaining ~1.5 orbits.

5.2 Descent times vs spin strategy

Table 1, below, shows SPEED dragsail descent times estimated by a spreadsheet that sums the descent times for eight 25 km altitude bands from 400 down to 200 km. The times are simply the sum of calculated descent times for each band, with spin-dependent sail drag area adjustments at each altitude. Max drag occurs when the total losses due to yaw, pitch, and cone angles and estimated sail shape memory (wrinkle) effects are least. It varies from 5 to 20 rpm during the descent.

Table 1. Descent times (400-200 km) vs strategy

Spin strategy & Descent sec.	**Time**	**Ratio**
Drag area=full sail area:	8401	0.92
Spin for maximum drag:	9106	1.00
70% of max-drag spin rate:	9748	1.07
5rpm spin or more:	9618	1.06
3.5rpm spin or more:	10920	1.20
Half "max-drag" spin or more:	11754	1.29
Inertially fixed gyro-stab spin>	13198	1.45

The first case assumes (unrealistically) that the full 100m^2 sail area can be kept normal to the orbit. The next case is a "Max Drag" reference case, that adjusts spin rate to give maximum drag in each altitude band. The 70% case uses spin-rates 30% slower than Max-Drag spin rates. This adds only 7% to descent time.

The "5rpm or more" case uses a fixed 5rpm spin at first but spins faster later. It adds less to descent time than the 70% case, but uses max drag for the first 50 km of descent. The "3.5rpm or more" case is like the 5 rpm case, but uses 3.5rpm initially. It increases descent time 20%. "Half max drag or more" spins half as fast as the max-drag spin at first. It adds 29% to Max-Drag time. Finally, inertially fixed gyro-stabilized spin adds at least 45% to Max-Drag time (=Pi/2 * full-area descent time).

One can change from one to another strategy during descent, or use other strategies, or intermediate spin-rates. These times are first-order estimates that neglect diurnal variations, oblateness, and other effects. The point here is to quantify the control available with several simple strategies. The next step is a computer model of sail response to spin and drag, to simulate sail dynamics and feedback control more realistically.

5.3 Effects of varying the sail release time

The final sail control option is adjusting the time of sail release. We want to release the sail before it can heat up enough to fail, to avoid adding new uncertainty to the reentry range. Adjusting sail release time is a nearly free control option available late in descent. The effects of adjusting release conditions are listed below in Table 2. The release criterion is sensed acceleration, in percent of gravity **(% G**). Next to that is the altitude in kilometers at which that is felt, followed by estimated free molecular flow aeroheating. Perigee and apogee at the time of sail release are next, followed by the peak reentry gee-load, **MaxG,** for a capsule with L/D=0.1.

Table 2. Effects of Sail Release on Reentry Range

% G	**Alt**	**W/m^2**	**Per x Apo**	**MaxG**	**ΔR_{lift}**	**Rng**	**ΔRng**
1.25	241	17	77 x 270	4.26	355	93311	
1.8	228	24	14 x 262	4.13	187	90992	-2319
2.5	218	33	-45 x 255	4.15	132	90071	-921
3.5	208	46	-112 x 248	4.34	97	89499	-572
5	198	65	-201 x 238	4.72	69	89050	-449
7	188	91	-305 x 229	5.16	59	88729	-321
10	178	129	-434 x 220	5.66	48	88475	-254
14	169	178	-583 x 210	6.14	40	88288	-187
20	161	250	-756 x 201	6.62	32	88139	-149

The next parameter, **ΔR_{lift}**, indicates how much range adjustment is feasible during reentry, by starting reentry with negative lift, but rolling over early enough to limit the increase in peak gees to 1.0. **Rng** indicates reentry range location, in kilometers downrange from sail deployment, and **ΔRng** indicates the range change between that case and the previous one. Most of the available range adjustment (from both sail release and lift control during reentry) occurs at higher sail release altitudes. Hence it may make sense to aim for sail release altitudes in the ~200-230 km altitude range.

The numbers highlighted in yellow above indicate potentially problematic values. A vacuum perigee of 77 km is low enough to ensure reentry, but range is very sensitive to variations in the upper atmosphere and L/D uncertainties. The highlighted heating values may be too high for very thin films because of their low infrared emittance. MaxG >6 (even before any increase due to negative-lift flight early in reentry) may also be higher than desired for some payloads.

5.4 Dragsail control calculations

It seems unrealistic to hope for a simple linearized feedback control directly using sensor data. Data must go into a fairly sophisticated plant model that infers the dynamics from all the observables, allows inference of sensor biases and residual uncertainties in vehicle state and expected drag along the rest of the trajectory, and selects control outputs with effects that are exponential more than linear. To be more specific, we appear to need explicit on-board computational models for:

- Orbit decay, based on GPS data or ranging to ISS,
- Thermosphere air density along the sail trajectory,
- Sun angle and magnetic field data (for attitude), and
- Spinning dragsail and lifting capsule behavior.

It appears necessary to rely either on GPS or on ranging from ISS to estimate orbit decay. The initial decelerations near ISS altitude are ~0.3 milligee. This may be too low to measure well with small sensors, especially with a spinning capsule and sail and some uncertainty in exact CM location and spin axis.

6. Comparison with Alternatives

In 1983, Carroll proposed the Small Expendable Deployment System, or SEDS, in response to NASA’s first SBIR solicitation. When SEDS-1 finally flew, in 1993, it demonstrated controlled deorbit of a passive payload by a swinging 20 km tether: Dave Talent of NASA JSC videotaped payload reentry and burnup west of Mexico. Carroll then worked on a Tethered Reentry Experiment Vehicle (TREV), as a test version of a “Station Tethered Express Payload System” (STEPS).

TREV and STEPS were sized to just fit through the 800mm Progress hatch, to allow testing and possible use with Progress. They each weighed ~40 kg loaded, to allow use of a thick tether (to reduce tether cut risks). Unfortunately, that made STEPS too heavy to justify flying frequently. So STEPS would not easily allow a large increase in ISS sample return rates.

In parallel with TREV/STEPS, ESTEC funded similar work on “SpaceMail” but focused on smaller capsules. This led to the YES2 flight test. No beacon signal was received from the YES2 capsule, so its fate is unknown. A more serious problem with both STEPS and SpaceMail is getting tethers approved for use on ISS. This may be a challenge, since the problems with TSS are better known than the successes with SEDS.

One can also imagine several versions of a small rocket-deboosted capsule that might be used with ISS. But handling a rocket inside ISS could lead to serious safety issues, while storing one outside and attaching it after the capsule is taken outside poses other challenges. More generally, any deorbit rocket that can ignite near ISS poses a risk of energetic capsule re-impact with ISS (>100 m/s), a risk that may not be cheap to eliminate.

Another option is limited to gee-tolerant payloads: a large-bore cold-gas gun. This eliminates the hazards of rockets, but imposes a recoil load on ISS. The recoil can be reduced by limiting capsule mass and/or venting some gas through the breech. The main challenge for such a gun is probably integrating it and its airlock with an ISS that has already been launched. Such guns may be more feasible with Bigelow facilities.

There is one operational sample return capability that could be used with ISS: the 150 kg Raduga capsule that was used to deorbit samples from Mir several times. It cannot deorbit itself: it must be deorbited by Progress after Progress leaves ISS. It is sized to fit the 800mm Progress hatch. Prior missions used ground recovery (~90 gees even with parachute), but mid-air capture could be used. This can only be used when a Progress leaves ISS and deorbits itself. The added Progress maneuvers may have substantial propellant costs.

In comparison with these alternatives, SPEED seems like a far less intimidating integration challenge for ISS. Initially, SPEED might be deployed during EVAs, or using the robotic airlock on the JEM module. One might also add a small airlock to some visiting vehicles, possibly as a modification of a late-access side hatch. The European ATV can spend up to 6 months at ISS, so it may be a suitable candidate. Eventually, a small airlock might be included on some module added to ISS in the future, such as a Bigelow module.

The best long-term airlock option may be to install a small airlock as part of a modified outside hatch of a larger airlock (either new or existing). Such a location may allow the easiest periodic maintenance.

One more alternative to SPEED needs mention: no priority return capability. That is the current situation. It may be good enough for many high-value uses of ISS. And anything that results in more traffic to and from ISS, such as attaching commercial modules (at least temporarily), could raise large-vehicle flight rates and hence sample return rates. But such ISS enhancements could make SPEED even more valuable, since SPEED could then expedite a much wider range of research.

7. Conclusions and Recommendations

SPEED is a novel sample-return concept. It is very challenging technically, but may be far easier to qualify for use on ISS than nearly any feasible alternative. Our goal for SPEED is a sample return capability useful and affordable enough to result in weekly commercial return of ~2 kg of samples from ISS.

Tether Applications, Inc., is seeking development funding from NASA because NASA has the most to gain from frequent ISS sample return, and because it has control over whether and how SPEED can be qualified for ISS. But we plan on SPEED as a fully commercial service available to all ISS users by the time SPEED is operational. We are teaming with Kentucky Space, developer of the NanoRacks and CubeLab capabilities on ISS, for help on qualifying and integrating SPEED with ISS. We are also exploring use of the JEM airlock, and options for addition of new SPEED-sized airlocks to the Dragon, ATV, or possible future ISS modules.

We envision the future "SPEED operator" as a focused start-up company, much like SpaceHab when it started. SPEED and its dragsail are novel enough that we cannot guarantee their reliability. But we can "throw our wallet over the wall" by stating an intent to charge only for successful returns. This would not have been reasonable early in the space age, but it is feasible now, and may be the best way to improve reliability while limiting costs.

Despite its small size, SPEED may be critical to the long-term value of ISS. SPEED's basic utility can be seen now, but its potential multiplier-effect on ISS value may not be clear until SPEED has been in operational use for several years. We encourage potential customers and entrepreneurs with an interest in SPEED to contact either author.

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Other sample return and small capsule concepts

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