WRANGLER: Capture and De-Spin of Asteroids & Space Debris

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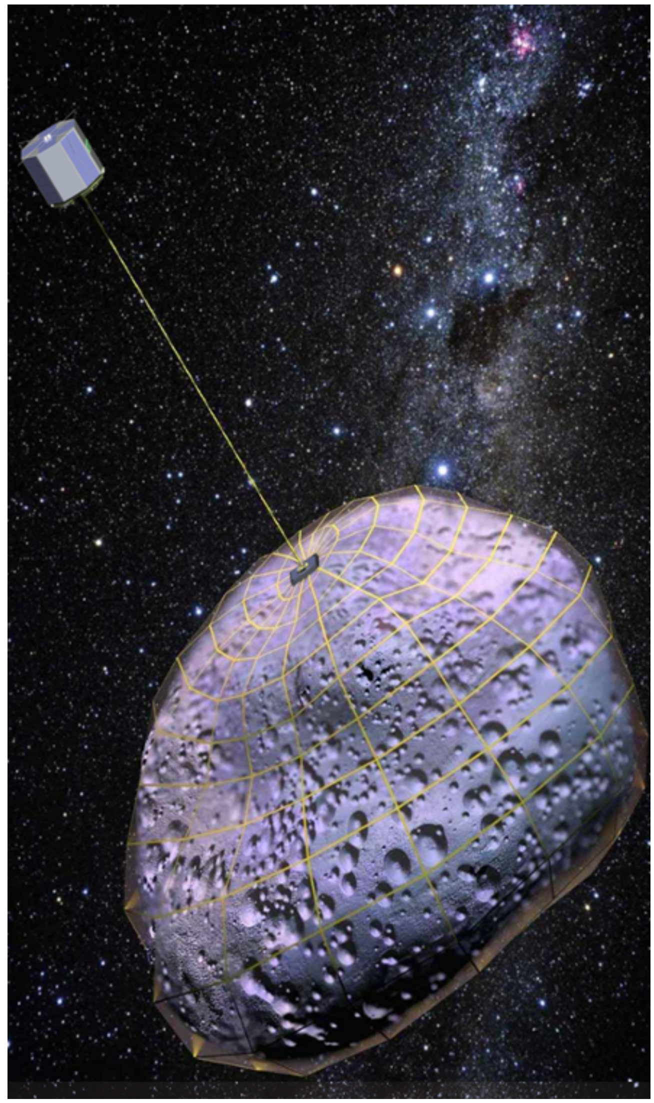

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13. ABSTRACT

The Phase I WRANGLER effort has demonstrated the feasibility and value of using a small tethered nanosatellite to accomplish capture and de-spin of space objects for future NASA and commercial efforts to acquire space resources from asteroids and actively remediate the space debris population. Current baseline architectures for capturing large space objects such as Near Earth Asteroids or spent rocket bodies rely upon a single high-value spacecraft to capture and reposition the target object as well as the use of thrusters to de-spin the object to allow maneuvering. Through detailed physics-based simulations we have demonstrated that tethered nanosatellites deployed from even the most massive “fast rotators” are effective at dramatically reducing the target’s body rates and can be successfully controlled using simple control laws and high-TRL tether deployment hardware. We have developed two WRANGLER system concept designs capable of serving a variety of Asteroid Redirect Mission (ARM) and Active Debris Removal (ADR) CONOPS. The first is a small 2U picosatellite used simply as a means of de-spinning the target and the second is a larger free-flying nanosatellite used to both capture and de-spin the target object. Comparison of these concept designs to conventional propellant-based approaches has demonstrated the significant mass savings afforded by the WRANGLER concept. Furthermore, fractionation of the mission architectures by using a tethered nanosat for capture and de-spin can signficantly reduce the risks and requirements imposed on large primary mission spacecraft. The technologies required to provide the benefits of the WRANGLER system are all hardware of mid- to high-TRL. TUI’s evaluation of the technology readiness of the concept indicates that a WRANGLER system that has the potential to provide order-of-magnitude performance improvements can be designed and integrated with minimal effort and modest investment. While the remaining risks of the WRANGLER system are non-trivial, they are well understood and have clear and proven mitigation strategies that can be implemented with the proper engineering effort. WRANGLER provides significant benefits to ARM, ADR and future commercial space resource development efforts by replacing hundreds or thousands of kilograms of propellant with a small, low-mass, low-cost system capable of enabling space systems to safely gain control of large space objects.

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Abstract

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Table of Contents

Table of Figures

Index of Tables

1. INTRODUCTION

WRANGLER uses a tethered nanosatellite to capture and despin massive asteroids and space debris, providing risk and mass reductions for asteroid sampling and active debris removal missions.

1.1 Motivation - The Challenges for Capture and Retrieval of Asteroids and Space Debris

NASA is currently pursuing the OSIRIS-Rex and Asteroid Redirect Mission (ARM) efforts to capture and retrieve materials from Near-Earth Asteroids (NEAs) to enable investigations of the nature of the early solar system. Additionally, several commercial ventures are seeking to harvest NEA space resources to support in-space manufacturing and delivery of rare materials to markets on Earth. The architectures considered for the ARM program utilize a single spacecraft to capture a small target asteroid or boulder from a larger asteroid and transport it to cislunar space. A significant technical challenge for these scientific and commercial efforts is the fact that astronomical observations have revealed that most of the NEAs that are small enough to be considered for relocation by the ARM program or asteroid mining companies are rotating relatively rapidly.[1] As shown in Figure 1, objects with diameters less than 20 m typically rotate with periods of a few minutes to a few hours.[2] Larger NEAs that are candidates for a 'boulder grab' operation or mining activities typically rotate at a rate just below that at which objects on their surfaces would fly off due to centrifugal acceleration. Reducing the rotation rate of one of the smaller NEAs to enable repositioning by the 'Plan A' option considered by the ARM program using the baselined thrusters will require a very large propellant mass, on the order of several hundred kilograms or more,[3] and despinning a larger object to facilitate commercial mining operations or reduce risks for the 'Plan B' boulder grab mission would require untenable quantities of propellant. Additionally, the rotational and optical characteristics of NEAs indicate that many of them may be loosely bound rubble piles, or are bodies surrounded by clouds of dust or gravel.[4] The presence of small particles poses collision, contamination, and charging risks to both ARM and commercial mining spacecraft.

Similar challenges to those posed by asteroid capture and retrieval also must be addressed to enable Active space Debris Removal (ADR) missions, which will require the capability to securely capture tumbling spacecraft, rocket bodies, or pieces of spacecraft resulting from collisions or fragmentation in order to enable safe and efficient maneuvering to a disposal orbit.

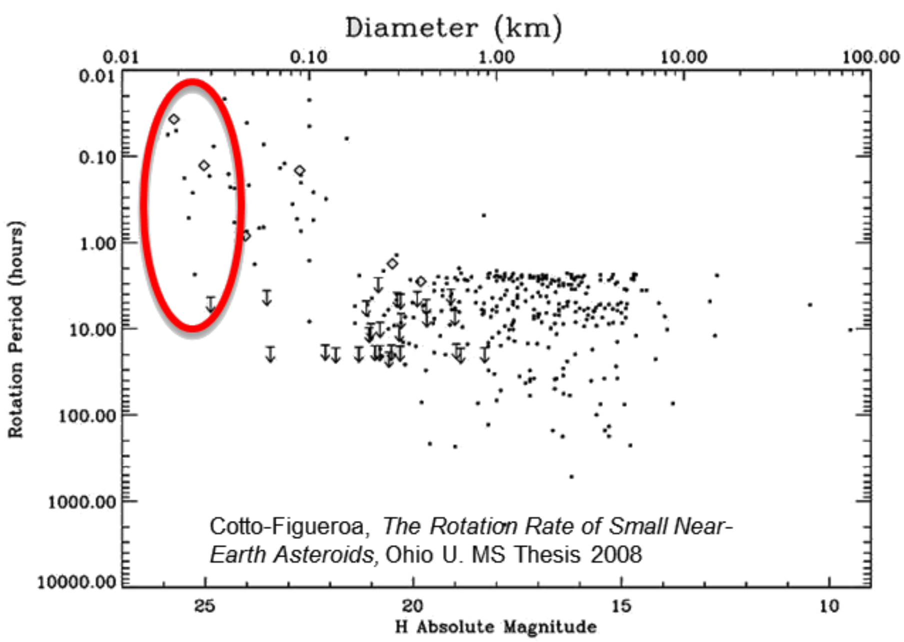

Figure 1. NEA Population rotation periods vs. size.[1] *Most small NEAs are "fast rotators."*

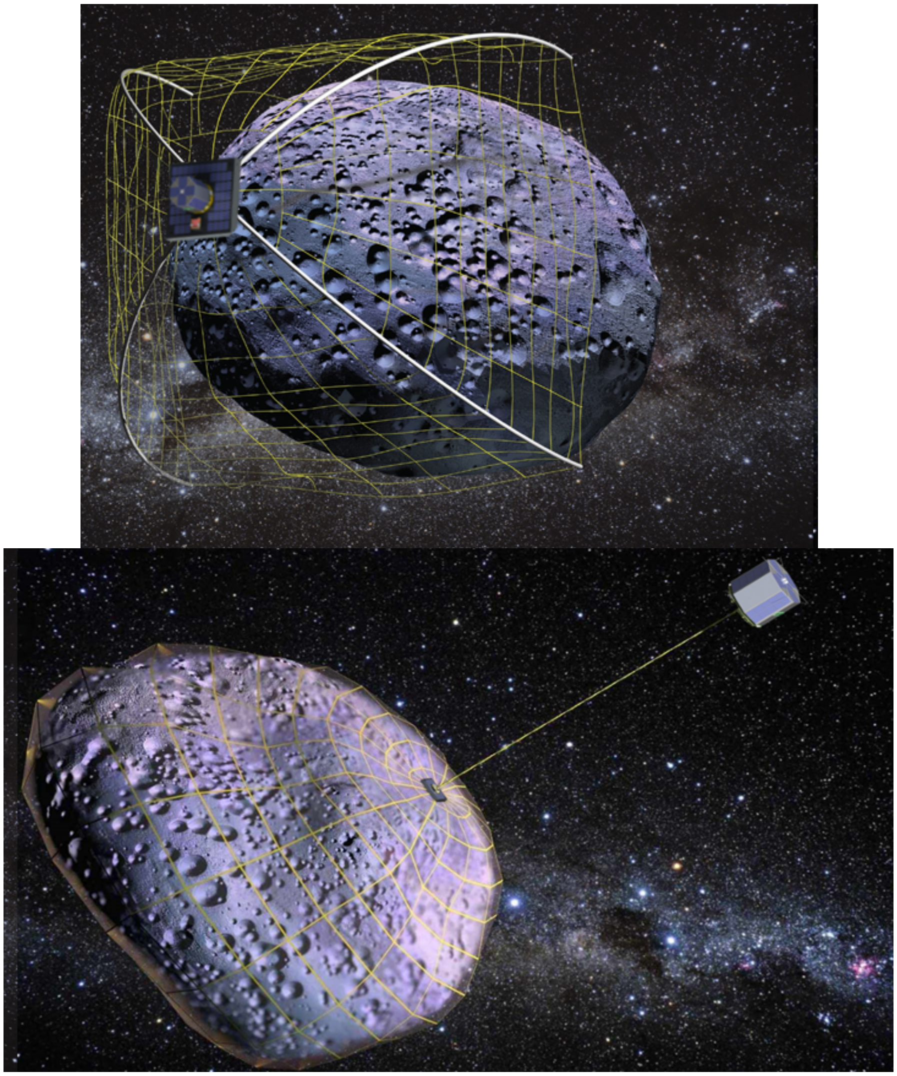

Figure 2. Free-Flying WRANGLER Capturing and De-spinning an Asteroid. *WRANGLER attaches itself to a rotating asteroid and then uses a lightweight tether to drain angular momentum from the object, enabling a tiny, low-mass nanosatellite to de-spin a massive asteroid.*

1.2 The WRANGLER Concept

This effort has investigated the technical feasibility and value proposition for using a "Weightless Rendezvous And Net Grapple to Limit Excess Rotation" (WRANGLER) nanosatellite to reduce the mass and risks for missions requiring capture and maneuvering of rotating space objects such as NEAs and orbital debris. A concept for a free-flying WRANGLER nanosatellite is illustrated in Figure 2. In this implementation of the concept, the nanosatellite first deploys and maneuvers a lightweight deployable bag or net around the asteroid and then collapses the bag to attach itself to a rotating asteroid. It then gradually deploys a lightweight, high-strength tether in between the capture bag and the nanosatellite. The system will maintain tension on the tether as it deploys it, and uses that tension to induce a torque on the asteroid that slows the rotation of the asteroid. Essentially, the concept takes advantage of the r^2 dependence of the moment of inertia of the nanosatellite as it orbits around the system's center of mass to efficiently drain angular momentum from the asteroid, much in the same manner a de-spin yo-yo device slows the rotation of an upper stage rocket. The leverage offered by using a tether to extract angular momentum from a rotating space object enables a very small nanosatellite system (~1 kg) to de-spin a massive asteroid (> 1,000,000 kg). This free-flying WRANGLER nanosatellite will enable the ARM mission to be fractionated to reduce both system mass and mission risk, using the WRANGLER nanosatellite can capture and efficiently de-spin the asteroid in preparation for docking and maneuvering by the electric propulsion (EP) tug spacecraft. Fractionating the mission architecture in this manner could enable the EP tug portion of the system to be built at lower cost by using one of the commercially available EP-propelled satellite buses rather than a custom, single-use spacecraft. The WRANGLER nanosatellite can also provide an affordable solution for capture and de-spin of space debris objects, such as rocket upper stages, many of which rotate at moderate rates and would need to be stabilized to enable maneuvers to de-orbit trajectories or to graveyard orbits.

In addition to the free-flyer WRANGLER nanosatellite, we also evaluated a simpler implementation of the concept in which a deployable tethered CubeSat, illustrated in Figure 3, is integrated onto the baseline ARM vehicle. In this tethered CubeSat approach, the ARM system would capture an asteroid or boulder using its inflatable bag or grappling arms as planned in the baseline ARM CONOPS, but then instead of relying upon thrusters to de-spin the asteroid, the ARM spacecraft would deploy the WRANGLER CubeSat and allow it to drain angular momentum from the system.

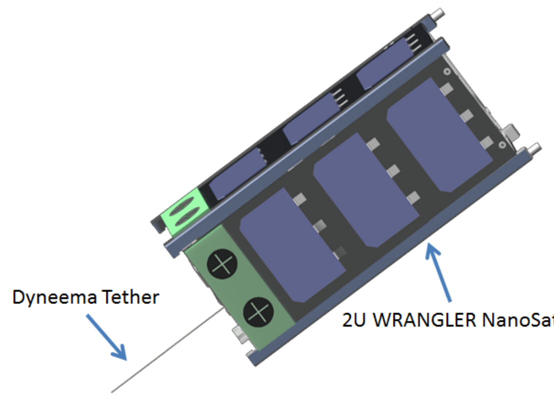

Figure 3. WRANGLER CubeSat Concept. *A tethered CubeSat can dramatically reduce the mass required for ARM to de-spin its target object.*

As we will show below, both the free-flyer WRANGLER nanosatellite and the tethered WRANGLER CubeSat can significantly reduce the mass required to de-spin many of the candidate NEAs, freeing up hundreds of kilograms or more of system mass. This mass savings could enable the ARM system to perform larger total ΔV maneuvers, expanding the number of NEAs it can reach, or it can enable it to carry more scientific payloads for characterizing the space objects.

1.3 Summary of the Phase I Effort

The objective of the Phase I effort was to evaluate the technical feasibility and value proposition of the WRANGLER concept with respect to baseline concepts for asteroid capture. To do so, we developed concept-of-operations for both WRANGLER free-flyer nanosat and tethered CubeSat systems for ARM and ADR missions. Because the most significant risk identified was the potential for contact or wrapping of the tether on the target object, we used analytical methods and detailed physics-based simulation tools to develop and validate a simple control scheme to ensure well-behaved tether deployment. We used the simulation tool to characterize the performance of this tether deployment method for both single-axis and multi-axis asteroid rotations, as well as for varying attachment locations on the asteroid. The results of these analyses demonstrated that controlled, well-behaved tether deployment is readily achievable with a very simple control methodology. We then developed detailed conceptual designs for both the tethered CubeSat and the free-flying nanosat implementations of WRANGLER. Using scaling estimates derived from these concept designs, we evaluated the value proposition for the WRANGLER method by comparing WRANGLER to the ARM baseline of relying upon chemical thrusters to de-spin the target NEA, and found that WRANGLER provides significant mass and size benefits over propellant based de-spin approaches for the majority of identified near earth objects. Additionally, we evaluated the WRANGLER concept for ADR missions, and found that it could enable affordable remediation of high-risk debris objects using secondary payload ride opportunities. Finally, we identified key technology risks for implementation of WRANGLER systems and developed a plan for technology maturation in flight-test validation follow-on efforts.

2. WRANGLER CONOPS

In this Phase I effort, we developed and evaluated Concept of Operations (CONOPS) for two different potential implementations of the WRANGLER de-spin method. We began the effort focused on the CONOPS is for a free-flying nanosatellite as described in our Phase I proposal. This nanosatellite captures and de-spins a target object so that a tug spacecraft can safely dock to the object and maneuver it to a different orbit. After discussions early in the project with one of NASA/HEOMD's ARM program managers, it became clear that the ARM program was unlikely to seriously consider a dramatic departure from their baseline architecture such as fractionation of the system into an EP Tug and a free-flying daughter nanosatellite, and at their suggestion we also developed and evaluated CONOPS for using a simpler tethered CubeSat to de-spin the ARM vehicle and asteroid after the spacecraft has captured the NEA. In addition, we considered application of the WRANGLER nanosatellite to the challenge of active debris removal to reduce the population of high-risk debris objects.

2.1 Free-Flying WRANGLER NanoSat CONOPS

The first WRANGLER mission architecture fractionates the ARM architecture by introducing a free-flying nanosatellite that both captures and de-spins the target asteroid ahead of the primary ARM spacecraft. This architecture utilizes the WRANGLER tether concept and TUI's Grapple, Retrieve, And Secure Payload (GRASP) deployable capture module, a device that uses lightweight, temporary inflatable tubes to deploy a capture bag or net. TUI developed and validated the GRASP technology in microgravity testing in 2004 under a DARPA/TTO seedling contract.[5]

The CONOPS for the free-flyer implementation is illustrated in Figure 4. Nominally, the WRANGLER nanosatellite would ride with the host spacecraft as it maneuvers into the vicinity of the target NEA. WRANGLER deploys from the host and maneuvers itself towards the target. Once the ARM spacecraft sufficiently characterizes the object, a target docking location is chosen, the host spacecraft will release the WRANGLER nanosatellite (1), the WRANGLER maneuvers to prepare to capture the target, and the

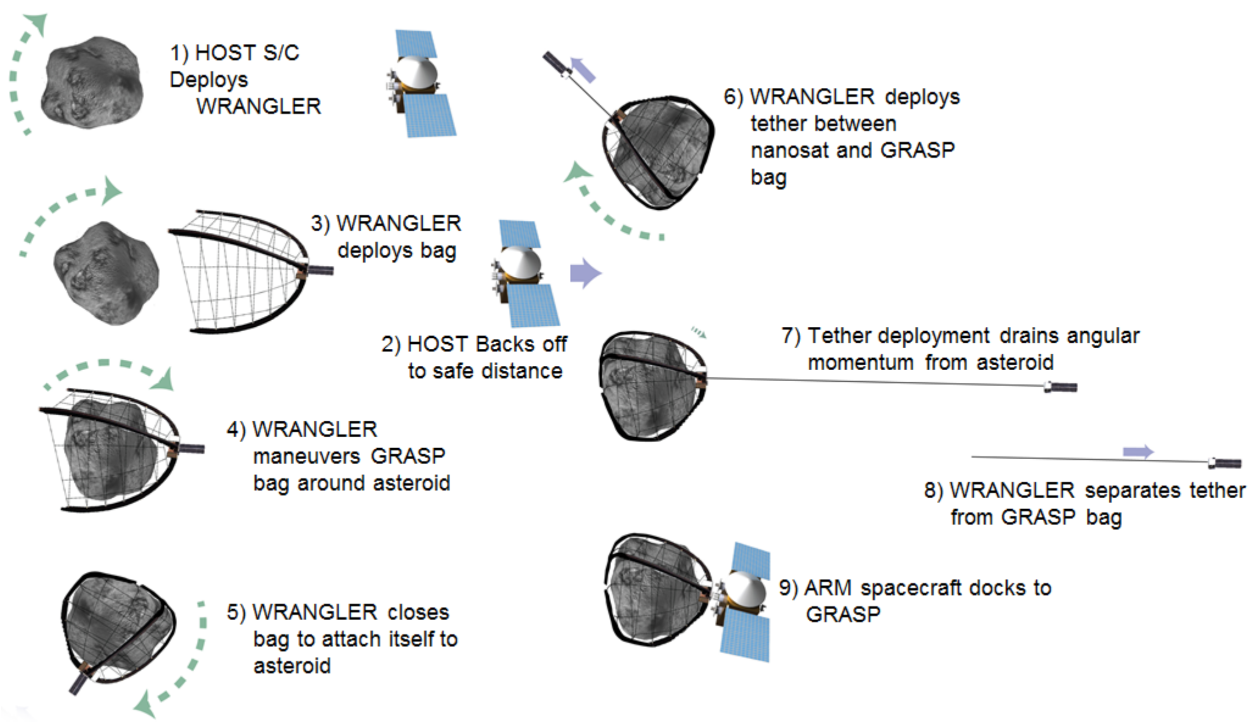

Figure 4. Free-Flying WRANGLER CONOPS. *Utilizing TUI's GRASP technology WRANGLER can de-spin massive asteroids with a low mass nanosatellite scale system ahead of primary ARM spacecraft.*

ARM spacecraft can back away to a safe distance (2), preferably above one of the spin poles of the asteroid so that it can observe the tether maneuver without any chance of contact between the tether and ARM spacecraft.

Alternatively, WRANGLER nanosatellites could be launched to one or more target NEAs to characterize, capture, and de-spin the NEAs prior to launch of the EP maneuvering tug, ensuring that the target object is suitable and safe prior to launch of the high-value EP tug.

Just prior to conducting the final maneuver to the target, WRANGLER deploys the GRASP capture bag (3). Upon confirmation of a successful GRASP deployment, WRANGLER maneuvers GRASP around the target (4) and closes it using a drawstring mechanism (5). It then tightens the bag by further retracting the drawstring, and as the bag constricts around the asteroid the WRANGLER system will affix itself to the asteroid, and friction between the bag and asteroid will cause the WRANGLER nanosatellite to rotate with the asteroid. With the GRASP bag secure around the target, WRANGLER then deploys a lightweight but strong tether in between the nanosatellite body and the GRASP capture device (6). As the nanosatellite moves radially outward from the rotating asteroid, the tether tensions due to centrifugal forces on the nanosatellite, and the tether tension causes a torque on the asteroid that acts to de-spin the system (7). Once the desired rotation rate of the system is reached, the WRANGLER system separates the tether from the GRASP device (8), and the nanosatellite and due to their small residual velocity with respect to the asteroid, the nanosatellite and tether will drift away from the asteroid into interplanetary space. The ARM spacecraft then approaches and docks to a docking fixture on the GRASP module (9).

2.2 The Tethered WRANGLER CubeSat CONOPS

The tethered WRANGLER CubeSat CONOPS, illustrated in Figure 5, retains many aspects of the currently proposed ARM CONOPS but utilizes WRANGLER in lieu of propellant-intensive thrusting in order to de-spin and de-tumble the target asteroid. In this concept WRANGLER rides on the ARM spacecraft as a secondary payload. A CubeSat deployer such as the Cal-Poly P-POD or Planetary Systems CSD could provide a high-TRL, low risk mechanical interface. As in the baseline ARM CONOPS, the host spacecraft would perform thrusting to match rotation rate about the asteroid's center of mass and then capture its target NEA or boulder using an inflatable bag or grappling arms. After capturing the target asteroid, the primary ARM spacecraft releases the WRANGLER nanosatellite. WRANGLER deploys a lightweight tether between itself and the ARM spacecraft, controlling the deployment to maintain tension on the tether. As the tether deploys, the WRANGLER nanosat drains angular momentum from the asteroid-spacecraft system. Once the desired rotation rate of the system is reached, the ARM spacecraft cuts the tether, releasing the WRANGLER nanosat and tether to drift away into interplanetary space. After discarding the WRANGLER system, the ARM spacecraft can then begin to transfer the asteroid to cislunar space.

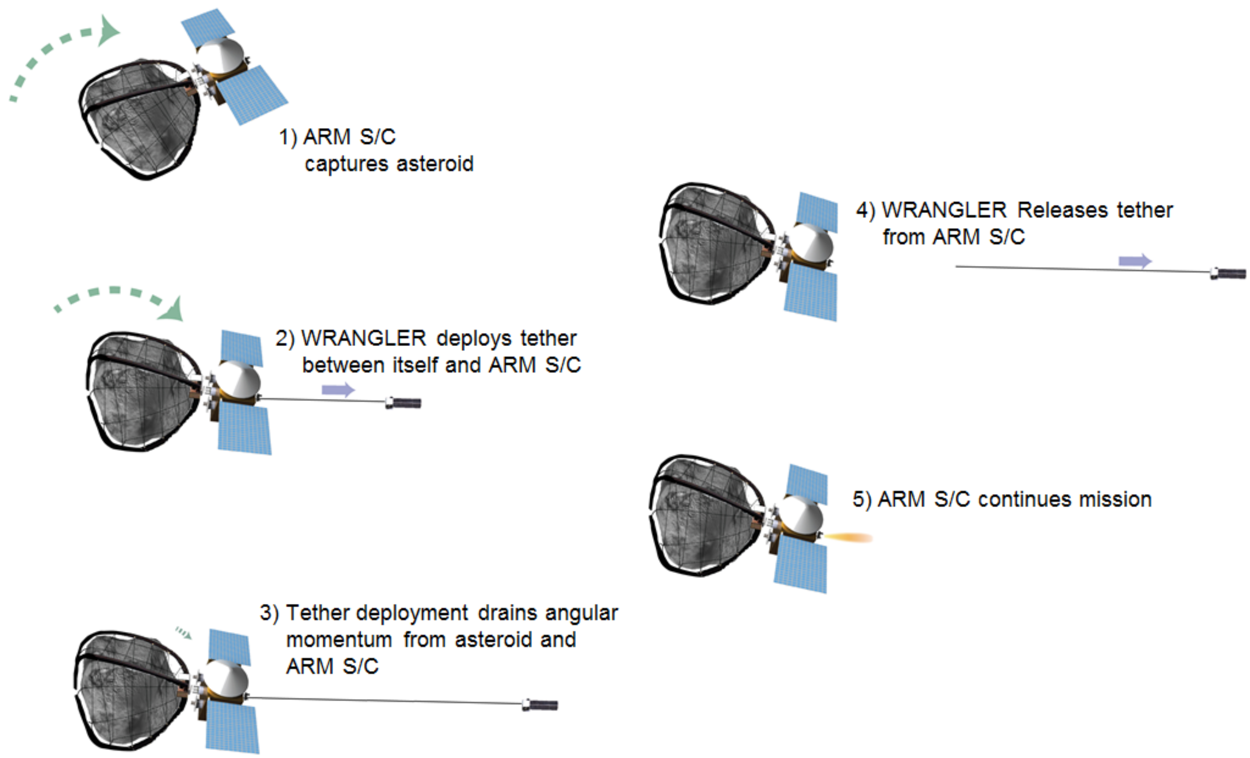

Figure 5. Deployable WRANGLER CubeSat CONOPS. *WRANGLER can be integrated into existing ARM architectures to enable significant mass savings .*

2.3 Active Debris Remediation Application

The free-flying WRANGLER nanosatellite can also provide a basis for a low-cost small satellite ADR system. Small satellite architectures, particularly ones that can be launched as secondary payloads, offer compelling advantages for ADR operations. A nanosatellite-scale ADR spacecraft has the potential to use a large number of secondary payload launch opportunities as the basis for an ADR program, eliminating the need to secure dedicated launches specifically for ADR operations. In addition, each launch of a new primary satellite could deliver multiple secondary payload ADR spacecraft to enable each launch to accomplish a net reduction in the orbital population. As can be seen in Figure 6, a system capable of removing just 5 objects a year can have a dramatic impact on the future of the orbital debris problem.[6] Further aiding this architecture is the fact that, as seen in Figure 7, the debris objects of highest concern are concentrated in similar orbits. This allows multiple small satellites deployed from a single launch to make a substantive impact on the debris problem without the need to conduct expensive out-of-plane transfers. While the majority of the work conducted in the Phase I WRANGLER effort has focused on the application of the concept to asteroid capture, we have also evaluated applicability to capture and stabilization of large orbital debris objects to prepare them for de-orbit or transfer to graveyard orbits. Many of the highest-risk existing debris objects are rocket upper stages. These spent stages typically end up rotating at moderate rates with a single axis of rotation, so they are excellent candidates for capture and de-spin by a tether system. The CONOPS considered for ADR applications is equivalent to that of the free-flying WRANGLER ARM concept illustrated in Figure 2, except after de-spin of the debris object, the WRANGLER system would either use a conducting portion of the tether to induce electrodynamic drag to de-orbit the debris object, or the WRANGLER nanosat would use its remaining fuel to maneuver the object to either a de-orbit trajectory or a graveyard orbit.

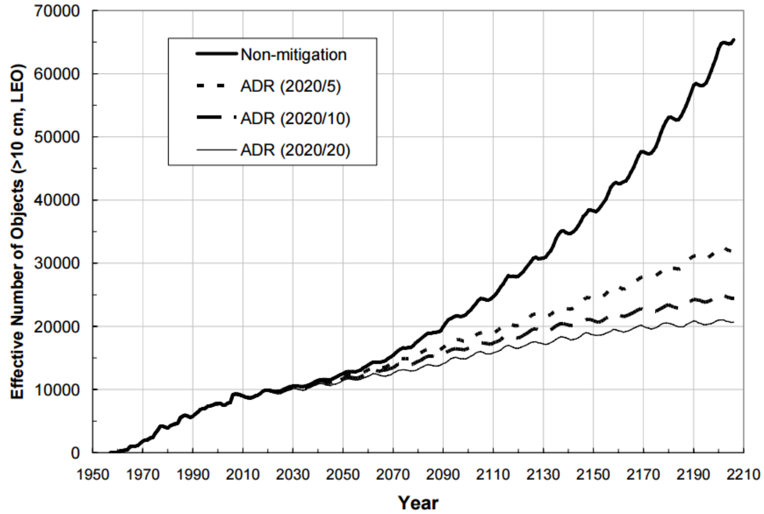

Figure 6. Effectiveness of ADR Missions. *Removing as few as 5 objects a year can have a significant impact on the projected orbital debris population.*

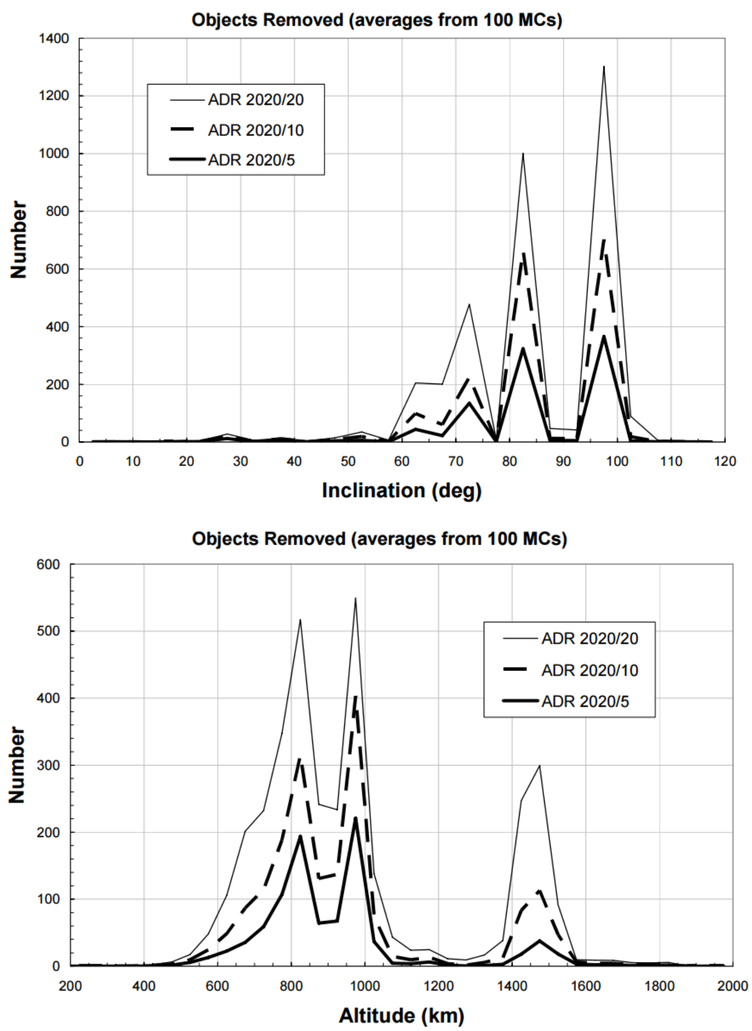

Figure 7. Debris Object Populations. *The grouping of 'worst offending' objects into a small range of orbits enables the removal of multiple objects with a single launch through the use of secondary payload ADR systems.*

3. Tether Deployment Analysis

Regardless of the mission architecture selected for the WRANGLER system, two tasks must be completed in order to de-spin and de-tumble a target object. First WRANGLER must securely attach itself to the target object. Second WRANGLER must deploy a multi-kilometer tether with an attached nanosatellite endmass. Leveraging the r^2 dependence of the moment of inertia of the tethered nanosat with respect to the spinning object's reference frame, WRANGLER 'drains' angular momentum from the target and induces a corresponding reduction in the object's rotation rate. While many strategies and options have been identified for capturing an asteroid, including deployable bags or nets as investigated in our prior GRASP effort, inflatable bags or grappling arms as baselined in the ARM program, and harpoons as investigated by the NIAC SRSEE and Comet Hitchhiker studies, the challenges of ensuring reliable, well-controlled tether deployment remain nearly identical across the span of potential mission architectures. The efficacy and feasibility of the tether deployment is therefore critical to the overall feasibility of the WRANGLER concept.

An often-asserted risk of tethered de-spin schemes is the potential for the dynamics of the tether to cause it to contact or 'wrap around' the target during deployment. Contact with the surface could cause snagging or cutting of the tether, and wrapping would reduce the system's effectiveness at de-spinning the object. In the Phase I effort we have sought to both characterize the dynamics of the tether deployment and develop strategies to mitigate risks associated with any unwanted dynamic behavior. Prior to embarking on a time-intensive physics simulation effort, we developed an initial analytic model of the tether deployment to confirm the feasibility of the WRANGLER concept across the range of target masses and rotation rates. The work conducted on the analytical model also allowed us to narrow the scope of investigation for the physics-based simulation effort by identifying which cases posed the greatest potential challenges to the WRANGLER concept.

3.1 Analytic Model

In order to quickly evaluate the efficacy and feasibility of de-spinning a given target object we developed an analytic model to provide insight beyond that available through a simple angular momentum analysis. The analytic model developed to study the WRANGER system considers a non-inertial frame co-rotating with a target object at an angular velocity Ω. The external forces acting on the tethered endmass in such a system are the familiar artifacts of the frame selection, the Coriolis, centrifugal and Euler forces. The centrifugal force, purely a result of the rotation of the reference frame, is given by,

$$F_{cf} = m\big((\Omega\times\mathrm{R})\times\Omega\big). \quad (1)$$

The Coriolis force, a result of a body's motion within the rotating frame, is given by,

$$F_{cor} = 2m\dot{R}\times\Omega. \quad (2)$$

The Euler force a result of the acceleration of the frame itself, is given by,

$$F_{euler} = m(\mathrm{R}\times\dot{\Omega}). \quad (3)$$

From Equations (1), (2), and (3) the equation of motion of the tethered nanosatellite can be approximately written as,

$$\ddot{R} \cong \frac{\big(\mathrm{R}\times\dot{\Omega} + 2\dot{R}\times\Omega + (\Omega\times\mathrm{R})\times\Omega\big) + (T - \Delta T)}{m}. \quad (4)$$

Where T is the tension force vector on the nanosatellite, and ΔT is the reaction force vector from the tether deployment on the nanosatellite. The reaction force is given by,

$$\Delta T \cong \rho\dot{s}^2\boldsymbol{\tau}, \quad (5)$$

where $\dot{s}$ is the deployment rate of the tether and $\boldsymbol{\tau}$ is the unit tension vector. Equation (4) allows the dynamics of the tethered nanosatellite to be propagated forward however in order to accurately simulate the WRANGLER system the loop must be closed and the effects of the tether and nanosatellite deployment on the target must also be considered.

Since there are no external torques acting on the target-WRANGLER system, angular momentum within the system is conserved. Conservation of angular momentum allows the WRANGLER spacecraft to effectively reduce the spin rate of the target object. Once the WRANGLER spacecraft is initially attached to the asteroid the conservation of angular momentum dictates that,

$$C = L_{Target} + L_{WRANGLER}, \tag{6}$$

where $L_{Asteroid}$ and $L_{WRANGLER}$ are the angular momentum of the target and WRANGLER respectively and where C is a constant. Differentiating equation (6) yields,

$$\frac{dL_{WRANGLER}}{dt} = -\frac{dL_{Target}}{dt}, \tag{7}$$

implying any change in the angular momentum of the wrangler spacecraft will lead to a corresponding decrease in the angular momentum of the target. Since the torque on the target is a result of purely internal system forces, the torque on the target can be easily written as,

$$\tau_{target} = r \times T, \tag{7}$$

where r is the radius vector pointing from the spin axis to the attachment point of the tether and T is tension force in the tether. By the definition the torque incident on the target can further be resolved into the angular acceleration of the target body through

$$\alpha_{Target} = \frac{\tau_{Target}}{I_{Target}}, \tag{8}$$

where α_{Target} is the angular acceleration of the body about the spin axis and I_{Target} is the mass moment of inertia of the target body about its spin axis. Combining Equations (7) and (8) yields an expression for the angular acceleration of the target,

$$\alpha_{Target} = \frac{r \times T}{I_{Target}}. \tag{9}$$

Equations (4) and (9) taken together complete a pair of coupled differential equations,

$$0 = \left(\mathrm{R} \times \dot{\Omega} + 2\dot{R} \times \Omega + (\Omega \times \mathrm{R}) \times \Omega\right) + \left(\frac{T - \Delta T}{m}\right) - \ddot{R},$$
$$0 = \frac{\tau_{Target}}{I_{Target}} - \dot{\Omega} \tag{10}$$

which can be solved numerically to approximate the dynamic behavior of the system.

Since the differential equations that define the dynamics of the system are coupled and extremely stiff an implicit propagator was chosen to provide the best long term stability. MATLAB's ode15i variable order implicit propagator was used to solve the system of differential equations given by, given in Equation (10). The analytic model was used to provide insight and quick analysis across the range of potential system input parameters. Figure 8 demonstrates one such analysis used to determine the maximum tension expected in the tether across a range of asteroid diameters. These analyses were verified against first order analytic

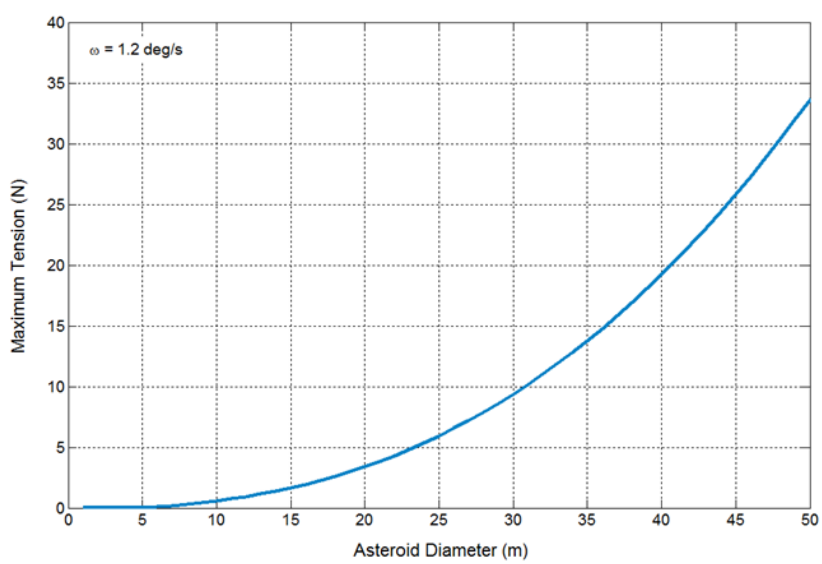

Figure 8. Max Tension vs. Asteroid Mass. *An analytic MATLAB model was used to provide analysis across the range of potential system parameters.*

calculations and were used extensively in system sizing and conceptual design development. While the analytic model was useful in determining the general feasibility and providing useful analytics for the design of system components, the lack of tether dynamics modeling rendered the model unreliable for detailed deployment dynamic analysis, particularly under conditions where tension in the tether was low. In order to overcome these shortcomings of the simple analytical model detailed deployment analysis was completed with our physics based TetherSim software.

3.2 TetherSim Analysis

TetherSim™ is a physics based code developed by TUI that models both tether and spacecraft dynamics and allows for accurate modeling of the dynamics of tethered systems. We have utilized TetherSim in previous efforts to simulate the use of tethers to de-spin and de-tumble large objects and a similar approach has been used to tackle the WRANGLER deployment problem. Deployment of a multi-kilometer long tether from a spinning object poses several control challenges that must be resolved in order to successfully de-spin or de-tumble the target. An examination of Eqn. (4), reveals that a significant concern for the deployment of a tethered endmass from a spinning object is excessive libration or 'wrapping' of the tether caused by the Coriolis and Euler forces driving the endmass away from the local vertical (in the co-rotating frame) during deployment. While some libration of the tether is necessary in order to impose a torque on the asteroid and thereby achieve a corresponding decrease in the rotation rate, excessive libration will cause the tether to contact the asteroid. As we identified with our initial analytical modeling efforts this behavior is of particular concern when the tension, which acts as a restorative force on the tethered endmass, is low.

Our initial simulations of uncontrolled WRANGLER tether deployments, utilizing a representative small NEO, demonstrated that a simple constant deployment rate control scheme was insufficient to prevent the tether contacting the surface of the asteroid during deployment. Impact of the asteroid by the tether poses a number of risks including destruction, fouling, or degradation of the tether and must be prevented to ensure the success of the WRANGLER concept. In order to control the dynamic behavior of the tether we implemented a control scheme in which the deployment rate of the tether from the nanosatellite is used to control its position. As seen in Eqn. (5), varying the deployment rate of the tether will cause a corresponding change in the reaction force on the nanosatellite. If the tip of the tether begins to lag behind the desired libration angle, the deployment rate of the tether is slowed to bring the tether back towards the local vertical. Controlling the deployment rate of the tether in this manner, whether from a deployer on the tethered endmass or from a deployer fixed to the tether attachment point, can be used to minimize dynamic behavior of the tether and maintain a desired tether libration angle. This control concept has been demonstrated on-orbit with the SEDS-2 experiment, shown in Figure 9, in which a 20 km tether was successfully deployed from a Delta-II upper stage and the libration of the tether limited to 4° through the use of a deployment rate control system[8].

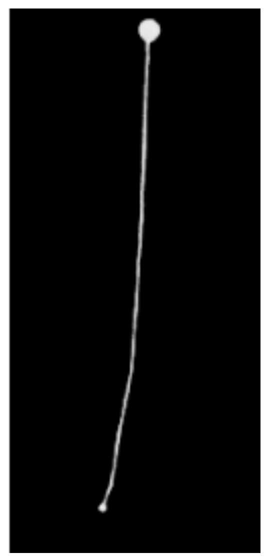

Figure 9. SEDS-2 Tether Deployment[7].

Implementing a simple deployment rate control scheme, in which the tether deployment rate was slowed in the case of excessive tether libration, we were able to simulate successful WRANGLER deployments beyond 10 km without the tether 'wrapping' or impacting the asteroid. The simplest case that can be used to demonstrate the WRANGLER concept is an asteroid spinning about a single principle axis of rotation. Figure 10 shows a successful WRANGLER deployment of a 1kg nanosatellite from a 10 m diameter asteroid with mass 1,000,000 kg rotating at an initial rate of 0.22 revolutions per minute. In this scenario, a 3.8 kilometer tether deployment reduces the spin rate to under 0.05 revolutions per minute in fewer than 2 days. During this deployment the tether remains well behaved with the maximum libration of the tether effectively limited by the control scheme to 30 degrees. Once a viable control law was established and demonstrated through simulation we began a simulation campaign of tether deployments from asteroids of various sizes, masses, and rotation rates. Simulation representative of various small NEO candidates were conducted to verify previous analytical analysis effort and demonstrate that tethers can effectively de-spin a wide range of potential targets while effectively mitigating the risk of unwanted dynamic tether behavior.

The initial TetherSim simulation campaign demonstrated that the control law we developed is robust

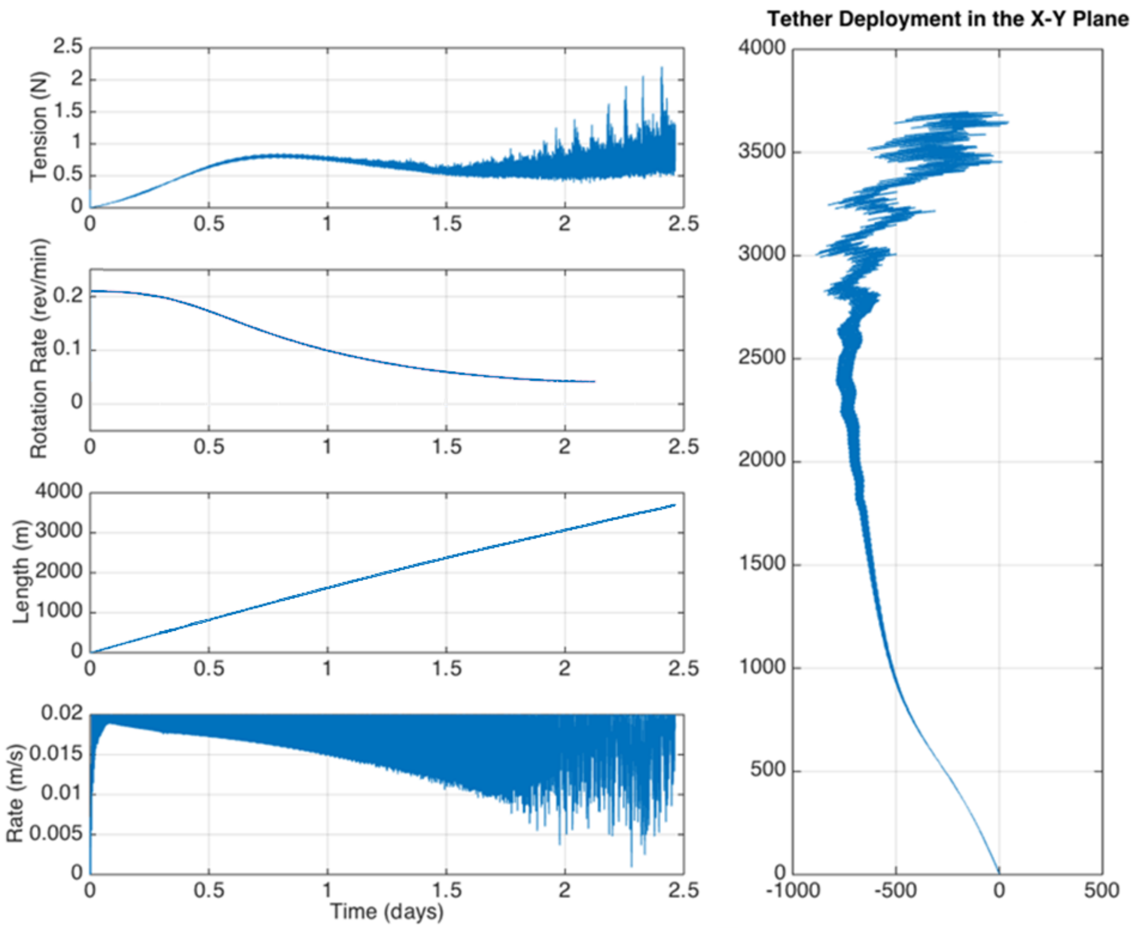

Figure 10. Successful WRANGLER Deployment From a 1000t Asteroid Rotating at 0.22 RPM. *WRANGLER can effectively de-spin asteroids without incurring unwanted tether dynamics.*

enough prevent variations in the physical characteristics of the target object from negatively impacting the performance of the tethered system. Our next simulation effort focused on determining what if any impact the location of the tether attachment has on the effectiveness of the de-spin or de-tumble effort. Simulation of de-spin efforts with varying initial tether attachment point demonstrated that attachment of the tether off of the equatorial plane of a given spin axis will drive the target into forced gyroscopic precession and result in the target's spin pole migrating to the attachment point of the tether. As seen in Figure 11, the precession of the target limits the amount of angular momentum that can be extracted from the target by the tethered endmass. Achieving attachment of the tether to the equatorial spin plane of the axis or axes of rotation is an important consideration for the design of the WRANGLER system. A design which allows for adjustment of the attachment point on the asteroid will maximize the potential benefit of the WRANGLER concept and allow for greater errors in the initial capture of the target object.

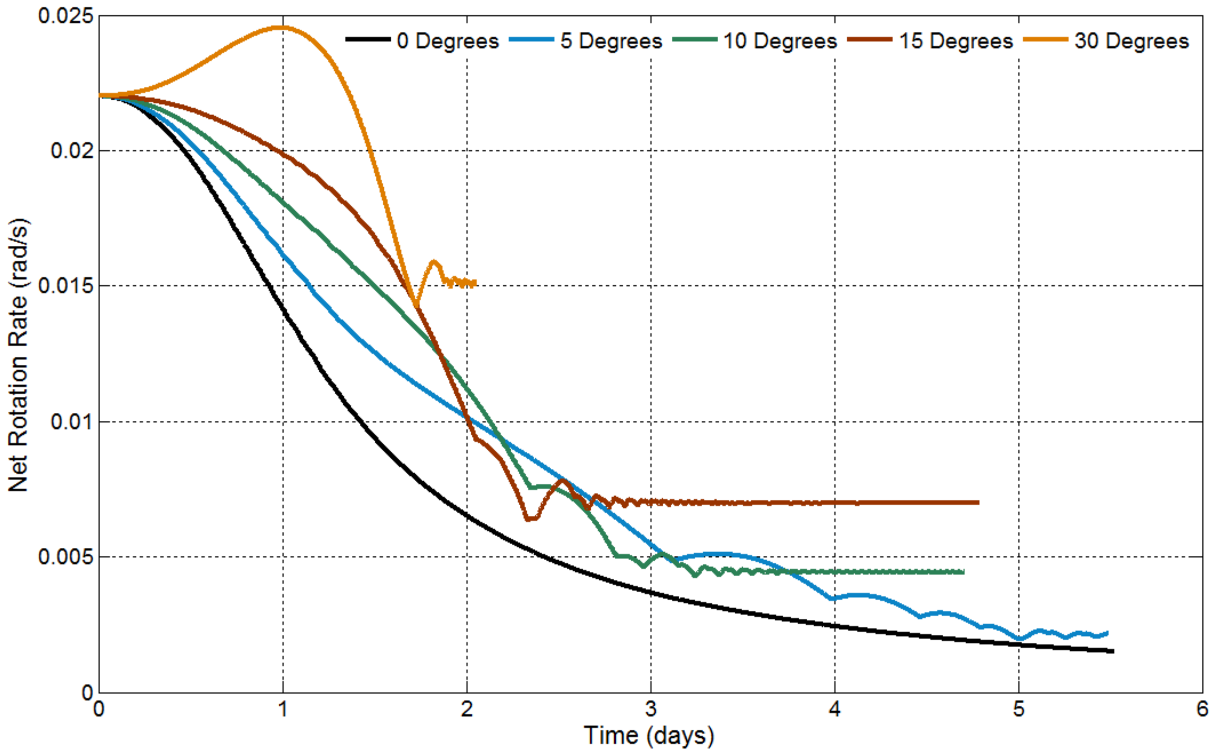

Figure 11. Effect of Off-Axis Tether Attachment. *WRANGLER must be attached at the equatorial spin axis of the target in order to conduct the most effective de-spin.*

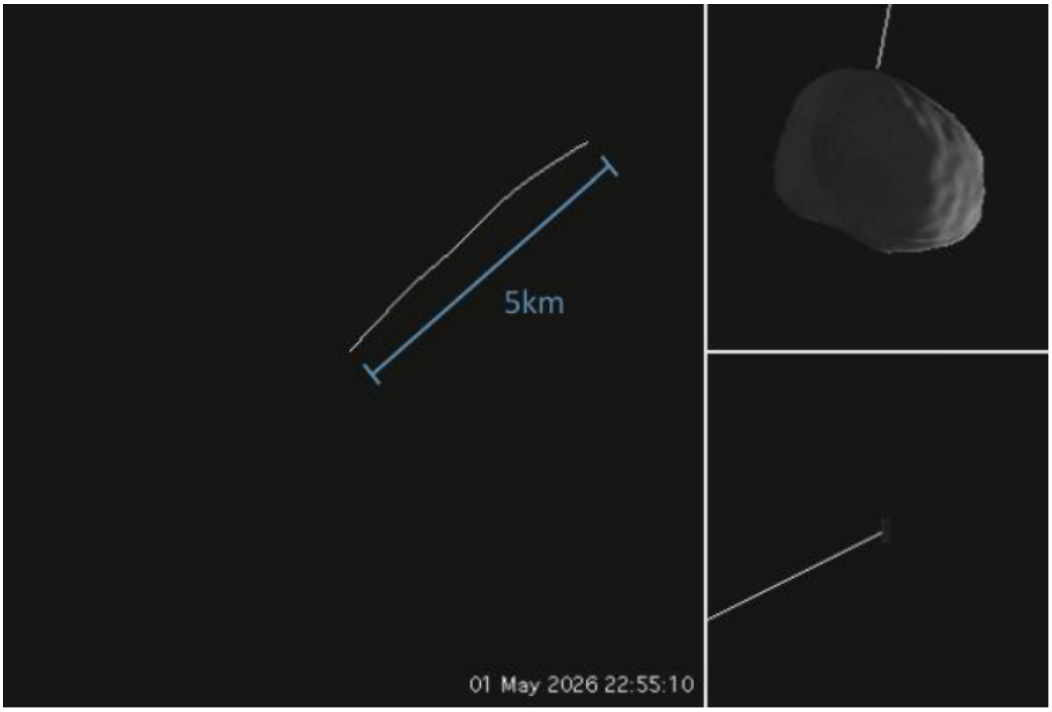

Figure 12. TetherSim Visualization of Asteroid De-Tumble.

In addition to determining the effectiveness of using tethers to de-spin a target object with a single principle spin axis, we also investigated the efficacy of using tethers to de-tumble an object spinning about multiple principle axes. While the gyroscopic precession induced by tether attachments off of equatorial spin planes limits the capability of a single tether to de-tumble a target with an initial three-axis spin, tumbles that can be decomposed into two principle axes of rotation can be effectively stopped with a tether attached at the intersection of the two equatorial spin planes. Figure 12 and Figure 13 show the effectiveness of a 5 km tether deployment from a 13 m diameter 1,000,000 kg asteroid spinning with a principle axis of rotation rate of 0.22 revolutions per minute and a secondary principle axis of rotation rate of 0.05 revolutions per minute. A significant reduction in the spin rate of both principle axes of rotation is achieved without the induction of gyroscopic precession or tether wrapping.

Through the use of an extensive simulation utilizing our TetherSim Software TUI has demonstrated that the WRANGLER concept is both feasible and effective through a systematic investigation of the use of tethers to de-spin targets characteristic of NEOs of interest to near future missions. We have validated the WRANGLER concept for targets across a wide range of initial rotation rates, sizes, and masses. Using simple control schemes, that have been demonstrated on-orbit, we have shown that the risks of unwanted tether behavior associated with deployment of the tether can be mitigated and that contact of the tether with the target object can be prevented. Furthermore we have demonstrated that tethers can be used effectively on both spinning and tumbling objects provided a suitable attachment point is chosen.

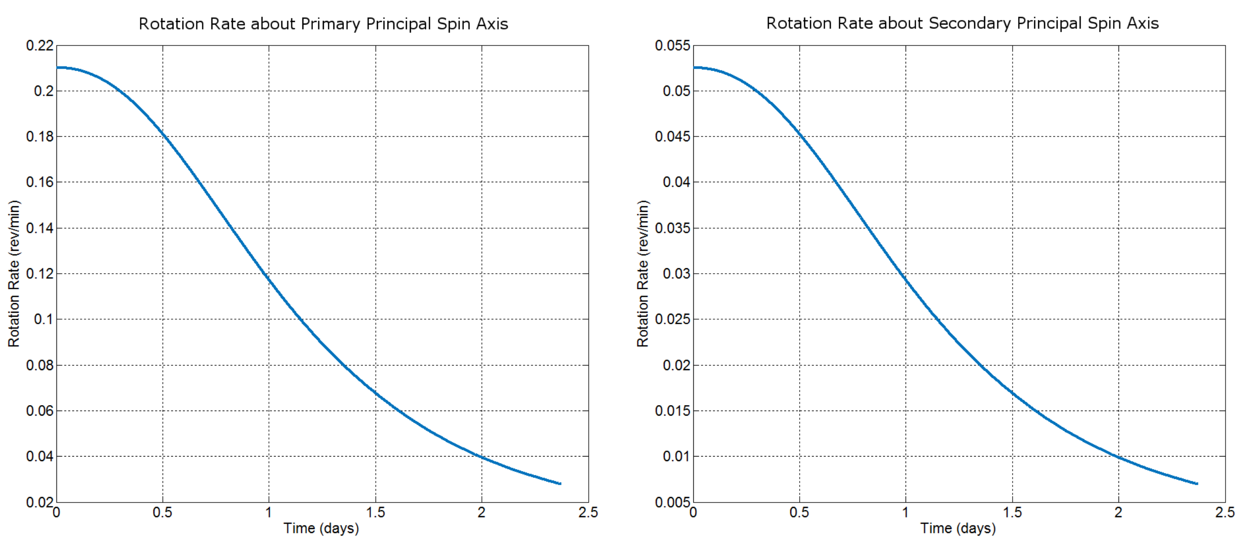

Figure 13. Successful WRANGLER De-Tumble of Asteroid Spinning about Two Principle Axes of Rotation.

4. WRANGLER Conceptual Design

In order to provide realistic estimates of the mass and size of the WRANGLER system, TUI has developed conceptual designs for both the free-flying WRANGLER architecture capable of conducting ARM and ADR missions and the tethered nanosatellite de-spin system. In addition we have completed a detailed preliminary design of the tether needed for the proposed WRANGLER CONOPS. The conceptual designs draw from NASAs currently proposed ARM architectures, the WRANGLER simulation validation effort, and TUIs past effort with our GRASP system.

4.1 WRANGLER Tether Design

The tether design for the WRANGLER system is driven by the required strength of the tether. Higher tension forces require the use of correspondingly stronger and therefore more massive tethers. However, as Figure 8 shows, the tension forces on the tether during de-spin of representative NEO objects is extremely small, on the order of 10 N. As shown in Figure 14, the small tension forces imposed on the tether allows the tethers used for the WRANGLER effort to be extremely lightweight and thin, much thinner than dental floss, while still providing adequate strength.

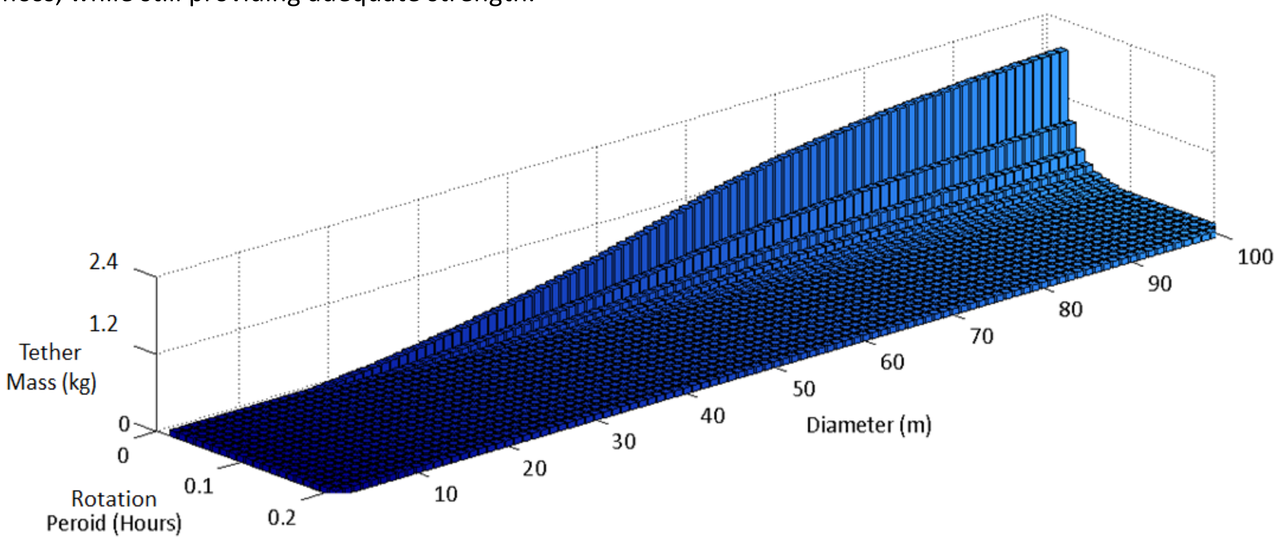

Figure 14. WRANGLER Tether Design. *WRANGLER can de-spin massive asteroids using an extremely small tether.*

The tether design for the WRANGLER system is baselined on the use a monofilament Dyneema SK-75 fiber. Shown in Figure 15, Dyneema SK-75 is a highly-oriented high molecular weight polyethylene with a tenacity of 3.5 N/Tex (1 Tex = 1 g/km). This is the thinnest yarn tow available of the highest strength-per-weight fiber commercially available. Each monofilament is 0.02 mm in diameter and has a linear mass density of 0.7 Tex. In order to provide resistance to micrometeoroid impacts multiple monofilament fibers are braided together in a Hoytether™ structure to prevent tether severing under impact. A minimum tether is composed of 12 monofilament strands, is capable of supporting 29.4 N, and has a mass of 84 grams for the desired 10 km length. Figure 14 shows how the mass of the 10 km WRANGLER tether scales with both the rotation rate and diameter of a target asteroid assuming an endmass of 1 kg, a target density of 2.8 g/cc, and a factor of safety of F=2. As evidenced by this analysis the tether required to despin even a massive, quickly rotating asteroid

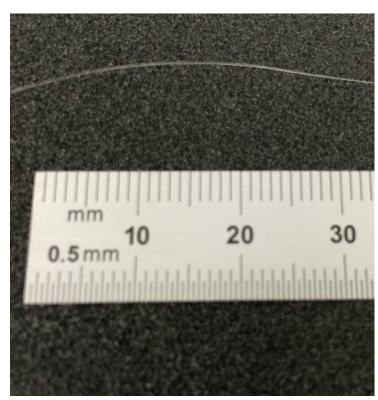

Figure 15. Monofilament Dyneema SK-75. *The tether required to de-spin most NEOs can be thinner than dental floss.*

can easily be packed into a 1U CubeSat volume and provides significant mass savings over current ARM architectures.

4.2 Deployable WRANGLER Conceptual Design

Utilizing the WRANGLER tether design and CONOPS for a tethered nanosatellite, TUI has developed a conceptual design of a 2U WRANGLER tethered nanosatellite. This small 1.7 kg payload concept, a mock-up of which is shown in Figure 16, leverages our existing high Technology Readiness Level (TRL) flight qualified hardware to create a system that can be integrated into current ARM architectures with relatively low cost and little nonrecurring engineering effort. Table 1 summarizes the estimated mass breakdown for the 2U WRANGLER design. This 2U design would be deployed by a primary ARM or ADR spacecraft and would be used to de-spin or de-tumble the coupled target and primary spacecraft, providing significant mass savings over current ARM architectures which propose using hundreds of kilograms of propellant.[3]

The spool and tether deployment mechanism used in the WRANGLER 2U conceptual design are flight hardware developed for the Multi-Application-Survivable-Tether (MAST) experiment. A Hoytether of the minimum viable size, capable of conducting the deployment shown in Figure 10, provides a representative tether for mission targeted at a NEO. Despite Dyneema's relatively low density of 970 kg/m^3 the 10km tether packs into a volume of 86 cc. The MAST spool, which is contained in the first volume of the satellite, houses the tether and feeds it into the deployer on the front of the satellite. The MAST deployer is composed of a set of driven pinch rollers which provide control of the tether deployment rate and allow WRANGLER to control the dynamics of the tether during deployment.

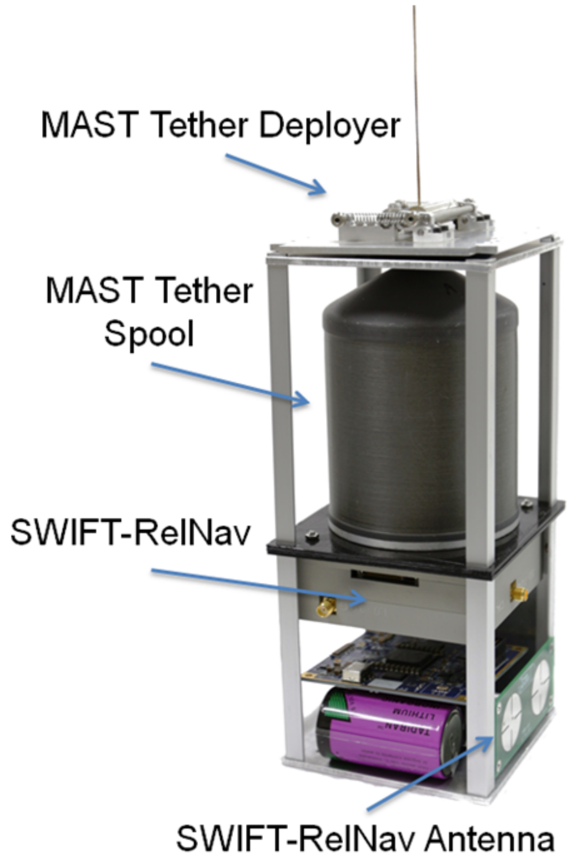

Figure 16. Photo of WRANGLER 2U Mock-Up. *The 2U WRANGLER design integrates existing high TRL, flight qualified technologies.*

Component	Mass (kg)
Structure & Mech.	0.4
Avionics	0.3
Batteries	0.8
Tether & Deployer	0.2
TOTAL	**1.7 kg**

Table 1. Mass Breakdown for 2U WRANGLER.

To provide control, communications, and relative position information the 2U design will leverage TUI's existing "SWIFT-RelNaV" radio. The SWIFT-RelNav radio, shown in Figure 17, is a software defined radio designed to provide small satellites cross link communication as well as measurements of relative range and position between satellites. It is capable of measuring range to ≤0.1 m, and relative position to ≤ 1 degree. SWIFT-RelNav provides more than enough accuracy to meet the needs of the WRANGLER control scheme and its onboard processing capabilities can be used to control the tether deployment.

Figure 18 illustrates the initial deployment of the tethered WRANGLER system. The 2U concept has been designed to integrate with P-POD and other CubeSat standard deployers to ease integration of the WRANGLER system into existing ARM and ADR mission architectures. The force imparted by the CubeSat deployer initiates the tether deployment and provides the initial separation between the WRANGLER and host spacecraft. A careful investigation of the initial tether deployment dyanmics will be an essential part of preparing the WRANGLER concept for flight operations.

Figure 17. SWIFT-RelNav Radio Prototype.
TUI's SWIFT-RelNav radio provides cross-link communications at up to 12 Mbps in addition to range and direction tracking.

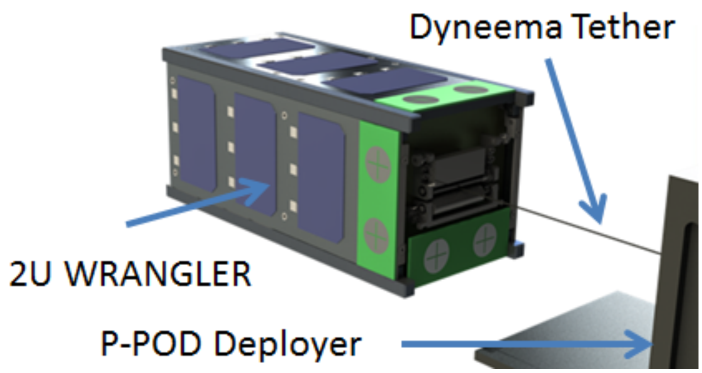

Figure 18. 2U WRANGLER Deployment from P-POD
The tethered WRANGLER concept is compatible with a range of CubeSat standard deployers for easy integration into existing mission architectures.

4.3 Free-Flying WRANGLER Conceptual Design

In parallel with our development of the tethered WRANGLER conceptual design, we developed a design for a free-flying nanosatellite that leverages our GRASP technology to both capture and de-spin the target. This architecture can be used in conjunction with a primary spacecraft in order to mitigate the risk and challenges associated with proximity operations with a massive spinning target or can be launched independently ahead of ARM and ADR missions to prepare targets. The design of the free-flying system, shown in Figure 19, was developed based on the proposed CONOPS of a free-flying WRANGLER system and TUI's experience from the effort to develop the GRASP system. As with the 2U concept design the design of the free-flying system leverages a number of TUI's existing high TRL technologies to reduce cost and nonrecurring engineering effort.

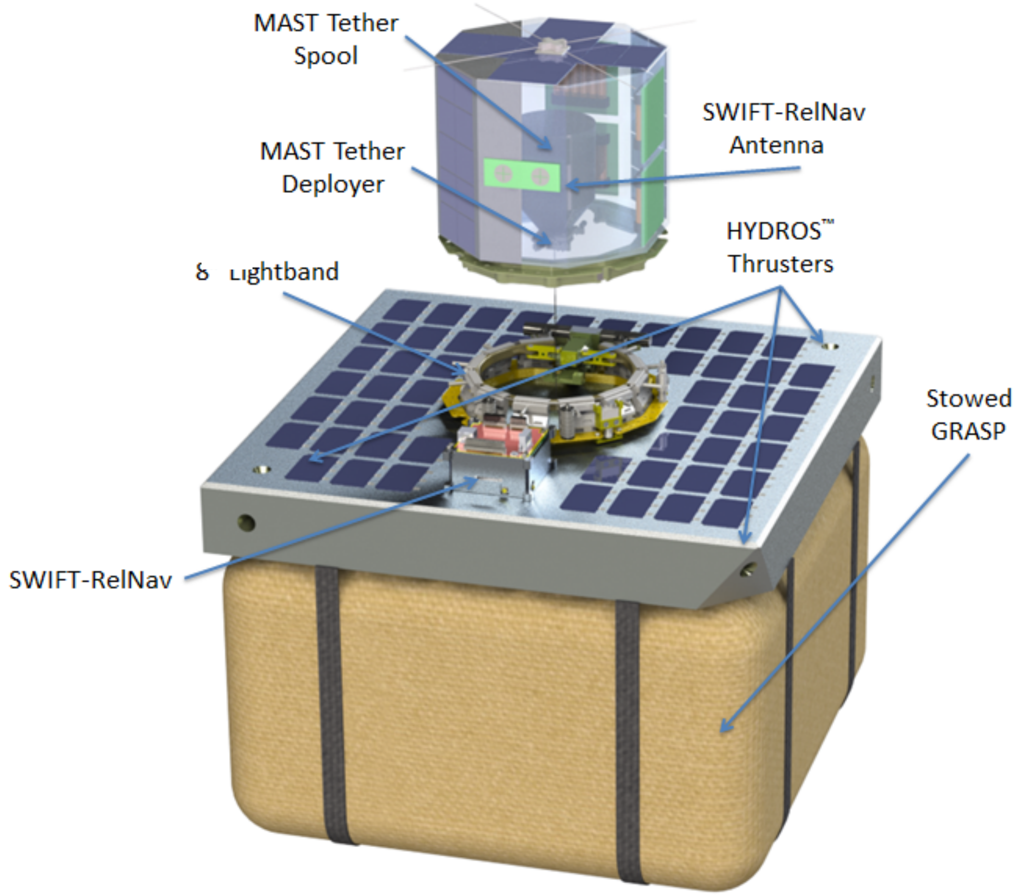

Figure 19.Free-flying WRANGLER Conceptual Design.

The free-flying WRANGLER concept consists of two fundamental subsystems: a small tethered nanosatellite which contains the tether and tether deployment hardware, and a larger baseplate which incorporates the GRASP capture bag, propulsion, and a docking collar. In operation the tethered nanosatellite remains attached to the baseplate throughout the proximity operations and capture of the target object. Once the target has been secured in the GRASP bag the tethered nanosatellite deploys from the baseplate and despins the coupled system. The tether, tether spool, and tether deployment mechanism contained within the tethered nanosat remain unchanged from the smaller 2U WRANGLER concept and are composed of flight-qualified hardware. SWIFT-RelNav radios at both the baseplate and tethered nanosatellite to provide the communications, relative position, and processing capabilities required for execution of the WRANGLER CONOPS.

TUI, under a previous DARPA/TTO effort (MDA972-03-C-089), developed GRASP a simple, small, and readily scalable device to enable capture of space debris. GRASP uses lightweight, temporary inflatable tubes to deploy and expand a net or bag, and then uses a drawstring mechanism to enclose that net around a target object and cinch it down to provide a secure connection. In 2004 TUI conducted testing of a GRASP prototype onboard a Zero-G aircraft. These tests, shown in Figure 20, successful validated the GRASP deployment mechanism, confirmed GRASPs ability to successfully capture a tumbling object, and demonstrated GRASPs tolerance to moderate relative position and velocity errors.

Figure 20. Microgravity Test of GRASP Prototype. *GRASP provides a scalable solution capable of capturing tumbling objects.*

TUI has conducted a scalability analysis for the GRASP system to investigate the mass and volume of a system capable of capturing NEOs. Concerns about the composition of NEOs, including suggestions that many NEOs may be composed of gravitationally attracted boulders covered in a surface of loosely bound regolith, have driven the use of bag to completely encapsulate target objects in current ARM architectures.[4] In light of these concerns we have baselined a GRASP design for use with WRANGLER composed of four 50 mm diameter temporarily inflatable arms made of aluminized Nomex® that will open a high strength Kevlar® net backed by a thin aluminized polyethylene terephthalate bag. Figure 21 shows how this baseline GRASP system scales with the diameter of the GRASP system. A 25 m diameter GRASP bag capable of capturing a 13m tumbling asteroid was used as a baseline in the development of the free-flying WRANGLER design. Such a system would have a mass of 18 kg and stow into a volume of 18,000 cubic centimeters or 18U.

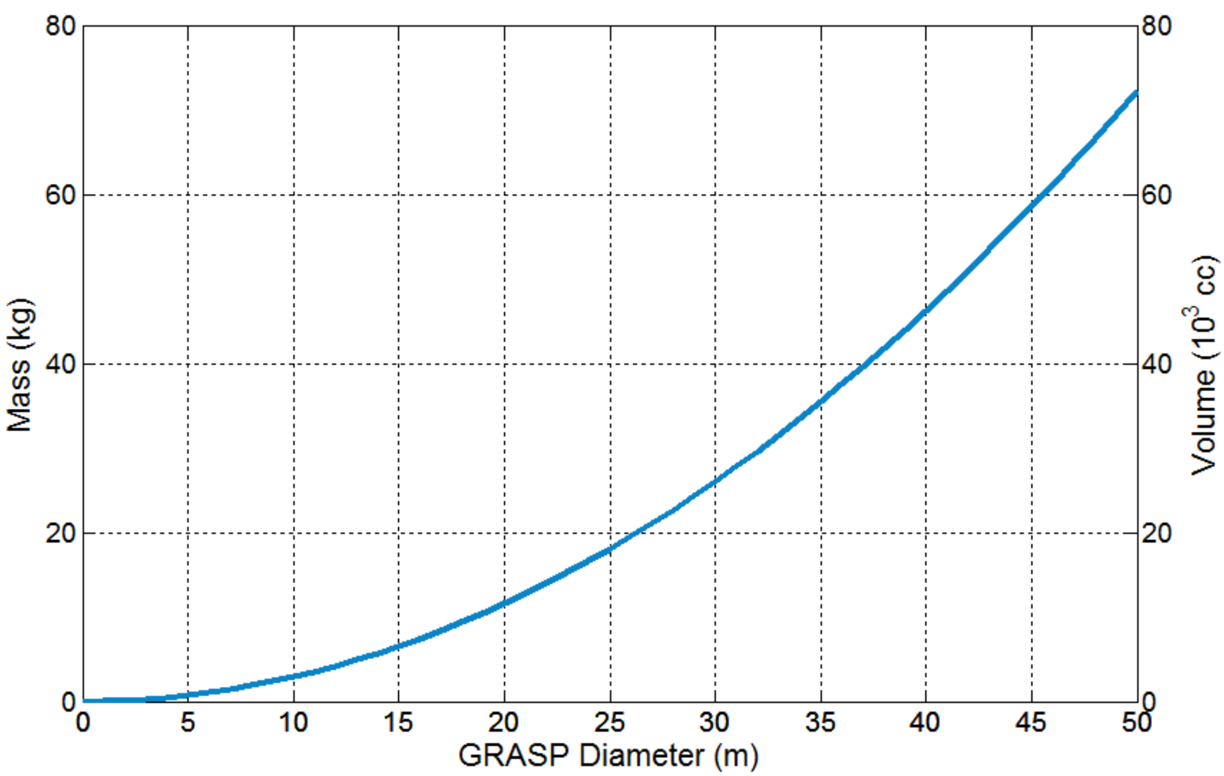

Figure 21. GRASP Sizing with a thin-film bag. *GRASP can be readily scaled for asteroid retrieval or ADR missions.*

Unlike the concept for the 2U WRANGLER the free-flying WRANGLER concept must be capable of providing its own propulsion. TUI's HYDROS water electrolysis based propulsion system provides an ideal solution for the proximity operations maneuvering required of the WRANGLER system. HYDROS utilizes water, an inert propellant which is unpressurized at launch, making it particularly well suited for secondary payload operations. Once deployed the water is electrolyzed into hydrogen and oxygen gas which is then burned in a bipropellant thrusters for high thrust high I_{sp} propulsion or utilized for low impulse-bit cold gas maneuvering. The simplicity of the HYDROS design, seen in Figure 22, allows HYDROS to be easily integrated into the geometry of the WRANGLER baseplate and easily scaled to accommodate the propulsion requirements of the WRANGLER concept.

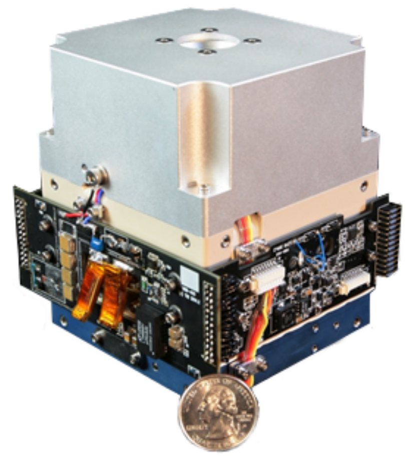

Figure 22. HYDROS Prototype Unit.

HYDROS's gas generation capability can also be leveraged to provide the gas needed to inflate the arms of the GRASP capture device. The diameter of the arms and the desired inflation pressure drive the amount of gas that will be required to deploy GRASP. Figure 23 shows how the amount of water need to deploy GRASP scales with the diameter of the arms and the inflation pressure for a 25 m GRASP system. Storing liquid water and electrolyzing it to produce gas using propulsion system hardware provides an extremely volumetric and mass efficient method for deploying GRAP's inflatable structures.

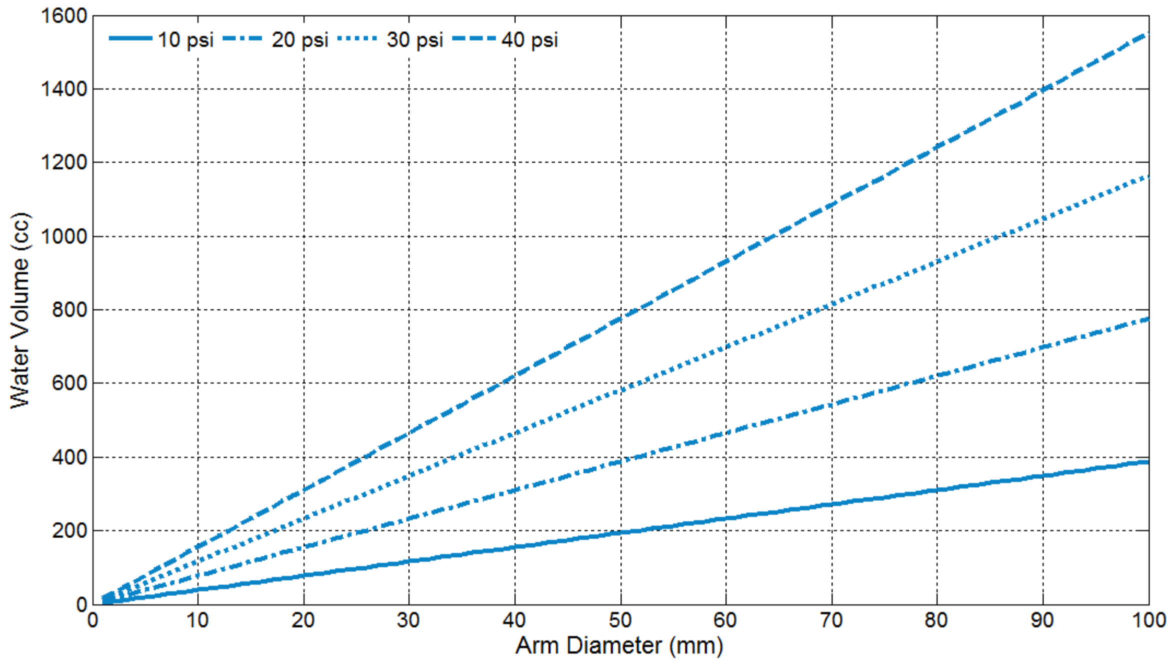

Figure 23. Water Requirements for HYDROS inflation of GRASP. *HYDROS provides a mass and volumetrically efficient way to generate gas for inflation of GRASP.*

Table 2 provides a summary of the mass breakdown for a free-flying WRANGLER architecture targeted at a 13m tumbling asteroid. The total system has mass is less than 50kg and a volume of less than 26U, making it compatible with secondary payload launch opportunities and allowing for integration with existing spacecraft architectures. Since the mass and size of the GRASP system and the amount of propellant required will be highly dependent on the target and mission CONOPS a thorough design optimization and scaling of the free-flying WRANGLER system architecture will be required to adapt it to a specific mission.

Component	Mass (kg)
Structure & Mech.	28
GRASP	17.7
Propulsion & Fuel	8
Avionics & Batteries	4.5
Tether & Deployer	0.2
TOTAL	**48.4 kg**

Table 2. Mass Breakdown for Free-flying WRANGLER.

5. WRANGLER Value Proposition

TUI has established the feasibility of the WRANGLER concept through intensive TetherSim simulations and conceptual design development. However for WRANGLER to offer a substantive benefit to ADR and asteroid capture missions it must provide more than merely a suitable replacement for existing technologies. We have established that WRANGLER offers the potential to provide significant mass savings over current approaches by conducting a detailed analysis of the mass required to de-spin NEOs utilizing thrusters and comparing it to the mass of commensurate WRANGLER systems. Additionally we have shown that the WRANGLER concept offers the potential to reduce the risks and costs of proposed ARM architectures.

5.1 WRANGLER Provides Significant Mass Savings

De-spinning and de-tumbling target objects is an integral part of currently proposed ARM and ADR architectures. The majority of current proposals for ARM and ADR involve the use of thrusters to apply a torque to the target object and reduce or eliminate its rotation. In order to characterize the efficacy and mass requirements of these proposals, we developed a MATLAB model simulating the use of thrusters to conduct de-spin operations. The inputs to this MATLAB model are: the diameter d, principal mass moments of inertia I, and initial angular velocity of the target object and the thrust T, and I_{sp} of the thrusters used.

Our MATLAB model resolves the initial conditions provided into an initial attitude quaternion q and initial body frame angular velocity vector ω of the target. The derivative of the target's attitude quaternion is given by the customary formula for the derivative of a quaternion,

$$\frac{dq(t)}{dt} = \frac{1}{2}\omega(t)q(t). \tag{6}$$

Euler's equations of rigid body dynamics under an applied torque,

$$\begin{bmatrix} \dot{\omega_1} \\ \dot{\omega_2} \\ \dot{\omega_3} \end{bmatrix} = \begin{bmatrix} \omega_2\omega_3(I_{22} - I_{33})/I_{11} \\ \omega_3\omega_1(I_{33} - I_{11})/I_{22} \\ \omega_1\omega_2(I_{11} - I_{22})/I_{33} \end{bmatrix} + \begin{bmatrix} \tau_1/I_{11} \\ \tau_2/I_{22} \\ \tau_3/I_{33} \end{bmatrix}, \tag{7}$$

are solved numerically to determine the angular acceleration vector $\dot{\omega}$. The torque provided by the thrusters is given simply by,

$$\tau = d\hat{r}\times\boldsymbol{T}, \tag{9}$$

where $\hat{r}$ is the unit position vector of the thrusters in the body frame and $\boldsymbol{T}$ is the resultant thrust vector of an optimal combination of thruster firings. Numeric integration of Equation (6) and Equation (7) and the thrusters mass flow rates,

$$\dot{m} = \frac{T}{I_{sp} g_0}, \tag{9}$$

is used to propagate the angular velocity of the target object and the mass used to de-spin the target. The thruster de-spin model was verified against both an analytical first order analysis and the results of ARM feasibility assessments including the Keck Institute for Space Studies *Asteroid Retrieval Feasibility Study*[3].

Utilizing our MATLAB model we determined the amount of propellant required to de-spin the prospective

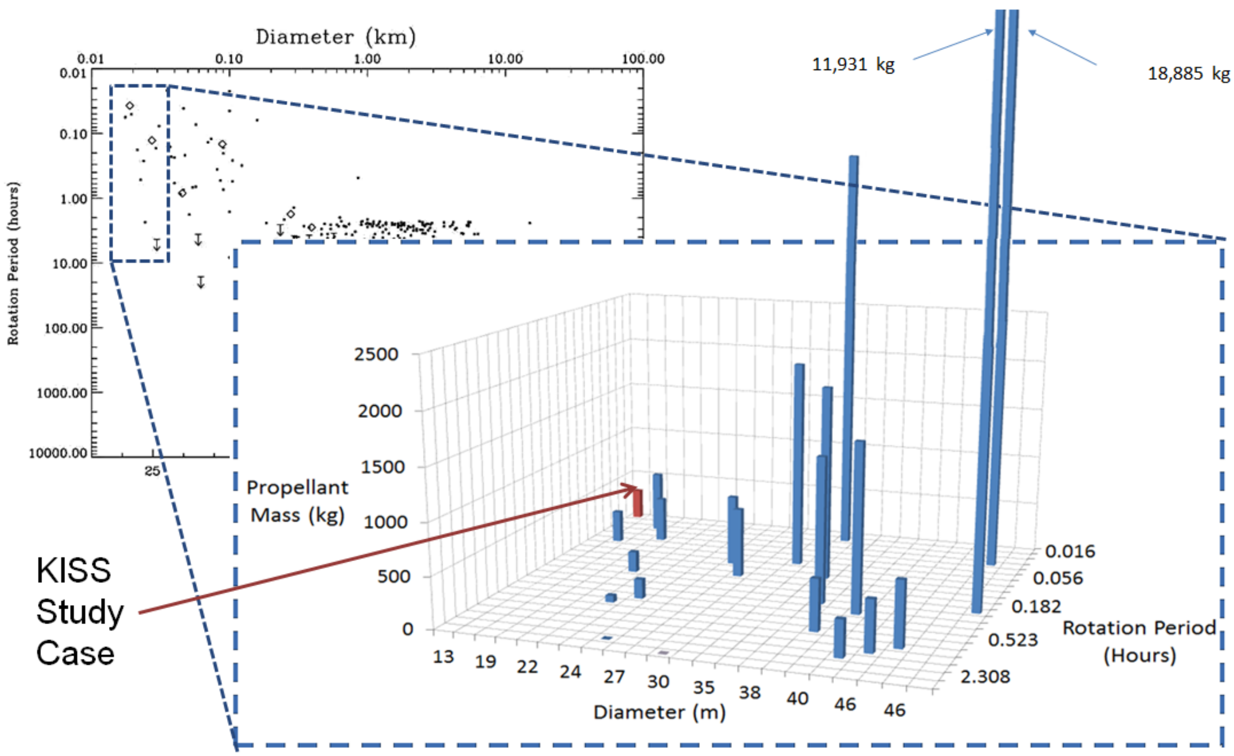

Figure 24. Propellant Required to De-Spin NEOs. *The majority of NEOs feasible for near future recovery require massive amounts of propellant to de-spin.*

NEO candidate objects highlighted in Figure 1 given their observed diameters and rotation periods. The analysis conducted assumed the objects were rotating about a single principle axis and have a uniform density of 2.8 g/cc. The same hypergolic bipropellant reaction control system, composed of 200N thrusters with a specific impulse of 278 s, baselined for the Keck Institute Study was chosen as the propulsion system. As can be clearly seen in Figure 24 the majority of NEO candidates require hundreds or thousands of kilograms of propellant to de-spin. The need to launch and transfer the required propellant plus an acceptable margin drives the mass and cost of mission architectures that rely exclusively on thrusters to de-spin and de-tumble their targets.

In contrast to the prohibitive mass required to de-spin a target using thrusters the WRANGLER system required to accomplish the same mission is orders of magnitude less massive. As previously discussed and shown in Figure 14 the mass of the tether scales with the tension force but remains relativity small (<10 kg) for even massive, quickly rotating NEOs. The remainder of the WRANGLER system excluding the GRASP capture mechanism, which scales as shown in Figure 21 but is not relevant to the mass required to de-spin the target, is composed of components of a fixed mass not subject to the size or rotation rate of the target. The mass of a WRANGLER system required to de-spin a target is therefore purely composed of a small fixed mass plus the mass of a tether strong and long enough to sufficiently de-spin the target.

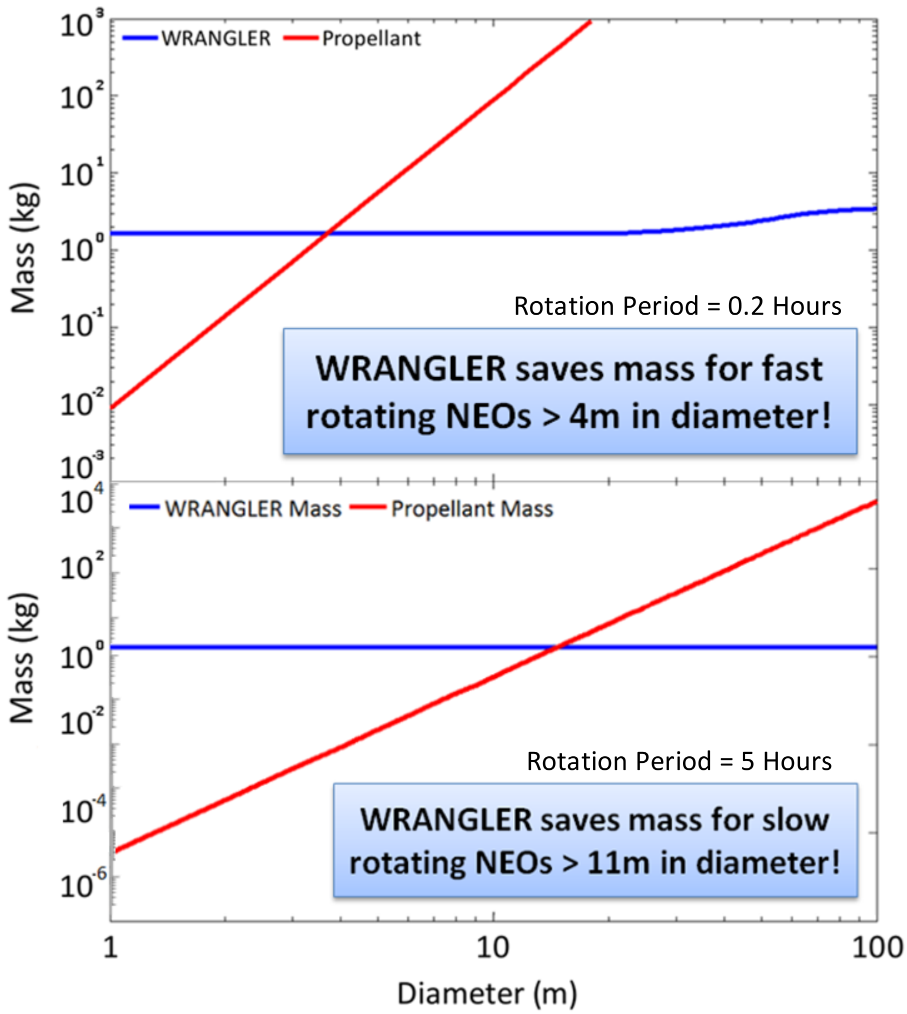

Figure 25. Comparison between a tethered WRANGLER system and the mass of propellant required to de-spin a target. *WRANGLER reduces de-spin mass requirement by orders of magnitude for large fast and slow rotators.*

Comparing the mass of propellant required to successfully de-spin candidate NEO targets with the mass of WRANGLER systems needed to conduct the same operations clearly demonstrates the potential of the WRANGLER concept. Figure 25 clearly shows that even comparing only the propellant strictly necessary to de-spin a target object to the mass of a commensurate WRANGLER system, WRANGLER provides mass advantages for objects larger than 4 meters. For objects greater than 10 meters wrangler provides order of magnitude mass savings compared to propellant intensive thrusting. Moreover, this result is likely overly-conservative since it does not consider additional propellant and tankage mass that would be required to provide an adequate safety margin. Figure 25 also demonstrates that these advantages hold for the main population of NEOs as well, indicating that WRANGLER can provide key advantages to future commercial space exploitation efforts.

5.2 WRANGLER Provides ARM Architecture Risk Reduction

In addition to providing orders of magnitude mass savings over current ARM architectures WRANGLER provides the potential to confer a significant reduction of risk to ARM and ADR missions. A free-flying WRANGLER system employing the GRASP capture technology, such as the one shown in Figure 26, fractionates the architecture for asteroid retrieval missions, allowing the required capture and proximity operations to be conducted by a small agile spacecraft. The use of a secondary spacecraft allows the primary mission spacecraft to stand-off during these high risk operations effectively mitigating the collision, contamination, and charging risks to large solar arrays and other sensitive spacecraft components.

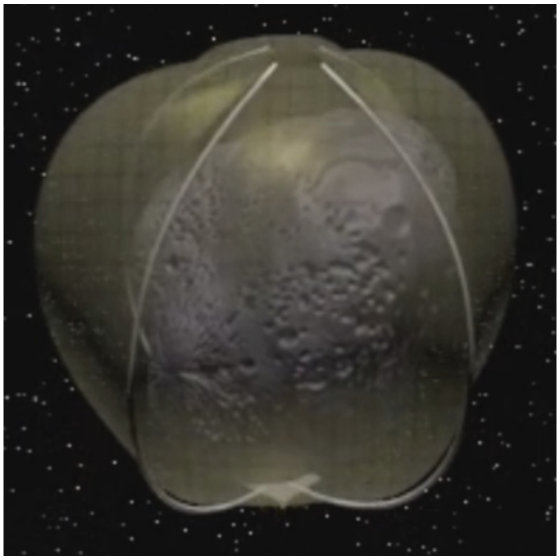

Figure 26. WRANGLER Capturing an NEO Ahead of a Primary ARM Spacecraft. *The WRANGLER architecture protects primary mission spacecraft from risks associated with capturing and de-spinning target objects*

Removing the primary spacecraft from the capture and de-spin operations not only mitigates the challenges posed by the unknown and potentially dangerous proximity environment but also simplifies the design of the primary spacecraft by eliminating the requirement for the spacecraft to handle the dynamic loading incurred during these operations. Current architectures have identified significant risks from torques induced during these operations to the large deployable solar arrays required for near future ARM missions. Folding booms, reinforced solar arrays, or similar methods for stowing or protecting solar panels during the capture and despin of targets have been proposed as potential strategies to mitigate the dynamic loading on the deployed spacecraft structures. While these methods may effectively mitigate the risk imposed by dynamic loading during capture and de-spin they inherently increase the complexity, and thereby the mass and cost of the required deployable structures. For example, the NASA/LaRC 300 kW Government Reference Array (GRA) is designed to sustain 0.1 gees, and this strength requirement drives the mass of its support structure.[9] If it did not need to sustain such high acceleration, the structural mass of the array could be reduced substantially, by factors of 2-10X, and this will translate into lower launch and life-cycle costs.[10]

In addition to increasing the mass and cost of the system the need for large foldable solar arrays induces risk due to the requirement for the deployment mechanisms to successfully actuate after years of exposure to the space environment during the transfer to the target and then redeploy after the de-spin has been completed. Long duration storage is a significant risk to any deployable technology and the foldable solar arrays baselined for current ARM architectures are no different. Even more risky than a deployment after a long period of storage is the requirement for the solar arrays to redeploy after conducting the required proximity operations. Failure of the solar arrays to redeploy would potentially lead to failure of the mission if insufficient power is generated to power the spacecraft's electric propulsion. Utilizing a small spacecraft, without multi-meter long deployable structures, that can be robustly constructed at low cost, WRANGLER effectively short-circuits the risks to the primary spacecraft imposed by the capture and de-spin dynamics by removing the primary spacecraft from the operations entirely.

5.3 WRANGLER Enables Small Satellite ADR Architectures

The parallels between the problems of asteroid retrieval and problems posed by potential ADR missions allows for the natural extension of ARM concepts and technologies to the ADR problem. As previously discussed the free-flying WRANGLER concept provides an extremely good baseline for a small satellite ADR architecture.

As demonstrated by Figure 7, a 7m Thor Agena D SLV-2 rocket body massing 670kg in an 800km near circular orbit at an inclination of 99° provides a suitable representative piece of debris for demonstrating the suitability of the free-flying WRANGLER architecture. A 15m GRASP system sized to capture such a rocket body would mass 6.5 kg and pack into a 6U volume. Furthermore, based on a ΔV budget of 490 m/s for the nanosatellite to maneuver to the rocket body and 160 m/s to deorbit both the nanosatellite and target[11] a HYDROS propulsion system would require 53kg of water propellant. Utilizing these sizing estimates Table 3 provides a conservative mass budget for a representative ADR system based on the free-flying WRANGLER architecture. Such a system would easily meet the mass and volume criteria for an ESPA class payload. Larger objects can also be targeted by scaling the GRASP system, as shown in Figure 21, and the amount of propellant carried, as shown in Figure 27.

Component	Mass (kg)
Structure & Mech.	15
GRASP	6.5
Propulsion & Fuel	58
Avionics & Batteries	4.5
Tether & Deployer	0.2
TOTAL	**84.2 kg**

Table 3. Mass Budget for WRANGLER ADR System.

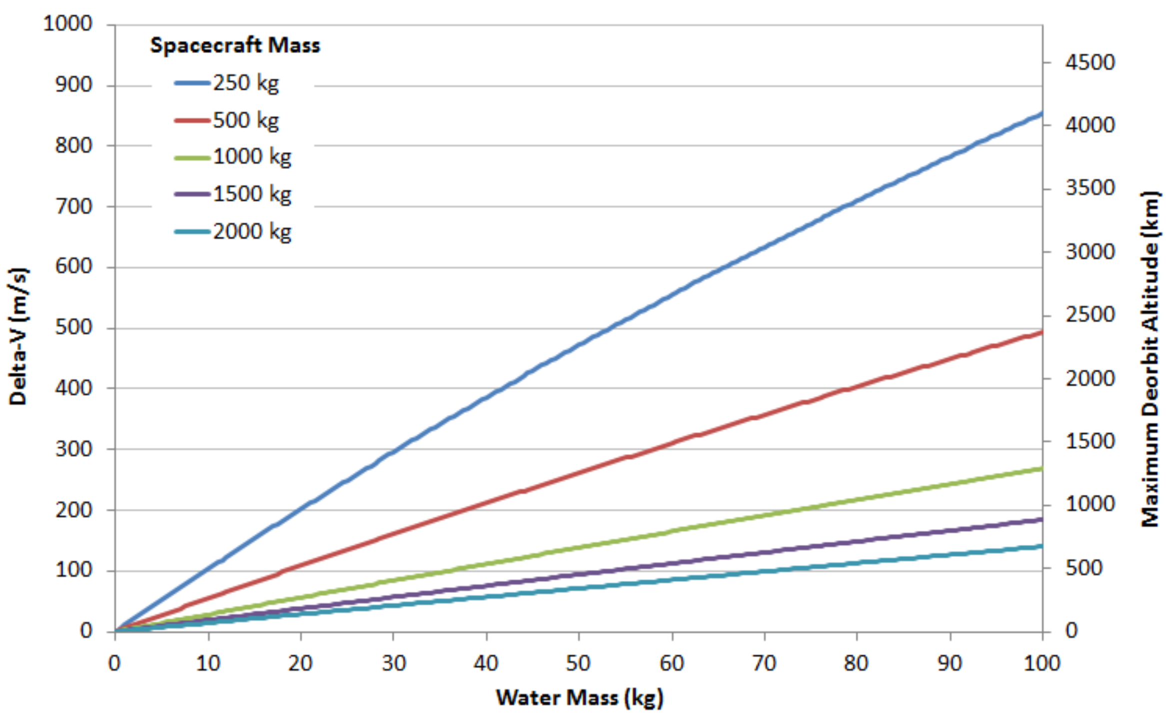

Figure 27. HYDROS Deorbit Performance Across a Range of Target and Water Masses. *Small ADR systems utilizing the HYDROS thruster*

6. Evaluation of Technical Maturity and Risks

6.1 Component Technology Technical Maturity

The component technologies of the WRANGLER system are predominantly “mid-TRL” to “high-TRL”. Table 4 provides a list of the key component technologies for the WRANGLER system, their TRL, and provides a summary of the justification of the TRL. In particular the technologies required for an integrated 2U WRANGLER de-spin system are almost all flight qualified and could be integrated quickly if needed. The technologies requiring the most development in order to mature them to flight readiness are the control algorithms required to control the deployment of the tether. Although these algorithms have been demonstrated in simulation, a concerted development effort is required to develop robust flight qualified software compatible with the onboard avionics. Additionally, the multiple technologies required for the free-flying WRANGLER concept will require a significant effort to integrate and validate.

Table 4. Technical Maturity of WRANGLER Component Technologies.

Component	TRL	Justification
Tether	5	• Prototypes of equivalent tethers fabricated under contract NNM04AA40C & tested under AO/UV exposure at NASA/MSFC SEE facility. • Tether samples flown in ISS space environment on MISSE-6 • Tether material survived 10 tears on orbit in TiPS mission
Tether Deployment Hardware	7	• Tether deployer and spool hardware flew as part of the MAST experiment, and equivalent larger deployers flew in SEDS 1 & 2
SWIFT-RelNav	6	• RelNav sensor demonstrated with prototype hardware using ISM S-Band frequencies in contract W31P4Q09C0272
GRASP	5	• Successfully conducted validation testing of prototype in zero-g environment.
HYDROS Propulsion System	5	• Integrated HYDROS propulsion system units have undergone successful validation testing at the Air Force Institute of Technology.
Host Integration	3	• The AeroCube 3 and TiPS missions successfully integrated and demonstrated tether deployment hardware from small satellite platforms
Flight Software	3	• The necessary tether control algorithms have been demonstrated in simulation (TetherSim, MATLAB)

6.2 Technical Risks

Although much of the technology required for the execution of the WRANGLER concept is technically mature there remain a number of key technical risks. Future efforts will be required to systematically address these risks in order to eliminate or mitigate them.

6.2.1 Tether Deployment Failure

Failure of the tether to properly deploy is the most significant risk to the WRANGLER concept. Although 75% of space tether missions have been completely successful including: SEDS-1, SEDS-2, Plasma Motor Generator, OEDIPUS-A, OEDIPUS-C, TiPS, AeroCube-3, and the JAXA T-REX experiment, a handful of failures among high profile tether missions have given tethers a reputation as a problematic technology. The failures of tether missions when they have occurred, most notably TSS-1 and TSS-2, have been a result of problems in the engineering process not problems associated with the fundamental physics of tethers. As with all space hardware, proper engineering and testing must be conducted to ensure tethered systems can function with high reliability.

WRANGLER will utilize legacy hardware in addition to systematic simulation and testing in order to reduce the risks associated with failure of the tether deployment. The MAST tether deployment hardware to be incorporated into the WRANGLER nanosatellites utilizes a simple "end-off" tether spool. The corresponding tether deployer from the MAST mission will be used by WRANGLER to control the deployment rate and thereby the dynamics of tether during deployment. Similar spools on the SEDES-1, SEDS-2, PMG, and TiPS missions were used to successfully deploy tethers on-orbit and deployment rate control schemes were successfully used by the SEDS-2[8] and TiPS[12] experiments to minimize the dynamic behavior of the tether. However unlike the SEDES-1, SEDS-2, PMG, and TiPS missions where initial deployment of the tether was provided by imparting an initial velocity to the tethered satellite the initial deployment of the WRANGLER nanosatellite must be slow and controlled to avoid excessive libration of the tether. Extensive simulation of the dynamics of the initial deployment together with extensive testing of the deployment hardware will be used to mitigate the risks imposed by this critical phase of the WRANGLER CONOPS.

6.2.2 Excessive Capture Dynamics

One of the most unknown and therefore most difficult to quantify risks for asteroid capture operations is the dynamic challenges posed by the physical capturing of the target object. TUI's GRASP technology like the majority of currently proposed ARM architectures utilizes a bag to encapsulate the target before using a drawstring mechanism to quickly close the bag and cinch the system down onto the asteroid. Excessive dynamic interaction between the capture mechanism and the asteroid is avoided by designing the characteristic time of the capture operation to be much shorter than the rotational period of the asteroid. A sufficiently short capture time should allow the capture mechanism to securely grab the asteroid and eliminate any relative motion without excessive 'scrubbing' of the asteroid surface by the bag or the imposition of unwanted dynamic loads to the nanosatellite.

TUI has developed a visualization tool, shown in Figure 28, to help quantify design, control, and deployment challenges associated with capturing an asteroid. The visualization tool was constructed using the Blender open-source professional 3D graphics software package. The semi-physical tool models both the semi-rigid body interactions of the GRASP arms and the soft body interactions of the GRASP bag. While the tool is helpful for some visualization such as the behavior of the bag with respect to the motion of the arms, many aspects of the tool are not yet driven by representative model of the physics of the interaction. An extensive effort to better simulate the capture dynamics either through analytical modeling or physical testing will be required to mitigate the risk posed by excessive capture dynamics.

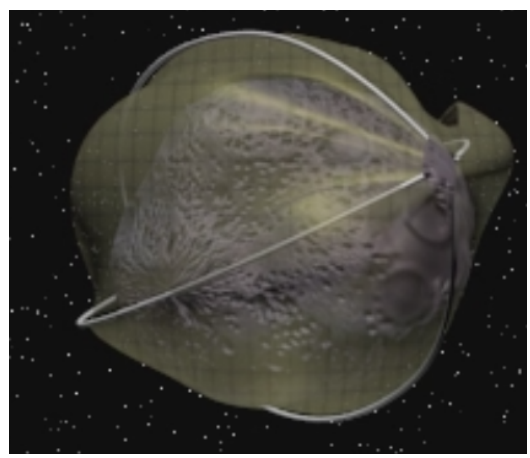

Figure 28. TUI's Asteroid Capture Visualization Tool. *Visualization allows for identification of design, control and deployment challenges.*

Frustrating better simulation and validation efforts is the unknown nature of the composition and physical properties of NEO surfaces and even the degree to which small NEOs are consolidated. Due to these uncertainties, the best approach to mitigating the risks associated with asteroid capture may be the design of a robust capture system coupled with extensive ground testing to validate its effectiveness over a wide range of possible targets. Future development of WRANGLER concepts will seek to mitigate the impact of unwanted dynamic interactions on the nanosatellite systems by designing concepts to protect the system from unwanted loading. These may include the use of airbags to protect WRANGLER from contact with the target and unwanted displacements or the introduction of compliance in the connection between the GRASP system and WRANGLER to help isolate the nanosatellite from the dynamics of asteroid capture.

6.2.3 Contact Between the Tether and Target Object

As previously discussed a significant risk for tethered de-spin missions is excessive libration of the tether causing the tether to impact the target. Contact with the target object must be avoided to mitigate the risks of severing or fouling of the tether. The uncontrolled nature of WRANGLER's targets limits the possible options to mitigate this risk. The most feasible solution is the implementation of a control scheme to manage the tether tension by varying the deployment rate of the tether. Deployment rate based control schemes have been successfully implemented on the SEDS-2 and TiPS missions to control the dynamics of the tether deployment. TUI has validated this control method for the WRANGLER system though extensive simulation using the TetherSim software. While this method has been shown both in practice and in simulation to be feasible and effective, development of a robust control method for flight hardware will require a significant investigation and design effort. An alternative approaches include the possible use of multiple tether attachment points or a boom or similar mechanism to move the tether attachment point away from the surface of the object. These methods sacrifice some of WRANGLER's inherent value by requiring a larger more complicated system and have not been fully investigated through simulation.

6.2.4 Micrometeoroid Impact Risks

Although the tether used by the WRANGLER system is extremely thin it is also many kilometers long. When fully deployed the tether will be at least 10 km long and such a deployment will likely take on the order of a week to complete. The length, exposure time, and potential fragility of the tether raise concerns of the possibility of the tether being severed by an impact. A WRANGLER system deployed to de-spin an asteroid will be exposed to both the interplanetary micrometeoroid flux and the environment in proximity to the target object. While interplanetary micrometeoroids pose distinct risks to the survival of the tether, particles in a vicinity of the asteroid will have relatively low velocities with respect to the surface of the target object and should not pose a danger to tether as they might to large solar arrays or other more delicate hardware.

In order to understand the risk posed to the tether by micrometeoroid impacts the flux of particles that will be seen by the tether during a WRANGLER deployment must be determined. For the ARM use case the interplanetary micrometeoroid flux is the sole source of potential collision objects. ADR missions operating in the LEO orbital debris environment must consider the man-made debris flux as well and have a correspondingly higher risk of impact and subsequent tether damage. The Grün micrometeoroid flux model, shown in Figure 29, represents the best model of the interplanetary micrometeoroid environment for typical NEO orbits of 0.9-1.4 AU[13]. A minimal WRANGLER tether is composed of 12 monofilament strands of Dyneema SK-75 arranged in an impact resistant Hoytether structure. The Hoytether structure is composed of 4 strands braided into 1 m lengths fail safe lengths which isolate damage in each length from the rest of the tether. Each strand of the tether is composed of three monofilliamant strands braided together with a diameter of 0.0431 mm presenting a cross sectional area of 0.431 m^2. The entire Hoytether structure has a diameter of approximately 0.104 mm and presents a cross sectional area of approximately 1.04 m^2. Assuming a lethality coefficient of 3, each strand can be cut by an impactor 0.014 mm in diameter or larger. However in order for the tether to fail from multiple impacts all four of the strands would need to be cut. The entire tether can be cut by a particle approximately 0.035 mm or larger. Using the cumulative flux from the Grün model[14] and multiplying by the strand area the total rate of cuts to each strand, c_s, is 2.32x10^{-8} per day and the rate of cuts to the tether, c_t, is 2.06x10^{-4} cuts per day. The probability of survival of the tether for the 5 day estimated mission duration, t, of 5 days is,

$$S(t) = e^{-c_t t}(1-(1-e^{-c_s t})^4)^{10000} \approx 99.90\%. \quad (10)$$

Although 9.28x10^{-4} strands are expected to be cut each day the Hoytether structure limits the damage caused by these cuts to the local 1 m length and prevents these cuts form jeopardizing the integrity of the remainder of tether. As demonstrated by Equation (10) a Hoytether is almost guaranteed to survive the 5 days length of the WRANGLER mission.

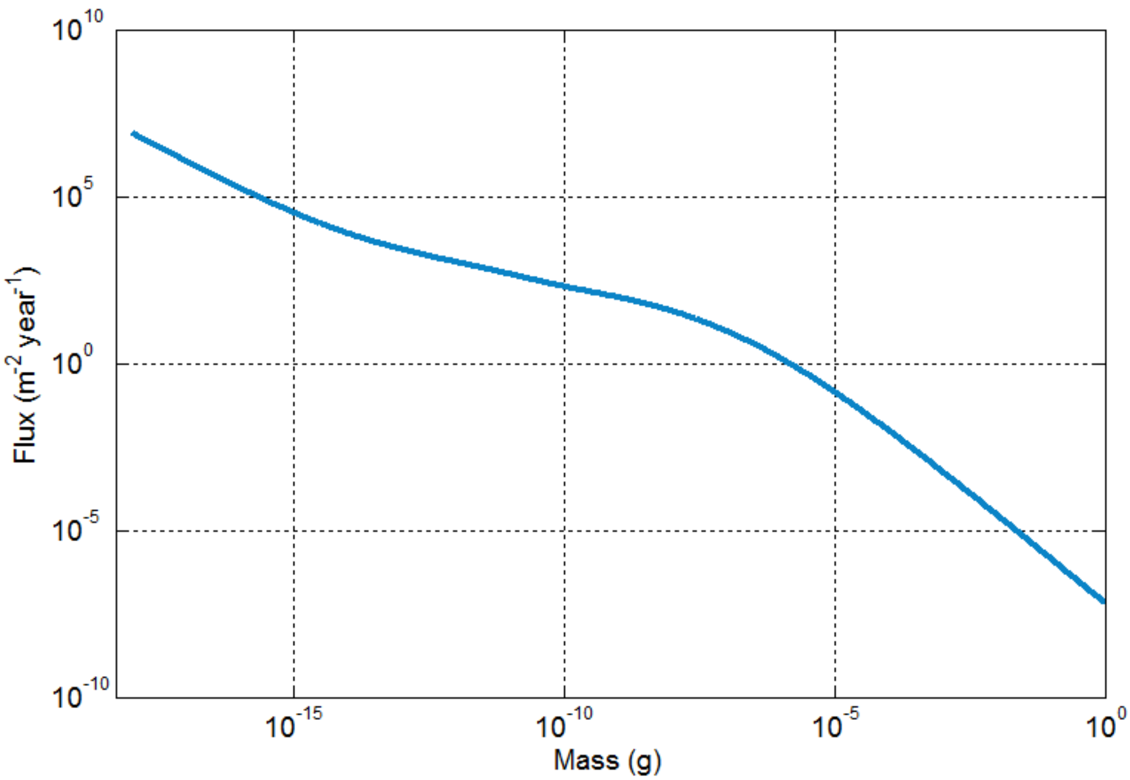

Figure 29. Grün Interplanetary Micrometeoroid Cumulative Flux.

7. Technology Maturation Plan

As demonstrated in Table 4 the majority of the component technologies required for the successful execution of the WRANGER concept are already mid- to high-TRL. The key technological developments that must be made before the concept is ready for flight demonstration are in the areas of the tether control scheme and integration into a suitable host platform. The tether deployment is the highest risk component of the mission architecture and additional simulation, control algorithm development, and software implementation are need to mature the deployment and control technology to a level appropriate for a enabling WRANGLER operations. Additionally, TUI must conduct a concerted effort to mature the design of the WRANGLER concepts to the point where they can be integrated into relevant host platforms for flight demonstration missions.

TUI has developed a technology maturation plan for the WRANGLER concept, shown in Figure 30, which illustrates a roadmap for integration of WRANGLER into future ARM and ADR missions. The Phase II NIAC effort will focus on developing parallel concepts for both integration with future asteroid retrieval, redirect, and exploitation missions and nanosatellite scale ADR systems. These integration efforts will both mature the existing conceptual architecture and hardware designs and seek to identify and incorporate appropriate host platforms for both the ADR and ARM efforts. In addition a Phase II NAIC effort will continue the analysis effort necessary to develop the control laws and flight hardware needed to effectively perform a de-spin of a target object. A Phase II NIAC effort coupled with ongoing SBIR and commercial development of key component technologies will place the WRANGLER system in a suitable position for flight testing under NASA's Game Changing Development and Small Satellite Technology programs. An effective flight demonstration effort would serve to validate the WRANGLER concept and could be used to demonstrate WRANGLER's potential for both gaining effective control of massive uncontrolled objects and its potential for a small satellite ADR platform.

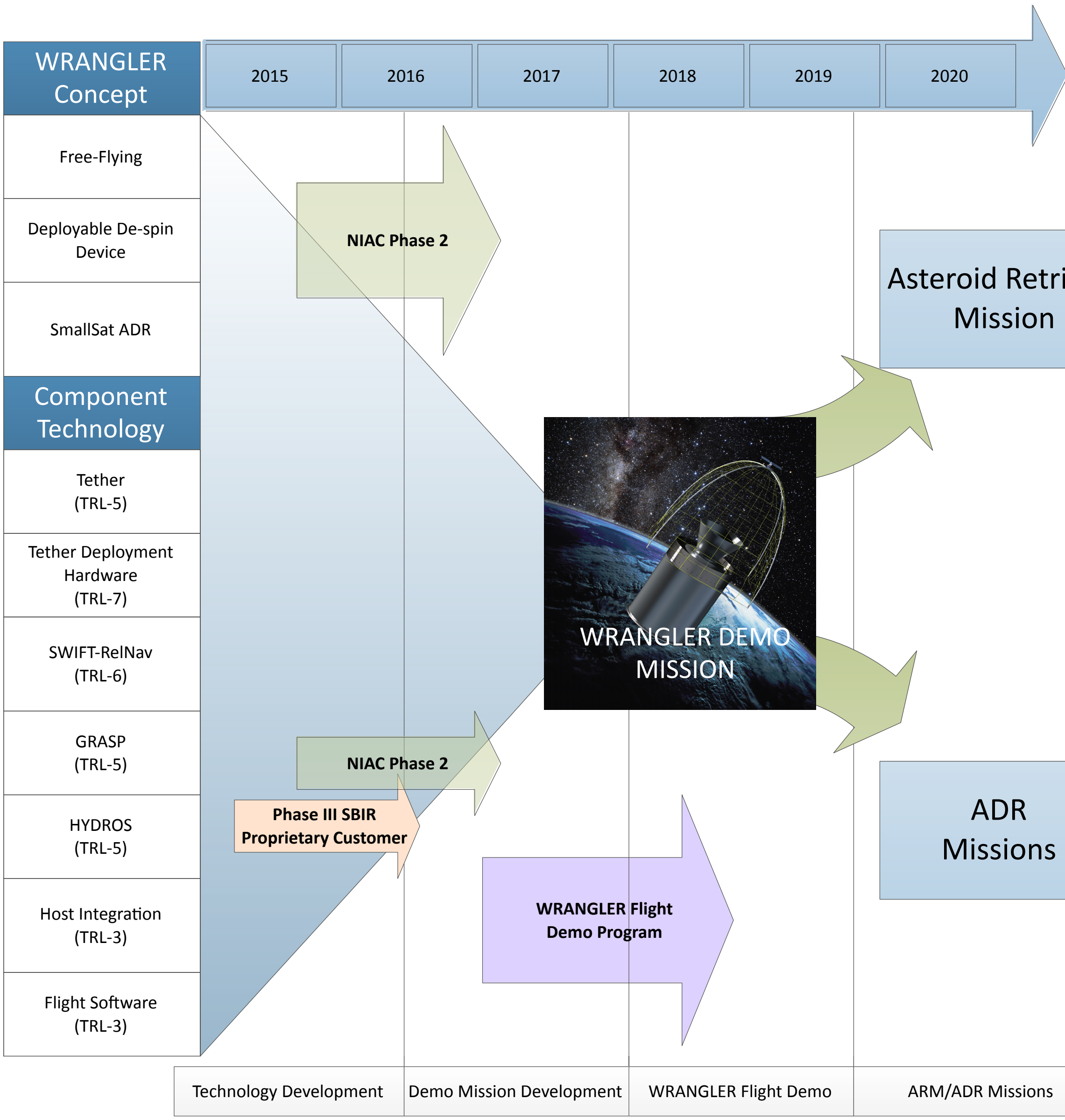

Figure 30. WRANGLER Technology Maturation Plan *Phase II NIAC efforts will position the WRANGLER concept for a flight demonstration mission and transition to operational missions.*

8. Conclusions

In the Phase I WRANGLER effort TUI has demonstrated the feasibility and value of the WRANGLER concept to future ARM and ADR efforts. Through intensive simulation efforts we have demonstrated that tethers deployed from even the most massive "fast rotators" are effective at achieving adequate reductions of the target's body rates and can be controlled through the implementation of simple and proven control laws and tether deployment hardware. Utilizing the results of this effort, we have developed two WRANGLER system architectures capable of serving a variety of existing ARM and ADR CONOPS: the first a small 2U nanosatellite used simply as a means of de-spinning the target and the other a larger free-flying nanosatellite used to both capture and de-spin the target object. Detailed conceptual designs of both architectures have been used to demonstrate the significant mass savings afforded by the WRANGLER concept when compared to the use of propellant intensive thrusting schemes. Furthermore, fractionation of the mission architectures by using a tethered nanosat for capture and de-spin can signficantly reduce the risks and requirements imposed on large primary mission spacecraft. The technologies required to provide the benefits of the WRANGLER system are all hardware of mid- to high-TRL. TUI's evaluation of the technology readiness of the concept indicates that a WRANGLER system that has the potential to provide order-of-magnitude performance improvements can be designed and integrated with minimal effort and modest investment. While the remaining risks of the WRANGLER system are non-trivial, they are well understood and have clear and proven mitigation strategies that can be implemented with the proper engineering effort. WRANGLER provides significant benefits to ARM, ADR and future commercial space resource development efforts by replacing hundreds or thousands of kilograms of propellant with a small, low-mass, low-cost system capable of enabling space systems to safely gain control of large space objects.

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