NanoTHOR: Low-Cost Launch of Nanosatellites to Deep Space

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Currently, opportunities to launch secondary payloads to Earth escape are rare, and using chemical rockets to propel secondary payloads from LEO rideshares to escape is problematic due to the risks posed to primary payloads. The NanoTHOR effort has explored the technical feasibility and value proposition for using a simple momentum-exchange tether system to scavenge orbital energy from an upper stage in geostationary transfer orbit in order to boost nanosatellites to Earth escape. A NanoTHOR module will accomplish rapid transfer of a nanosatellite to an escape trajectory by deploying the nanosat at the end of a long, slender, high-strength tether and then using winching in the Earth's gravity gradient to convert orbital angular momentum into rotational angular momentum. In the Phase I effort, we developed and simulated methods for controlling tether deployment and retraction to spin up a tether system, and these simulations demonstrated the feasibility of providing delta-Vs on the order of 800 m/s with a simple, low-mass tether system. Moreover, the NanoTHOR tether can act as a reusable in-space upper stage, boosting multiple nanosatellites on a single launch and doing so with a mass requirement lower than that of conventional rocket technologies. Serving as an escape-injection stage, NanoTHOR can enable a 6U CubeSat to deliver small payloads to Mars orbit, lunar orbit, and rendezvous with at least 110 of the known near-Earth asteroids. Evaluation of the technology readiness of the component technologies required for NanoTHOR indicate that the hardware required is all mid-TRL, and the lower-TRL controls and integration components can be advanced to mid-TRL with modest investment. By scavenging orbital energy from upper stages without any stored energy or propellant requirements, NanoTHOR permits deep-space nanosat missions to launch on rideshare opportunities, enabling NASA and commercial ventures to conduct affordable and frequent missions to explore deep space destinations.

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ABSTRACT

The rapid development of high-performance nanosatellite platforms is enabling NASA and commercial ventures to consider performing missions to the asteroids, the Moon, and Mars at lower cost and on shorter timelines than traditional large spacecraft platforms. Currently, however, opportunities to launch secondary payloads to Earth escape are rare, and using chemical rockets to propel secondary payloads from LEO rideshares to escape is problematic due to the risks posed to primary payloads. The NanoTHOR effort has explored the technical feasibility and value proposition for using a simple momentum-exchange tether system to scavenge orbital energy from an upper stage in geostationary transfer orbit in order to boost nanosatellites to Earth escape. A NanoTHOR module will accomplish rapid transfer of a nanosatellite to an escape trajectory by deploying the nanosat at the end of a long, slender, high-strength tether and then using winching in the Earth's gravity gradient to convert orbital angular momentum into rotational angular momentum. In the Phase I effort, we developed and simulated methods for controlling tether deployment and retraction to spin up a tether system, and these simulations demonstrated the feasibility of providing delta-Vs on the order of 800 m/s with a simple, low-mass tether system. Moreover, the NanoTHOR tether can act as a reusable in-space upper stage, boosting multiple nanosatellites on a single launch and doing so with a mass requirement lower than that of conventional rocket technologies. Serving as an escape-injection stage, NanoTHOR can enable a 6U CubeSat to deliver small payloads to Mars orbit, lunar orbit, and rendezvous with at least 110 of the known near-Earth asteroids. Evaluation of the technology readiness of the component technologies required for NanoTHOR indicate that the hardware required is all mid-TRL, and the lower-TRL controls and integration components can be advanced to mid-TRL with modest investment. By scavenging orbital energy from upper stages without any stored energy or propellant requirements, NanoTHOR permits deep-space nanosat missions to launch on rideshare opportunities, enabling NASA and commercial ventures to conduct affordable and frequent missions to explore deep space destinations.

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NanoTHOR scavenges orbital energy from rocket stages to deliver nanosatellites into Earth-escape trajectories using ride-share launches, enabling frequent and affordable interplanetary nanosat missions.

1. INTRODUCTION

1.1 MOTIVATION - THE LAUNCH CHALLENGE FOR INTERPLANETARY NANOSATS

The development of the CubeSat standard and other nanosatellite technologies is enabling many organizations to conduct a wide range of space missions at significantly lower cost and on shorter timelines than traditional large spacecraft platforms. Ongoing development of CubeSat and nanosat buses with high power and processing capabilities, high-bandwidth communications, and maneuvering propulsion could enable these low-cost platforms to play a significant role in both NASA and commercial efforts to explore Near-Earth Objects, Mars, and the Moon. Currently, however, opportunities for secondary rideshare launches into deep space trajectories are exceedingly rare. Limitations upon stored energy imposed by primary payload safety considerations make integration of high-thrust rockets onto secondary payloads highly problematic, and the cost of dedicated launches to escape would negate the cost advantages of such small satellite platforms. Furthermore, while electric propulsion technologies can mitigate the safety challenges of providing propulsion for a secondary payload, they require months-long durations to transfer a spacecraft from Earth orbit to escape due to their very low thrust levels.

1.2 THE NANOTHOR CONCEPT

The "Nanosat Tethered High-Orbit Release" (NanoTHOR) Module will enable frequent, affordable opportunities to deploy nanosatellites to destinations beyond Earth orbit by providing a means to launch small satellites into Earth orbit as secondary payloads and then deliver them promptly to escape trajectories by scavenging the orbital energy of the launch vehicle's upper stage. Figure 1 illustrates the concept of operations for NanoTHOR. The NanoTHOR module will be integrated along with one or more nanosatellites as secondary payloads on an upper stage rocket used to launch a satellite to geosynchronous orbit (GEO). After the rocket has completed its primary mission, the NanoTHOR module on the upper stage in geostationary transfer orbit (GTO) will deploy the nanosatellite at the end of a thin but high-strength,

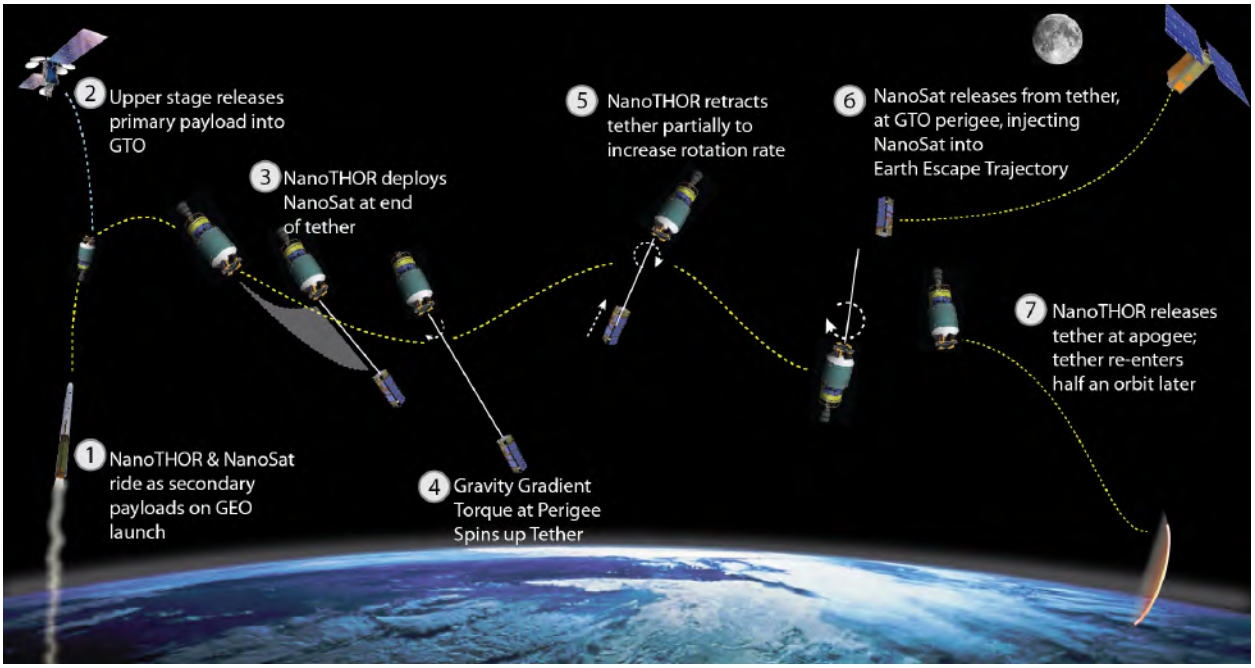

Figure 1. NanoTHOR concept for tossing a nanosatellite to an escape trajectory by scavenging orbital energy from an upper stage. *The NanoTHOR system requires only tether deployment and retraction to spin up the tether system to provide nearly 800 m/s of* ΔV *to the nanosatellite.*

multi-kilometer long tether. Then, using only deployment and retraction of the tether, the NanoTHOR module will spin up the system until the tether is rotating fast enough to toss the nanosatellite into an escape trajectory. NanoTHOR boosts the nanosatellite by a ΔV of almost 800 m/s using only a winch and a tether, transferring hundreds of megajoules of orbital energy from the upper stage to the nanosatellite without requiring any stored energy that could pose a threat to a primary payload during launch. Furthermore, the tether is re-usable, and can be used to toss multiple nanosats per flight, and this re-usability enables it to be mass competitive with conventional monopropellant thrusters for boosting as few as 2-4 nanosats per mission.

1.3 SUMMARY OF THE EFFORT

The objective of our Phase I effort was to develop a detailed concept design for the hardware and concept-of-operations for a NanoTHOR module, and use analysis and simulation to evaluate the feasiblity and value proposition of the concept relative to current state-of-the-art technologies. As we proposed to do, we first used spreadsheet-based tools to develop a preliminary system sizings for candidate nanosatellite platforms, and then used detailed, physics-based simulations to evaluate the feasibility of spinning up the tether and then tossing the nanosatellite to the desired escape trajectory. We investigated two different methods for spinning up a tether in a highly elliptical geostationary transfer orbit (GTO), one using scavenging of residual propellant left over on the upper stage, and the other using tether winching to scavenge orbital energy from the system. We also developed concept methods for spinning up a NanoTHOR tether in a circular LEO orbit and using it to either toss a nanosatellite to a higher LEO orbit or to an orbit with a different inclination. We then developed concepts for performing multiple nanosatellite toss maneuvers from a single NanoTHOR system to enable deployment of nanosat flotillas. We then developed preliminary designs for two NanoTHOR modules, one sized for 10 kg nanosats (such as 6U CubeSats), and one sized for 30 kg nanosats. We evaluated Size, Weight, and Power (SWaP) requirements for these modules, developed estimates for system cost, and compared its net ΔV-performance-per-mass to conventional technologies such as solid motors or bipropellant rockets. Finally, we identified key technology risks developed a plan for technology maturation in a Phase II effort and flight-test validation in follow-on efforts.

2. NANOTHOR CONOPS DEVELOPMENT & ANALYSIS

The NanoTHOR system concept involves (1) deploying a payload at the end of a multi-kilometer long tether, (2) inducing the tethered system to rotate rapidly in the plane of the system's orbit, and then (3) releasing the payload at a controlled time in order to inject it into an escape trajectory. The first and third steps, deployment and momentum-exchange release, have been demonstrated in previous space tether flight experiments, and thus are relatively mature aspects of the concept. Both the SEDS-1 and SEDS-2 experiments successfully deployed 20-km long non-conducting tethers made of Spectra® yarn from Delta-II upper stages, and the SEDS-2 experiment demonstrated control of the tether deployment to minimize dynamic behavior of the tether after deployment. The SEDS-1 mission intentionally released its tethered payload from the upper stage, and the resulting momentum exchange dropped the payload into a re-entry trajectory. The second step of the NanoTHOR system concept, that of controllably spinning up a tether system to a high tip velocity, has not yet been demonstrated in space, and thus represents a key issue for establishing the feasibility of the NanoTHOR system.

Several space tether propulsion concepts rely upon rotation of a multi-kilometer long tether system, including Moravec's "Lunavator",[1] the "Momentum-Exchange/Electrodynamic-Reboost" (MXER) proposed by TUI,[2,3] and the EDDE system proposed by Star Inc.[4] However, little work has been published discussing the challenge of setting a long space tether system into rotation. Spin-up of a long tether system is challenging for two reasons. First, the multi-kilometer lengths result in extremely large moments of inertia, requiring substantial torques for long durations to achieve significant rotation rates. Spinning up the system prior to tether deployment can help to initiate rotation, but it is not sufficient because the scaling of the moment of inertia with the square of the tether length means that astronomical pre-deployment spin rates would be required to produce a significant rotation rate after deployment of a multi-kilometer tether. Second, if the tether is in orbit around the Earth or another planetary body, gravity gradient forces make the dynamic behavior of a long, flexible structure very complex and potentially uncontrollable during slow rotation. Specifically, during the initial transition from a vertically oriented, gravity-gradient stabilized configuration to a rotating configuration, as the tether rotates up towards a local-horizontal orientation, the gravity gradient force vanishes. Unless the tether is rotating fast enough to maintain centrifugal tension on the system, the tether can become slack, resulting in difficult-to-predict and difficult-to-control longitudinal and transverse oscillations. Therefore the initial transition from hanging to rotating must be performed relatively rapidly – within substantially less than one quarter of an in-plane libration period – in order to maintain a predictable dynamic state.

In prior work to develop the MXER concept, we investigated the use of electrodynamics thrusting to spin up a tether system.[5] While electrodynamic spinup is viable for MXER systems in low Earth Orbit (LEO) orbits, in the GTO orbit contemplated for NanoTHOR, the system spends only about 20 minutes a day at the LEO altitudes where the ionosphere and magnetic field are both sufficiently robust for efficient electrodynamic thrusting. Consequently, relying upon electrodynamic thrust for spin up would require ei-

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1. Moravec, H., "A Non-Synchronous Orbital Skyhook," *Journal of the Astronautical Sciences.*, 25(4), Oct-Dec 1977, pp. 307-322.
2. Hoyt, R.P. and Uphoff, C.W., "Cislunar Tether Transport System," *J. Spacecraft and Rockets*, 37(2) March-April 2000, pp. 177-186.
3. Hoyt, R.P., Slostad, J.T., Frank, S.S., "A Modular Momentum-Exchange/Electrodynamic-Reboost Tether System Architecture," AIAA Paper 2003-5214, *2003 AIAA Joint Propulsion Conference*.
4. Pearson, J,. Carroll, J., and Levin, E., "Active Debris Removal: EDDE, the ElectroDynamic Debris Eliminator," Paper IAC-10-A6.4.9, *61st International Astronautical Congress*, Prague, Czech Republic, 27 Sep-1 Oct 2010.
5. Hoyt, R.P., "Cislunar Tether Transport System," NIAC Phase I Report on Contract 07600-011, 1999.

ther a relatively long duration (several months) or a prohibitively large power system to accelerate the nanosat payload to the ~775 m/s required.

For NanoTHOR, we have investigated two alternative means for spinning up the tether system. Both methods would provide rotational energy to the system by scavenging resources from the upper stage. The first method would involve "propellant scavenging" by using the upper stage's residual propellant and thrusters. The second would accomplish "orbital momentum scavenging" using winching of the tether. As discussed below, we found that the propellant scavenging method by itself is not an efficient means for tether spin-up, but the winching based method can accomplish spin-up in an efficient manner. We then considered combining the two methods, and found that this combination could provide interesting capabilities, especially in applications of NanoTHOR to launch of LEO nanosatellites.

2.1 ANALYSIS OF PROPELLANT-SCAVENGING-BASED SPIN-UP

The first CONOPS investigated for NanoTHOR involved deploying the nanosatellite at the end of a 5-km long tether and then having the upper stage perform thrust maneuvers to set the system into rotation. These thrust maneuvers could be performed by the stage's primary motor burning residual propellant, by the stage's attitude-control thrusters, or perhaps by simple cold-gas blowdown of residual propellant. Note that using the stage's primary motor would require one or more re-starts of that rocket, which would be a not-inconsequential impact to most launch vehicles' operations. Figure 2 illustrates the NanoTHOR concept of operations (CONOPS) using the stage's attitude-control thrusters to spin up the tether system.

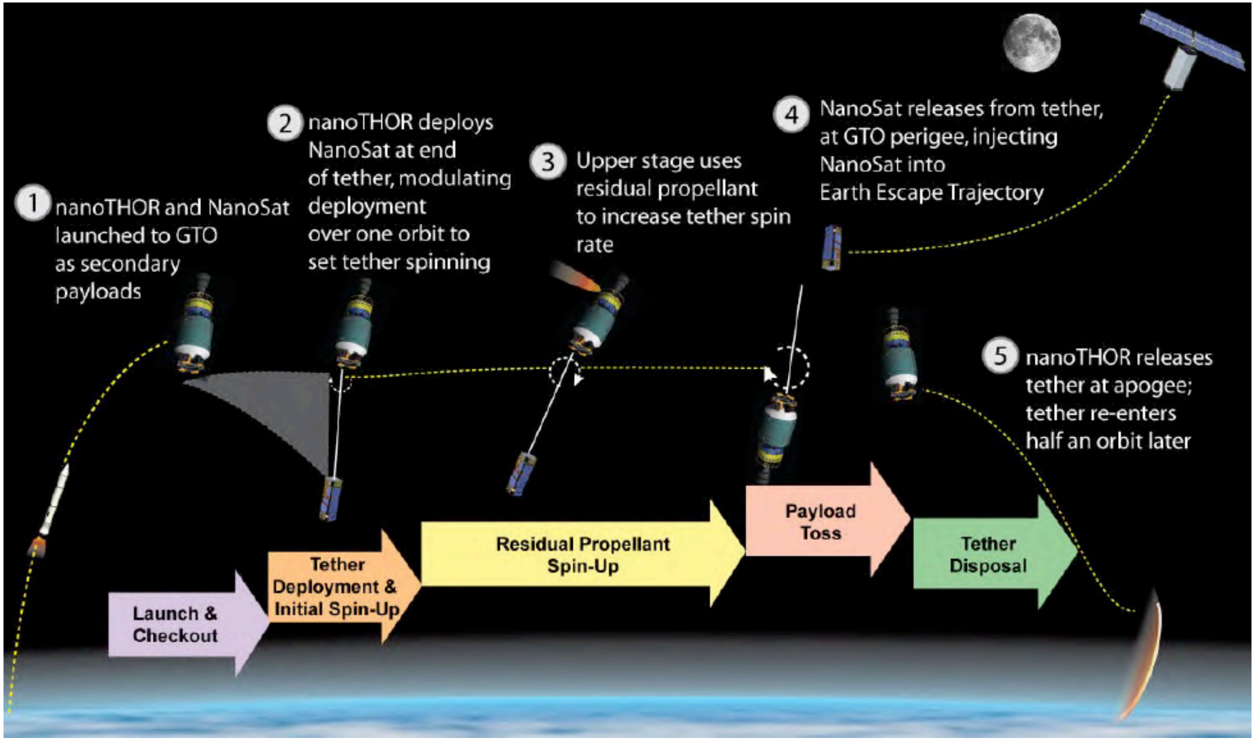

Figure 2. NanoTHOR CONOPS using thrusting by the upper stage to spin up the tether system. *NanoTHOR could 'scavenge' residual propellant on the upper stage to spin up the system.*

Using our TetherSim code, which models tether dynamics, orbital mechanics, and spacecraft attitude dynamics, we tested several approaches to using rocket thrusting by the upper stage to spin up the tether system, including short, high-thrust maneuvers by the primary motor, moderate thrust levels by attitude control thrusters, and long-duration, low thrust by cold-gas propellant blow-down. We investigated both thrusting perpendicular to the tether with a constant thrust level and thrusting back along the tether with an increasing thrust magnitude. Figure 3 shows a screen capture from one such simulation. The simulations revealed that maintaining dynamic stability of both the tether and the upper stage would require active control of the thrust level and vector, because the stage will tend to accelerate rotationally at a different rate than the tether system.

More importantly, we found that, unfortunately, performing thrusting on the upper stage end of the system is not an efficient means for spinning up the tether. Because the stage's mass is much greater than the nanosat payload, the center of rotation of the tethered system is very close to the stage - only about 20 meters, and this provides a very short 'lever arm' through which to apply torque to the system. Consequently, in order to achieve a desired tip velocity V_{tip} at the nanosat end of the system, the stage must perform a total ΔV maneuver roughly equal to V_{tip}. The large ratio between the stage mass and nanosat mass means that the 'effective Isp' for delivering the V_{tip} to the nanosat would be exceedingly poor, requiring a much larger propellant mass to accomplish the job than if the nanosatellite simply used a rocket motor to provide the same ΔV. If, however, the thrusting is performed at the nanosat end of the system, the spin-up is more efficient. Nonetheless, the total thrust impulse needed from the nanosat would be equal to or larger than that required to provide the desired ΔV using a rocket motor, so there would be no clear advantage to using a tethered system in this manner.

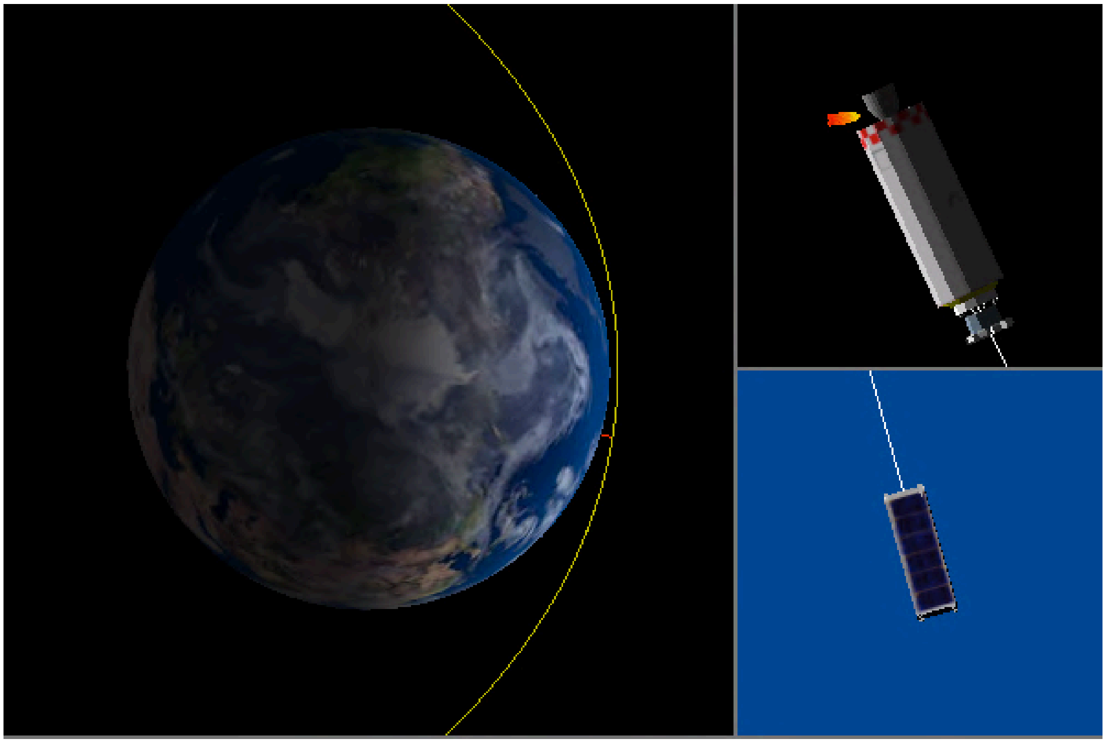

Figure 3. TetherSim simulation of NanoTHOR spin-up using thrusting by the rocket upper stage. *Thruster-based spin-up of the system would require active control of thrust vector and magnitude to ensure the upper stage spins up at the same rate as the tether to avoid 'wrapping' the tether onto the stage.*

Due to the lack of a clear advantage in terms of mass required and the practical challenge of requiring a launch vehicle operator to significantly change their operations to support NanoTHOR spin-up, we concluded that this "propellant scavenging" method alone was not optimal, and sought a better method.

2.2 ANALYSIS OF MOMENTUM-SCAVENGING-BASED SPIN-UP

Fortunately, there is a different potential method for achieving spin-up of the NanoTHOR system: using tether deployment and retraction operations to convert orbital angular momentum into spin angular momentum through interactions with the Earth's gravity gradient. The CONOPS for this method were illustrated in Figure 1. The spin-up maneuver involves deploying the nanosatellite at the end of a very long tether, using the gravity gradient to set the system into a moderate rotation, and then retracting the tether to increase the rotation rate via conservation of angular momentum. A significant advantage of this method is that it uses the upper stage as a passive source of orbital energy, and does not require significant changes in the operations of the upper stage.

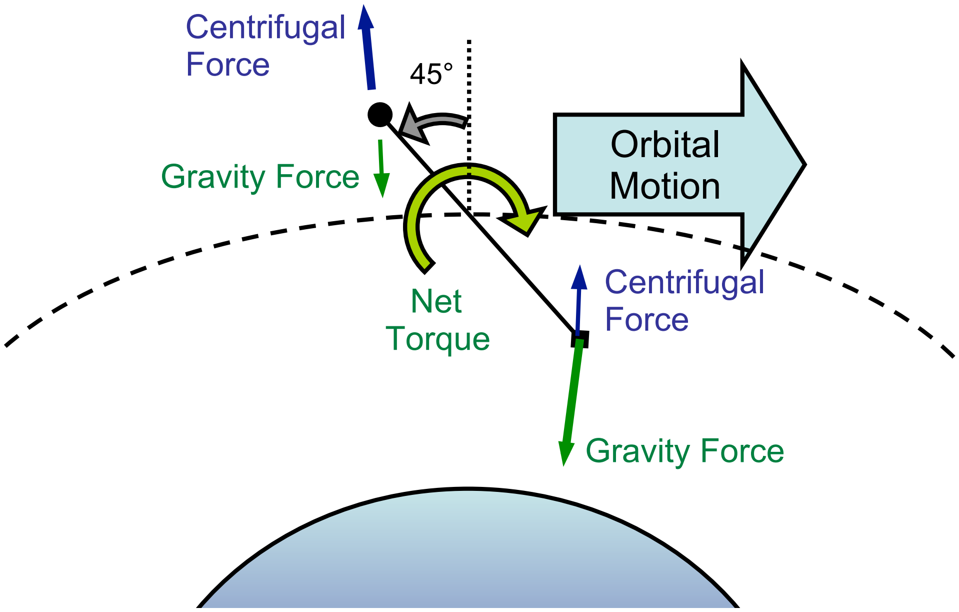

Figure 4. Torque on a tethered system due to the gravity gradient. *The gravity gradient tensions the tether and applies a torque that drives the system towards local vertical.*

This method relies upon the fact that the Earth's gravity gradient forces apply a torque to a tethered system when that tether is rotated away from the local vertical, as illustrated in Figure 4. Furthermore, because the NanoTHOR system is in a highly elliptical GTO trajectory, the gravity gradient varies rapidly as the system passes through perigee, and this rapid variation enables modest tether reeling maneuvers to result in significant transfer of angular momentum between the tether's orbit and its in-plane rotation.

Using a dumb-bell model of tethered system dynamics, with endmasses m_1 and m_2, tether mass m_t, and tether length L, the effects of tether deployment and orbit upon the rotational behavior of a tether are described by:[6]

$$\theta'' = 2\left(\theta'+1\right)\left[\frac{e\sin\nu}{1+e\cos\nu} - M^{*}\frac{\Lambda'}{\Lambda}\right] - \frac{3}{1+e\cos\nu}\sin\theta\cos\theta \tag{1}$$

$$\Lambda'' = \frac{2e\sin\nu}{1+e\cos\nu}\Lambda' - M^{**}\frac{\left(\Lambda'\right)^2}{\Lambda} + M^{***}\Lambda\left[\left(\theta'+1\right)^2 + \frac{3\cos^2\theta - 1}{1+e\cos\nu}\right] - T^{*} \tag{2}$$

where

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[6] WIlliams, P., "Dynamics and Control of Spinning Tethers for Rendezvous in Elliptic Orbits," *J. Vibration and Control*, 12(7): 737-771, 2006.

$$T^* = \frac{T}{m_1 \dot{v}^2 L\left(m_2+m_t\right)/\left(m_1+m_2+m_t\right)} = \text{normalized tether tension}$$

$$\mathrm{M}^* = m_1\left(m_2+\frac{m_t}{2}\right)\Big/\left[m^* m\right]$$

$$\mathrm{M}^{**} = \left(2m_1-m\right)\frac{m_t}{2}\Big/\left[m_1\left(m_2+m_t\right)\right]$$

$$\mathrm{M}^{***} = \left(m_2+\frac{m_t}{2}\right)\Big/\left(m_2+m_t\right)$$

$$m = m_1+m_2+m_t$$

$$m^* = \frac{\left(m_1+\frac{m_t}{2}\right)\left(m_2+\frac{m_t}{2}\right)}{m} - \frac{m_t}{6} = \text{reduced mass of system}$$

$$(\;)' = \frac{d(\;)}{d\nu}$$

$\nu =$ true anomaly

$e =$ eccentricity

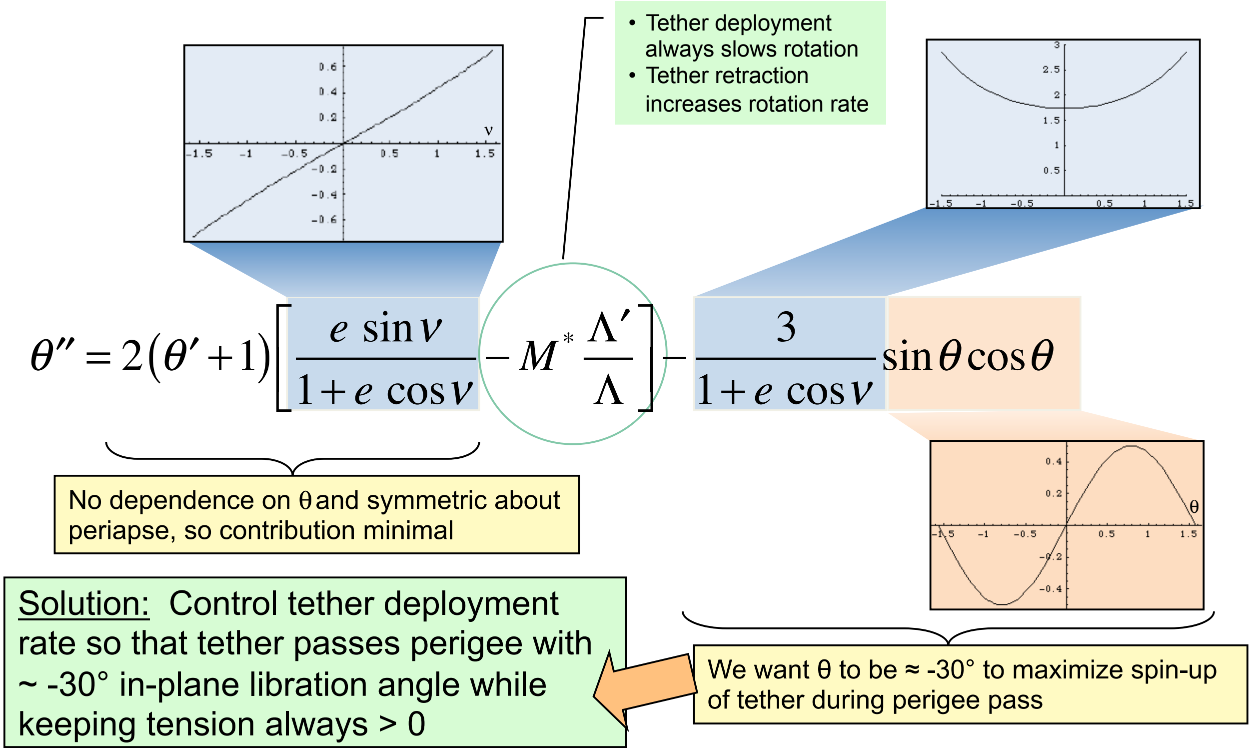
$\theta =$ in-plane libration angle

$\Lambda = \frac{\ell}{L} =$ normalized tether length

$\ell =$ deployed tether length

$L =$ total tether length

As illustrated in Figure 5, in Eqn. (1), if we assume that the tether reeling rate and rotation rate are small, the first term on the right hand side is essentially symmetric about periapse, and the second term determines the net change in rotation rate through a perigee pass. Inspection of that second term reveals that a tether libration angle θ of approximately 30° away from vertical will maximize the change in rotation rate during a perigee pass.



$$\theta'' = 2\left(\theta'+1\right)\left[\frac{e\sin\nu}{1+e\cos\nu} - M^*\frac{\Lambda'}{\Lambda}\right] - \frac{3}{1+e\cos\nu}\sin\theta\cos\theta$$

- Tether deployment always slows rotation
- Tether retraction increases rotation rate

No dependence on θ and symmetric about periapse, so contribution minimal

Solution: Control tether deployment rate so that tether passes perigee with ~ -30° in-plane libration angle while keeping tension always > 0

We want θ to be ≈ -30° to maximize spin-up of tether during perigee pass

Figure 5. Analysis of terms in Eqn. (1) describing the rotational acceleration of a tethered system in orbit. *Exchange of angular momentum from the orbit into tether rotation is maximized when the in-plane libration angle is approximately 30° during the perigee pass.*

2.2.1 Optimization of Winching Method for NanoTHOR Tether Spin-Up

To investigate this spin-up method, we implemented Eqns. (1) and (2) in an Excel spreadsheet-based simulation tool. Starting the simulation with an initial tether deployed length of 50 m and an initial very-slow rotation rate, we then used Excel's "Solver" tool to optimize the rate deployment of a 32.5-km long tether over several orbits so that the tether approached perigee with a libration angle of -30°. Figure 6 shows the deployed tether length, and Figure 7 shows the resulting tip velocity at the nanosat end of the tether. With deployment rates of 0.5 and 0.42 m/s during the first two orbits, the 32.5 km length of the tether was deployed and each time it passes perigee it receives a boost in rotation rate so that after the second perigee pass it has a tip velocity of approximately 60 m/s. At that point, the system is spinning fast enough that its rotation results in essentially no further increase in spin rate during a perigee pass regardless of orientation approaching the perigee. However, that 60 m/s of tip velocity on a 32.5 km long tether represents a tremendous amount of angular momentum. So, to further increase the tip velocity, we then retract 27.5 km of the the tether over the course of one or more orbits to increase the spin rate via conservation of angular momentum. In the simulation shown, the tether is retracted at approximately 25 cm/s over the course of 2 orbits (1 day), and then at a slower rate during a third orbit optimized to achieve the desired tip velocity with the tether oriented vertically when it returns to perigee. With this sequence of reeling maneuvers, the tip velocity reaches 776 m/s, and the peak acceleration on the nanosat is 14 G's. The nanosat will then release itself from the tether at perigee, injecting the nanosatellite into a C_3=0 escape trajectory.

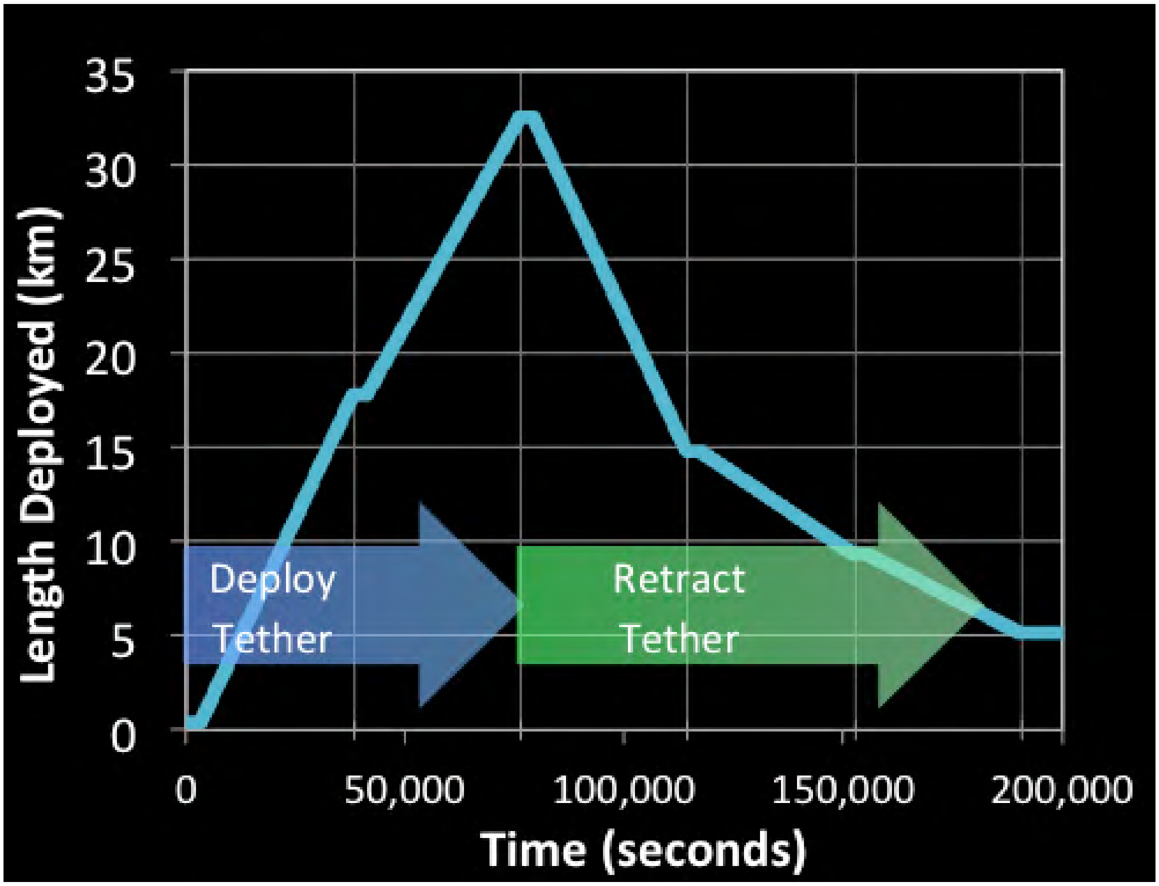


Figure 6. Deployed tether length during the spin-up maneuver. *The deployment rate is controlled to maximize conversion of orbital angular momentum into rotational angular momentum, and the retraction rate is controlled to preserve that angular momentum while keeping winch power requirements within acceptable bounds.*

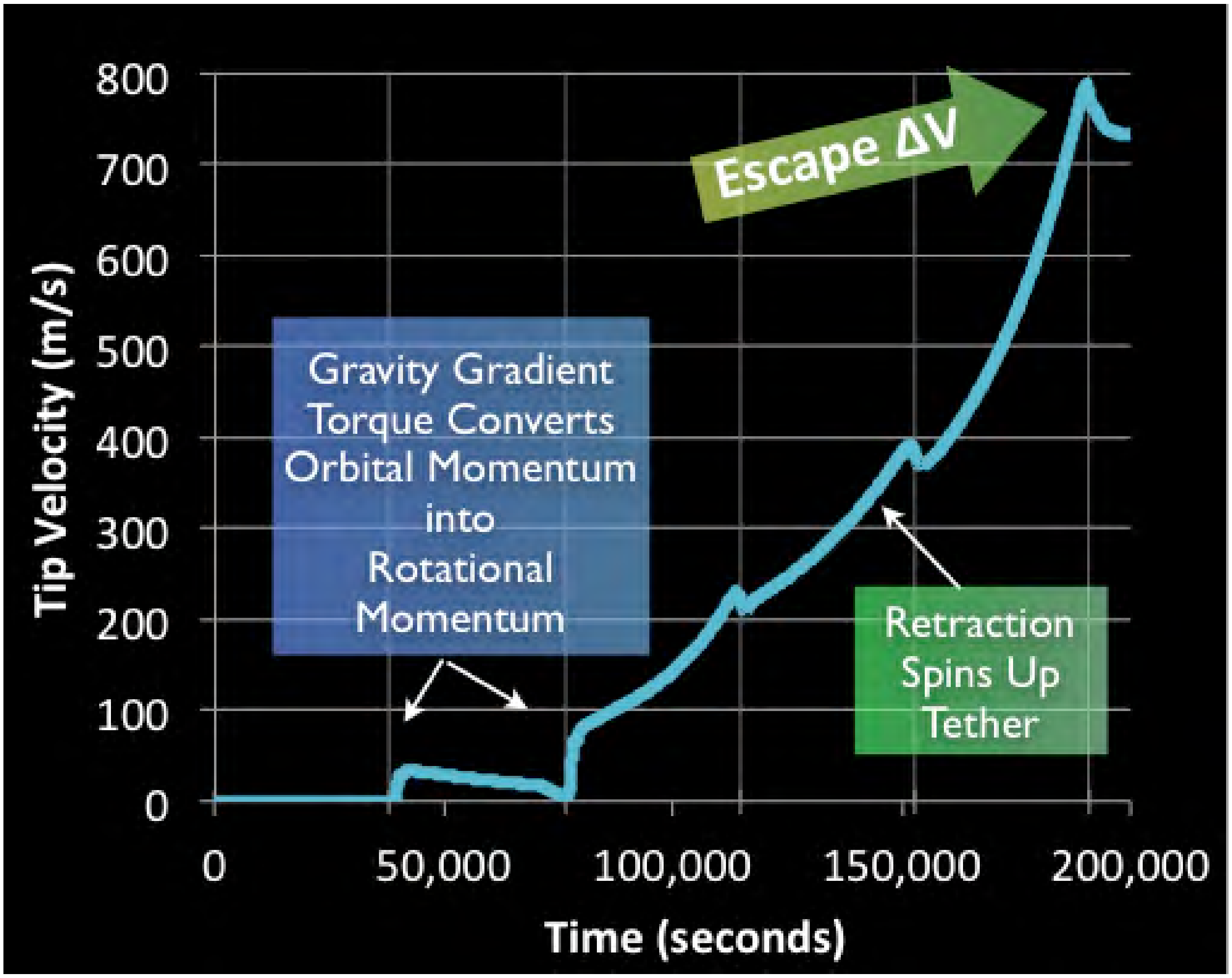
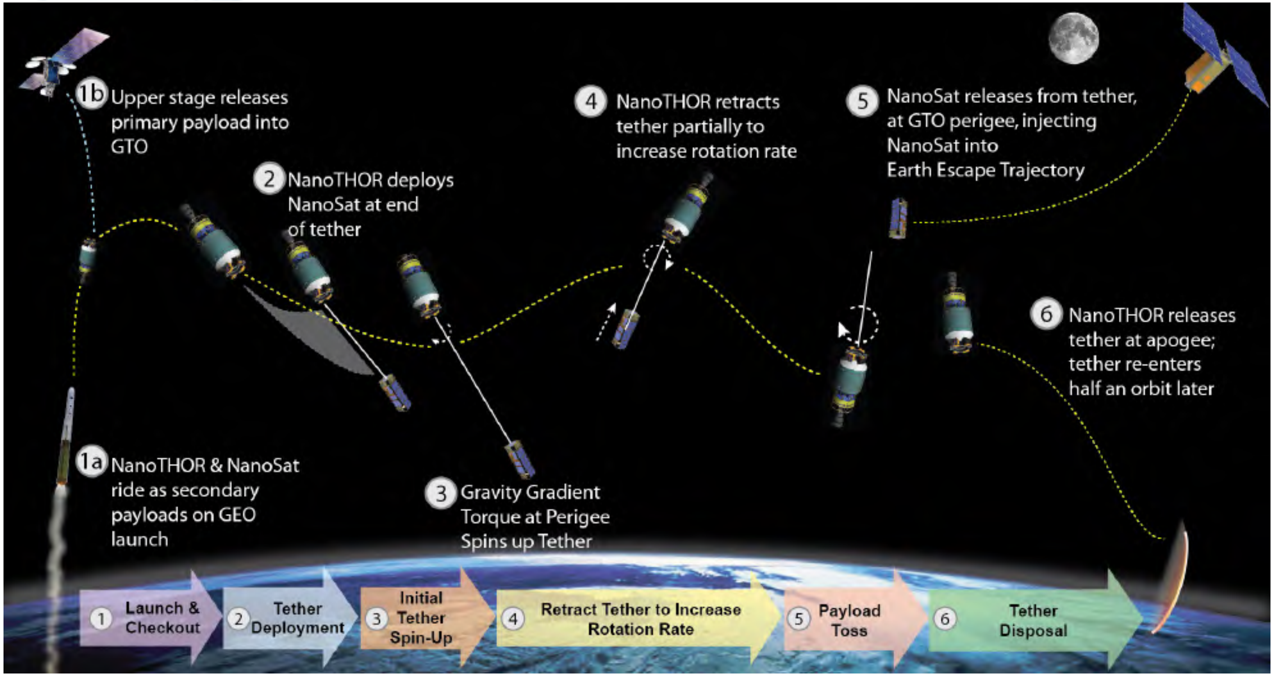


Figure 7. Tether tip velocity during tether winching. *Controlled-rate deployment and retraction of a tether is sufficient to provide the ΔV needed to boost a nanosat from GTO to escape.*

2.2.2 Momentum-Scavenging NanoTHOR CONOPS and Timeline

Based upon the optimized spin-up maneuver design detailed above, Figure 8 presents a concept of operations (CONOPS) and mission timeline for a momentum-scavenging NanoTHOR operation to boost a single nanosatellite from a GTO rideshare launch. Note that the simulation timelines in Figure 6 and Figure 7 begin after primary payload separation, so there is an offset between the timelines in those figures and that of Figure 8.



Stage		MET (hr)	Orbit Rev	NanoTHOR Actions
1a	Launch	0	0	NanoTHOR and nanosat dormant on upper stage
1b	Primary Payload Separation	5.3	0.5	NanoTHOR and nanosat dormant on upper stage
2	Deploy Tether	8	0.75	PPOD ejects nanosatellite and NanoTHOR winch deploys ~500m of tether; NanoTHOR uses RelNav to track relative motion of nanosat
3a	Initial Spin-Up, 1st Perigee	10.5	1	Gravity gradient induces initial tether rotation; NanoTHOR begins deploying tether at ~0.5 m/s and tracks nanosat at end of tether using RelNav; Upper Stage measures its own orbital position & attitude and provides data to NanoTHOR; Upper Stage adjusts attitude to maintain alignment w/ tether; NanoTHOR adjusts tether deployment rate to achieve proper alignment on 2nd perigee pass
3b	Initial Spin-Up, 2nd Perigee	21	2	NanoTHOR adjusts tether deployment rate to achieve optimal alignment on 3rd perigee pass
4a	Retraction Spin-Up, 3rd Perigee	31.6	3	NanoTHOR begins retracting tether at ~0.5 m/s
4b	Retraction Spin-Up, 4th Perigee	42.1	4	NanoTHOR adjusts tether retraction to ~0.15 m/s
4c	Retraction Spin-Up, 5th Perigee	52.6	5	NanoTHOR adjusts tether retraction to ~0.12 m/s; NanoTHOR tracks nanosat relative motion, adjusts retraction rate to achieve desired tip velocity and tether orientation at next perigee
5	NanoSat Toss	63.1	6	NanoTHOR commands NanoSat to release from tether when tether is at the top of its rotation at perigee, Nanosat injects into escape trajectory and activates any deployables to begin its mission.
6	Disposal	68.4	6.5	NanoTHOR cuts tether away when it is swinging behind the upper stage at apogee, releasing tether into trajectory to re-enter half and orbit later, OR NanoTHOR retracts entire tether

Figure 8. CONOPS and Timeline for a NanoTHOR mission. *NanoTHOR can accomplish injection of a nanosat into an escape trajectory within 3 days after launch.*

2.2.3 Required Winching Rate, Tension, and Power

This winching method will require power in order to retract the tether as the tension increases during the spin-up maneuver. In order to develop a concept design for a NanoTHOR system with a reasonable mass and cost, we used our tether simulation tools to refine the spin-up maneuver design in order to minimize the total maneuver duration while seeking to keep the power required below a reasonable threshold so as to minimize the mass and cost associated with providing that power. The process involves deploying 32.5 km of tether over the course of two orbits, and then retracting 27.5 km of that length over the course of 3 orbits. The retraction rate is varied over those three orbits, as shown in Figure 9, so as to optimize the conversion of orbital angular momentum into rotational angular momentum each time it passes perigee. These deployment and retraction rates of ≤ 0.5 m/s are well within the capabilities of tether deployers and winches that we have developed for other space tether applications. Figure 10 shows the variation in tether tension during the spin-up maneuver. The peak tension is just under 1400 N; this tension figure includes both the centripetal force that is applied by the tether to the 10 kg nanosatellite payload and the force that each segment of tether must bear to support the centripetal acceleration of the segments of tether further out from the center of rotation of the system. Note, however, that this peak tension is only reached when all but 5 km of the tether length has been retracted, and therfore most of the length of the tether has a much lower tension requirement.

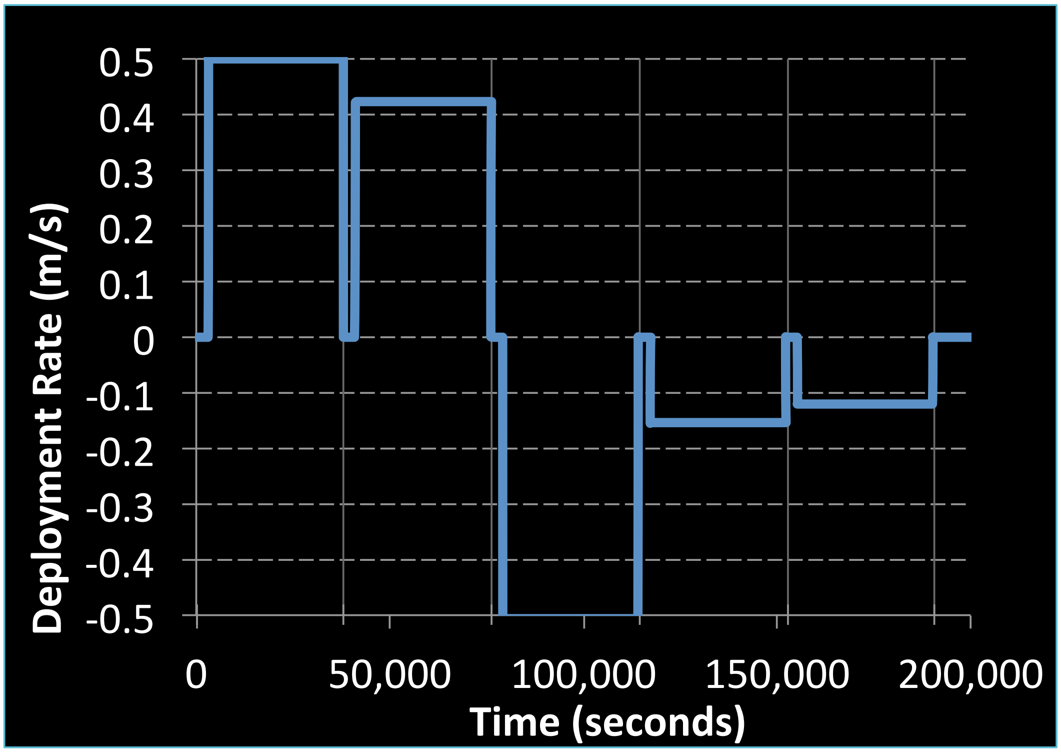


Figure 9. Deployment/Retraction Rate during the spin-up maneuver. *The deployment and retraction rates required are well within the capabilities of small, lightweight winching systems.*

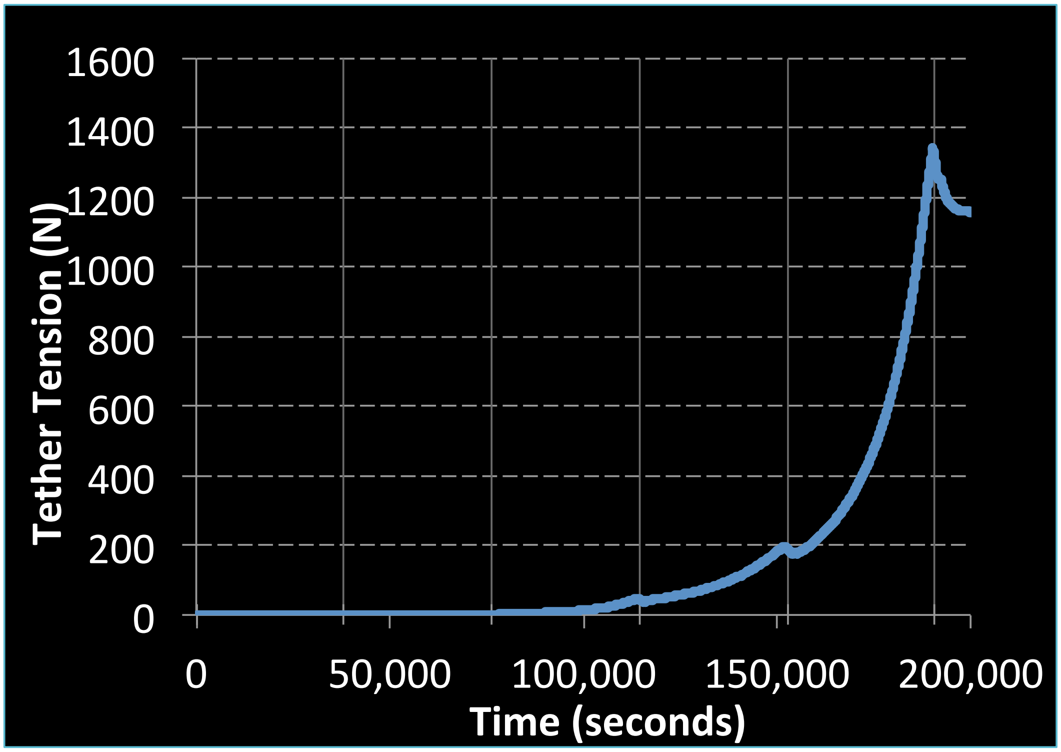


Figure 10. Tether Tension at the winch end during the spin-up maneuver. *The tether tension is well within the capabilities of high-strength tether materials and small winching systems.*

Figure 11 shows the resulting variation of power that must be provided to the winching system. For this maneuver, we chose the reeling rate so that the peak power requirement was less than 80 W. We chose 80 W because we have recently developed and qualified a deployable, steerable solar panel that is sized to provide 80 W power (post-PPU) to a 3U CubeSat, shown in Figure 12, and this CubeSat array can provide a good data point establishing that the NanoTHOR power requirements can be met with a SWaP of about 1.5 kg and a cost on the order of $150K. It should be noted that the orientation and location of the solar array will need to be chosen so that it can provide the required power level as the system rotates. Consequently, it may be necessary to locate several panels around the surface of the NanoTHOR module or on different positions on the upper stage vehicle to provide these power levels.

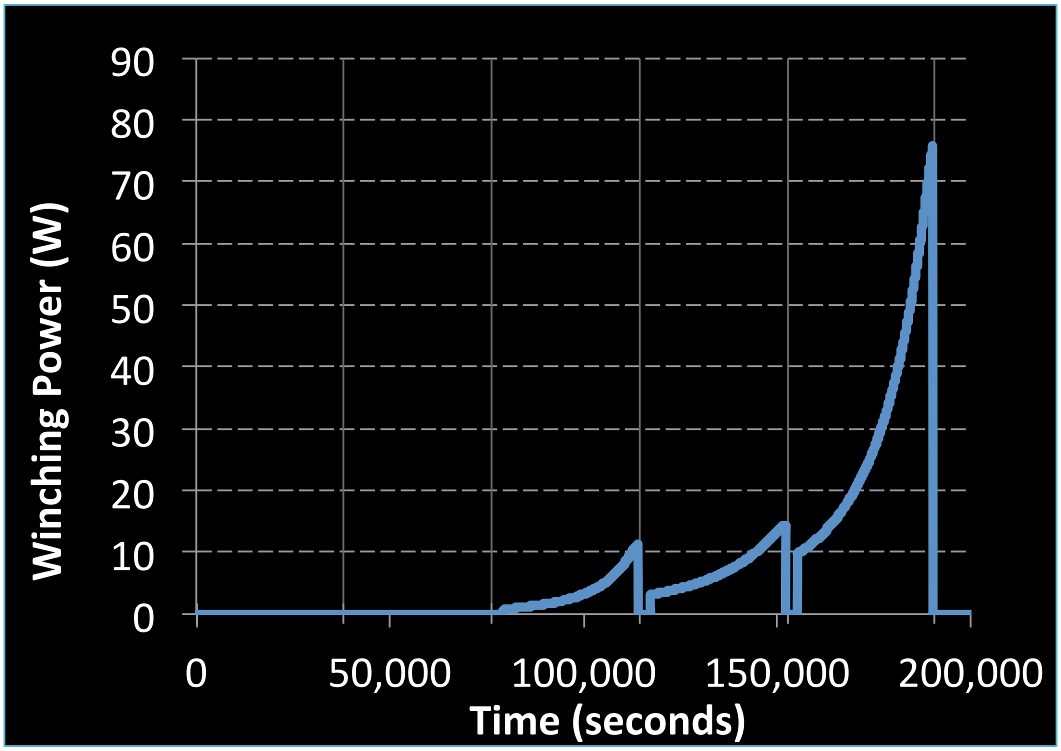


Figure 11. Power required for retracting the tether. *Power requirements are reasonable for a small, low-cost system.*

Figure 12. TUI's 'SunMill™' 80W Deployable, Steerable Array for CubeSats. *Although a different solar array configuration would likely be required for NanoTHOR, the SunMill Array provides a baseline for establishing that the power requirements for NanoTHOR can be provided within 1.5 kg in mass and approximately $150K in cost.*

2.3 NANOTHOR SPIN-UP IN A LEO ORBIT

While the focus of our efforts in this Phase I study has been on evaluating the feasibility of using a tether to toss nanosatellites from GTO to Earth escape, the NanoTHOR tether may have applications in Earth orbit as well, for boosting payloads launched as secondaries on LEO launches to higher orbits. Spin-up of the tether system in a LEO orbit, however, requires a somewhat different approach. In the GTO trajectory, the large eccentricity of the orbit naturally results in spin of the tether system. Moreover, the gravity gradient force varies dramatically over the orbit, providing a source of varying torque on a tether that can be used to efficiently convert orbital angular momentum into rotational angular momentum. In LEO orbits we do not have that large periodic variation in gravity gradient to work with. However, propellant scavenging and tether winching can still be used to spin up a tether system in LEO. As in the GTO CONOPS, the system would deploy the nanosatellite at the end of a long (30+ km) tether. In a propellant-scavenging approach, the host would then perform a 60-m/s burn to induce the tether system to rotate. In a winching approach, illustrated in Figure 13, the NanoTHOR system would reel the tether in and out in phase with its libration period to induce a swing in the tether and pump that swing up to larger amplitudes, much in the same way a child pumps up her swing on a playground swingset. In either approach, the NanoTHOR module would then use its winch to rapidly retract its tether, using the angular momentum in its libration to transition from a pendulum-like swing into rotation and then increase the rotation rate as in the GTO spinup CONOPS.

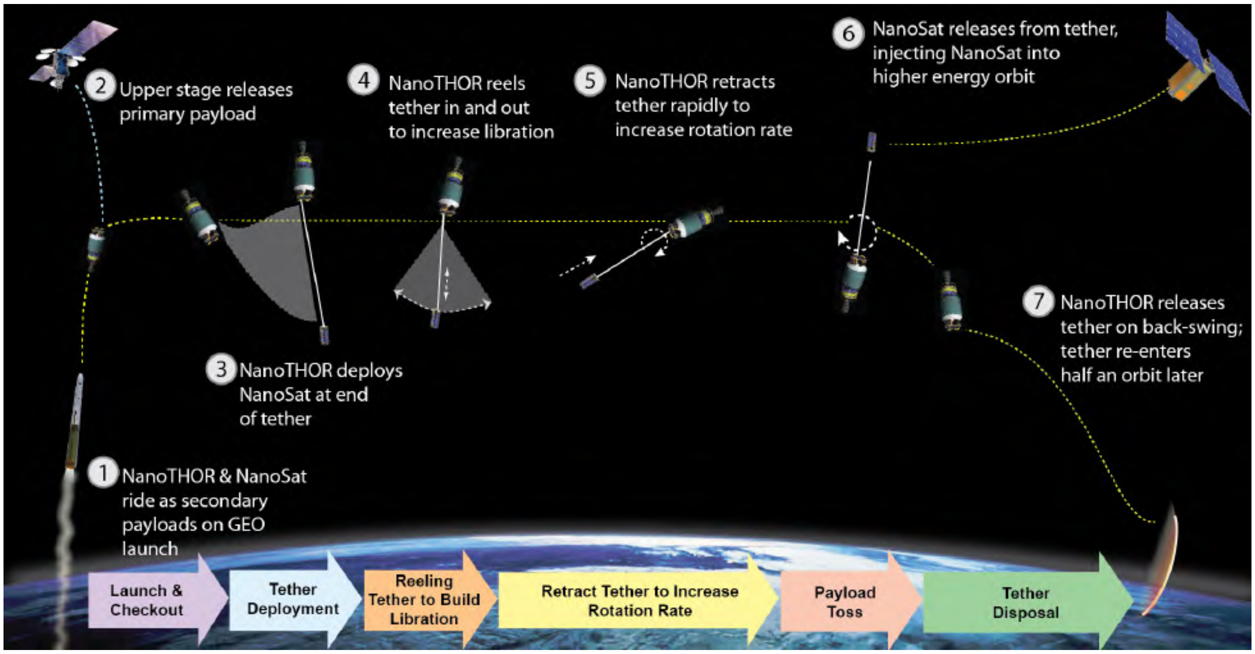


Figure 13. CONOPS for winching-based spin-up of a NanoTHOR system in a LEO orbit. *Reeling the tether in and out in phase with the pendulum libration of the tether can enable spin-up of a NanoTHOR system in a low-eccentricity LEO orbit.*

2.4 NANOTHOR INCLINATION CHANGE CONOPS

The combination of propellant scavenging and winching could enable a significant new capability for delivering secondary payloads to orbit inclinations different than the primary payload inclination. The CONOPS for an inclination-change toss is illustrated in Figure 14. The NanoTHOR module would first deploy the nanosat at the end of a 30+km tether. The upper stage would then use residual propellant to perform a cross-track burn, setting the tether system into rotation in the cross-plane direction. The NanoTHOR system would then retract most of the tether, increasing the spin rate. Once the tether retraction has increased the tip velocity to the desired amount, the nanosat would release from the tether, injecting it into an orbit with a different inclination.

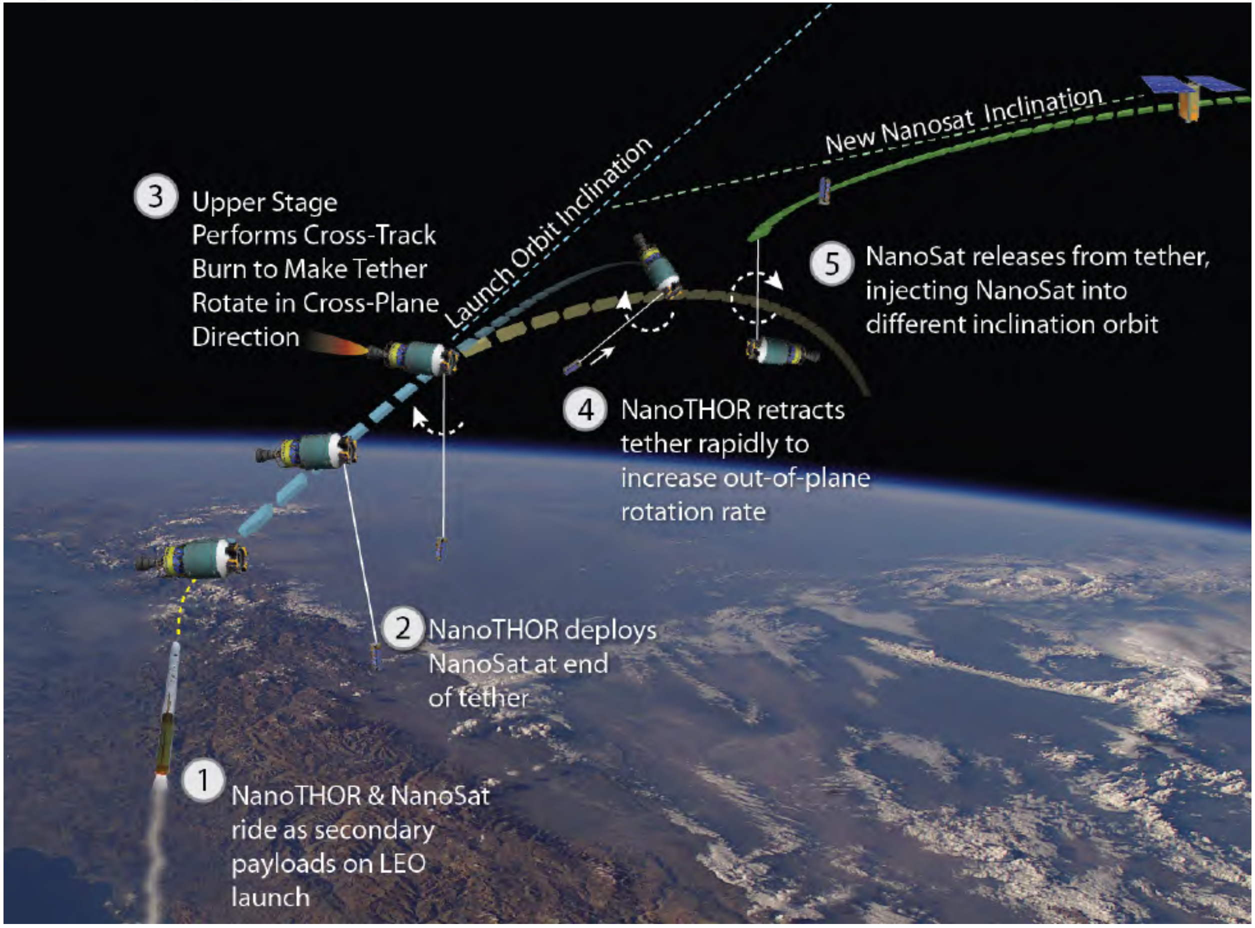


Figure 14. CONOPS for using a NanoTHOR tether to toss a secondary payload on a LEO launch into a different inclination orbit. *NanoTHOR can deliver a nanosat payload into an orbit with an inclination ±6° different than the launch orbit inclination.*

As an example, consider a scenario where an upper stage is launched into a 28.5°, 400 km orbit with a NanoTHOR module and nanosatellite payload. The NanoTHOR module on the stage deploys a nanosat at the end of a 32.5 km tether and then the upper stage performs a 60 m/s cross-track burn, setting the tether into rotation with a tip velocity of 60 m/s. The NanoTHOR's winch then retracts the tether to a length of 5 km, accelerating the tip velocity to 776 m/s, just as in Figure 7, and the nanosat then releases at the top of the tether rotation. The total cross-track impulse provided to the nanosatellite is approximately 60+776 = 836 m/s. This cross-track ΔV will inject the nanosatellite into a slightly higher orbit with an inclination of 34.7°. Thus a NanoTHOR tether system sized to deliver nanosats from GTO to escape could also provide a means for transferring orbital momentum from a LEO upper stage to a nanosatellite to deliver the nanosatellite to inclinations ±6° different than the launch inclination. In a GEO altitude, the same maneuver could toss a nanosat to an inclination ±15° around the host's orbit.

The advantage of the NanoTHOR module for performing this inclination change is that the tether acts like a 'lever arm' to multiply the ΔV provided by the upper stage, enabling a 60 m/s burn by the stage to deliver 836 m/s to the nanosat. We can quantify this advantage by considering a Delta IV Cryogenic Upper Stage with a dry mass of 3,490 kg and an Isp of 462 s. For this upper stage to perform an 836 m/s cross-plane burn to change inclination by 6° would require a fuel mass of approximately 588 kg. Using the NanoTHOR system we can reduce the mass required to approximately 46 kg of fuel (for the 60 m/s cross-plane burn) plus approximately 20 kg for the NanoTHOR hardware (as will be detailed in Section 3.2), for a total of 66 kg and a mass savings of 89%.

3. CONCEPT DESIGN OF NANOTHOR MODULES

In order to enable a comparison of the NanoTHOR concept to conventional propulsion technologies, we developed concept designs for NanoTHOR modules sized for two classes of payloads: 10 kg, 6U CubeSats, and 30 kg nanosats, comparable to the Kestrel Eye II imaging nanosatellite being developed by Army/SMDC or the Arkyd-200 asteroid "Interceptor" being developed by Planetary Resources, Inc. The design effort began by developing a design for tethers optimized for these payload masses, and then used estimates of tether volume, tension, and retraction rates to develop concept designs for the required hardware.

3.1 TETHER DESIGN

To determine the tether mass required to perform the winching-based spin-up maneuver, we developed designs for tethers that are tapered along their length to minimize its mass while ensuring the tether provides a safety factor of *F*=2 at all times as the deployed length, spin-rate, and centrifugal forces on the system all vary during the spin-up maneuver. We developed optimized tether designs sized for two classes of payloads: a 10 kg CubeSat, and a 30 kg nanosat. We developed the tether designs assuming the use of a yarn composed of two-ply 44-Tex Dyneema SK-75 fiber as the building block. This is the thinnest yarn tow available of the highest strength-per-weight fiber commercially available. The tapering in the tether design is therefore done on a stepwise basis. The number of yarns required along the length of the tether is shown in Figure 16. The total tether mass is 12 kg. Although this winching-based spin-up maneuver requires a very long tether length, most of the length of tether required is extremely thin, smaller than typical dental floss, so the total tether mass is quite reasonable. Figure 15 shows a photo of the 2x44-Tex Dyneema yarn used in the design.

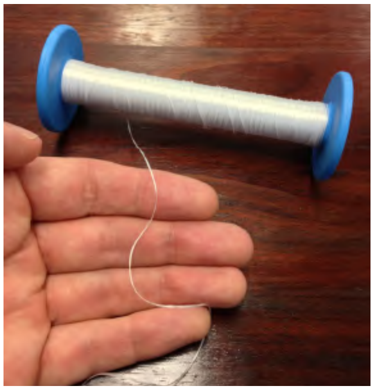


Figure 15. Two-ply yarn of 44-Tex Dyneema SK-75. *Most of the tether length needs to support only a tiny load, and can be thinner than dental floss.*

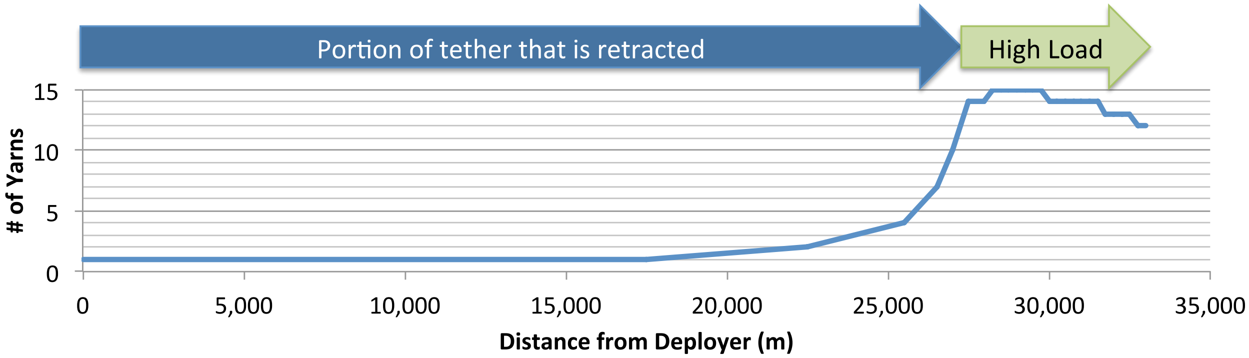


Figure 16. Stepwise-tapered tether design for a 10-kg payload. *Total tether mass is 12 kg.*

Figure 17 shows the design of the dual-taper tether optimized for a 30 kg payload. Although the mass of the payload is tripled, only the high-load section of tether must be tripled in capacity. Most of the length of the tether supports a very tiny load, and the minimum size of this section of tether is driven by the minimum yarn tow that we can acquire and handle reliably on our braiding machine. Consequently, the mass of the tether does not need to triple relative to the 10 kg payload version - the total mass of this tether sized for 30 kg payloads is just 23 kg.

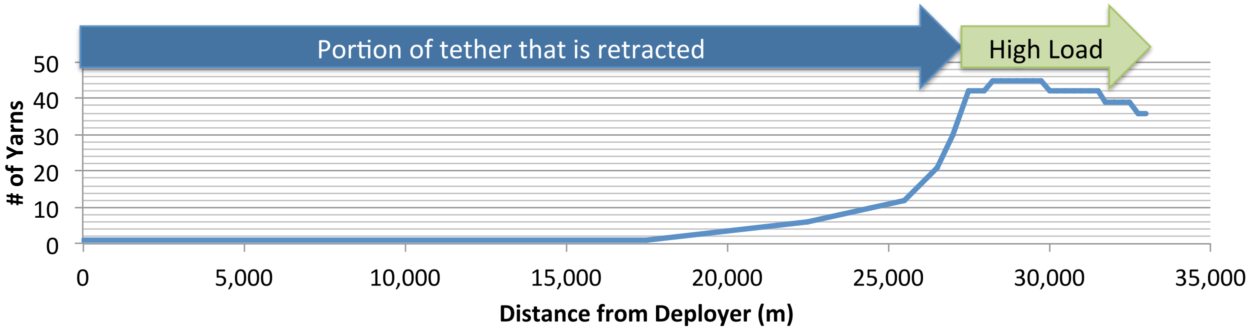


Figure 17. Stepwise-tapered tether design for a 30-kg payload. *Total tether mass is 23 kg.*

3.2 CUBESAT NANOTHOR MODULE

We then used SolidWorks CAD design tools to develop a concept design for a NanoTHOR module sized for tossing 10 kg, 6U CubeSats to escape. The concept design, shown in Figure 17, uses a relatively simple configuration of a rotating spool to hold the wound tether, a driven capstan to enable winching of a highly-loaded tether, a level wind mechanism to wind the tether onto the spool in a neat and compact manner, and pinch rollers at the infeed/outfeed to maintain tension on the tether within the deployer during the very low-tension phase of the retraction.

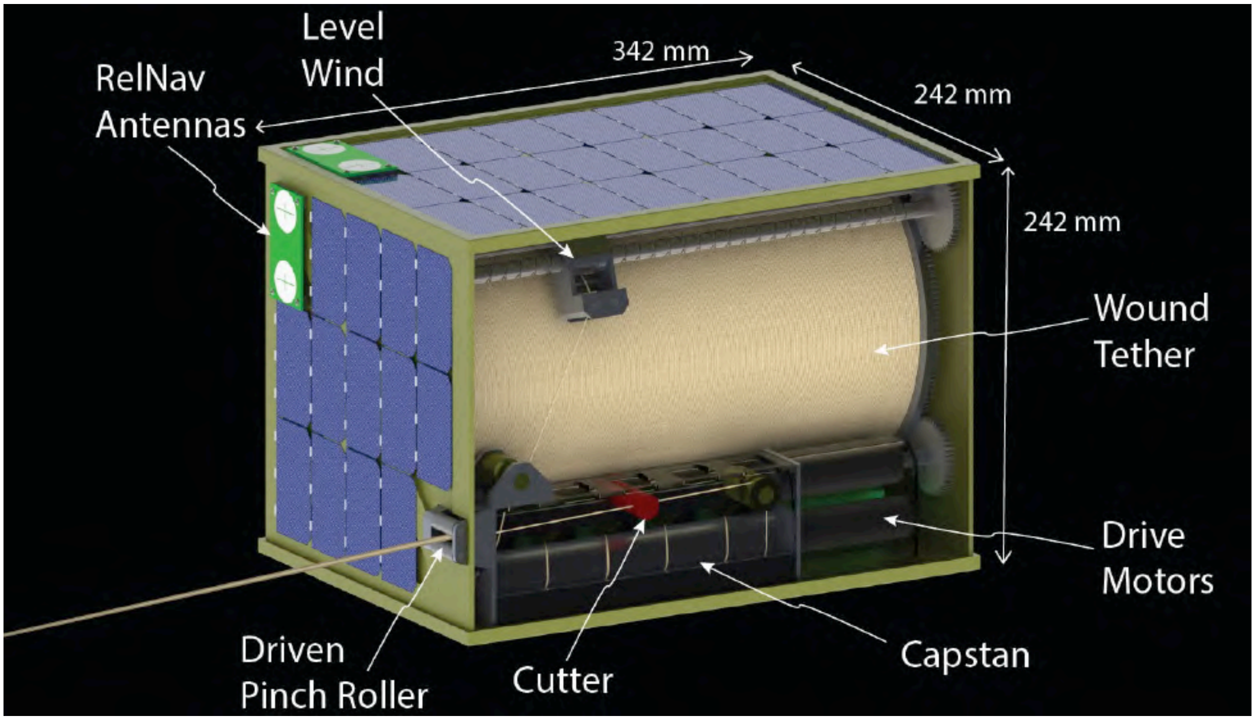


Figure 18. Concept design for a NanoTHOR module sized for boosting 10 kg CubeSats to escape. *The NanoTHOR module fits in an 18U volume, and requires only relatively simple mechanisms and configurations.*

Table 1 summarizes the estimated mass breakdown for the NanoTHOR module, based upon the preliminary design. The total module mass is less than 20 kg. Although the tether only masses 20% more than the 6U CubeSat payload it is designed to toss, it requires a larger volume, approximately 18U, because the Dyneema yarn has a relatively low density of 970 kg/m^3. If volume is a tighter commodity than launch mass, the tether could be fabricated using Zylon (PBO) yarn instead, which has comparable strength-per-weight but a higher density of 1560 kg/m^3. This could reduce the volume of the NanoTHOR module by up to 50%, but result in a higher total mass due to the need to coat the Zylon yarn to protect it from degradation due to solar UV light.

In addition to its mechanisms, the NanoTHOR module will include controlling avionics based upon CubeSat components, as well as a "RelNav" radio. The RelNav radio, shown in Figure 19, is a software-defined radio designed to provide CubeSat cross-link communication as well as measurements of relative range and heading between satellites. It is capable of measuring range to ≤0.1 m and relative heading to ≤1 deg. The NanoTHOR module will use the RelNav unit to communicate with its nanosatellite payload as well as to determine the position of the nanosat relative to the upper stage vehicle in order to measure and control the dynamics of the tethered system and determine the optimal time at which to release the nanosat.

Figure 20 illustrates a concept for integrating both the NanoTHOR unit and a 6U CubeSat into a 24U deployer, and using the deployer's ejection mechanism to push the CubeSat out to initiate tether deployment as well as to allow the NanoTHOR unit to 'pop out' so as to provide access to the sun for its solar panels.

Table 1. Mass Breakdown for the NanoTHOR Module sized for 10kg, 6U CubeSats.

Component	Mass, kg (CBE)
Structure & Mech.	4.7
Avionics	2.3
Motors	0.4
Tether	12.0
TOTAL	**19.4 kg**

Figure 19. RelNav Radio Prototype. *TUI's RelNav radio provides cross-link communications at up to 12 Mbps as well as measuring range to ≤0.1 m and heading to ≤1°.*

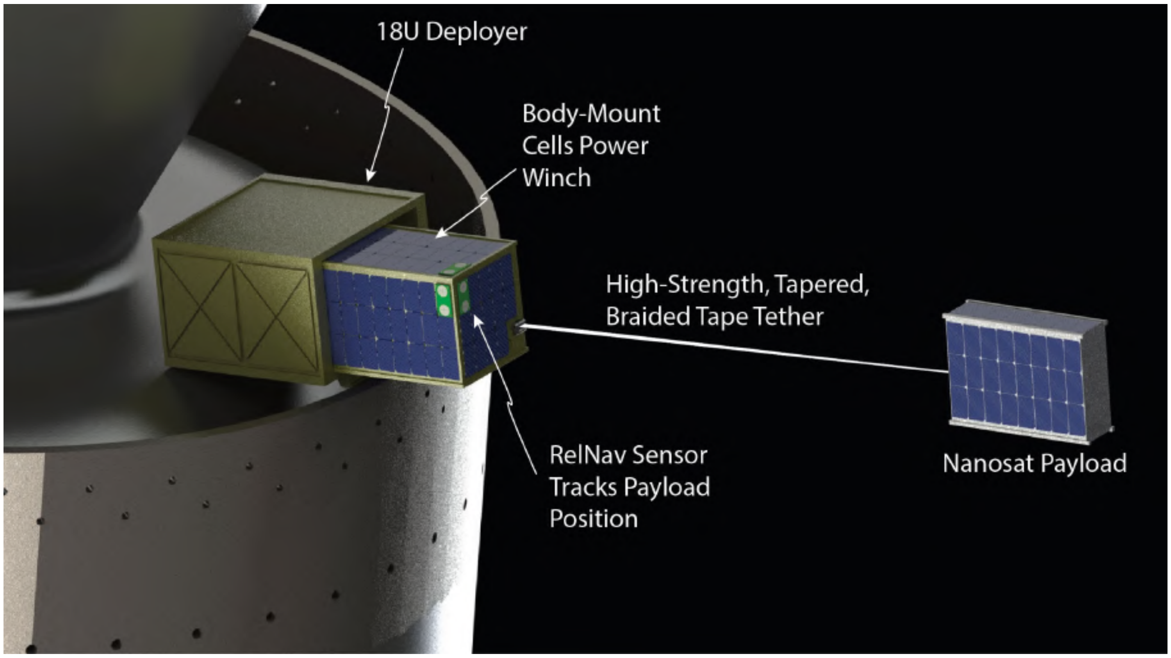


Figure 20. Concept for launching a NanoTHOR module and 6U CubeSat in a 24U deployer. *NanoTHOR and its payload can be packaged within a standardized, containerized nanosat deployer to minimize integration costs and risks to primary payloads.*

3.3 MULTI-PAYLOAD CAPABILITY CONCEPT DESIGN

One of the most significant potential advantages of a momentum-exchange tether system relative to conventional propulsion systems is that a tether is re-usable. Due to the fact that the required tether mass scales exponentially with the square of the ΔV, rather than exponentially with ΔV like a rocket system, for ΔV's of more than a few hundred meters per second a momentum exchange tether is not mass-competitive with a rocket system for boosting a single payload. If it used to boost multiple payloads, however, its reusability can enable it to be very advantageous in terms of total system mass.

Figure 21 illustrates a conceptual method for integrating multiple nanosatellite payloads with a single NanoTHOR module to enable the NanoTHOR to toss the nanosats one after the other. The method involves connecting each of the payloads to the tether using a 'leader' line and an 'eyelet'. The eyelets would allow the tether to pass freely though until a drawstring mechanism is actuated to clamp the eyelet onto the tether. To toss the multiple nanosats, the system will eject the first nanosat, deploy the tether, partially retract the tether to spin it up, and toss the nanosat. The next nanosat will then actuate its drawstring to clamp onto the tether, and the system will re-deploy the tether. As it deploys the tether, the nanosat will loosen the drawstring clamp so that it can slide down to the tether's end. Using control of the reeling rate during deployment over two orbits, the NanoTHOR module will increase the tether's rotation rate, and then partially retract the tether to increase the spin rate and toss the second payload... and repeat. In this manner, a single NanoTHOR system could boost a number of nanosat payloads. In Section 4 we will compare the NanoTHOR system to conventional propulsion technologies as a function of the number of payloads it tosses.

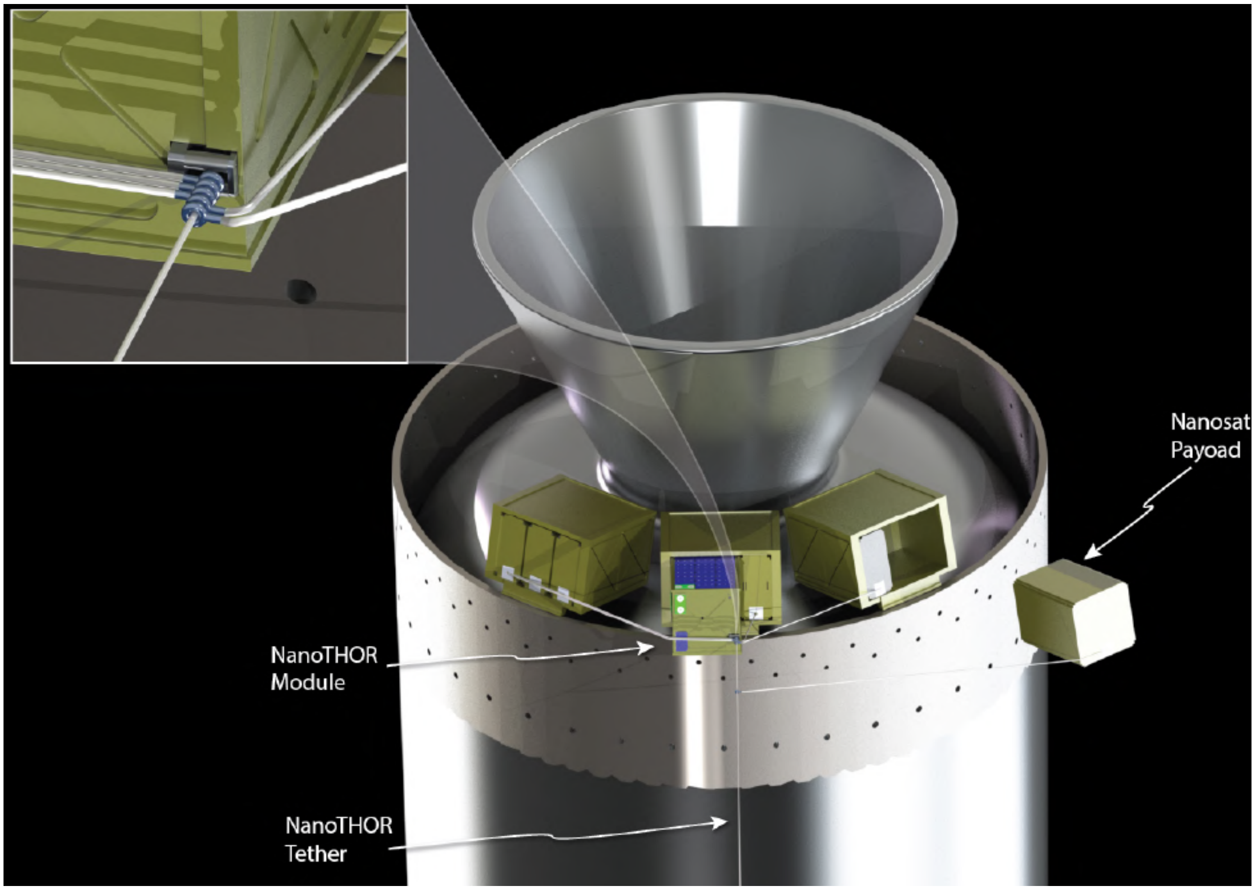


Figure 21. Concept for a method to enable a NanoTHOR module to sequentially toss multiple nanosats. *Each nanosat would use an eylet/drawstring mechanism to latch onto the tether as it is re-deployed.*

3.4 ESPA NANOTHOR MODULE

Figure 22 illustrates a concept for integrating a NanoTHOR module into an ESPA ring in order to toss larger nanosatellites to interplanetary trajectories. The NanoTHOR module shown is sized to toss 30-kg nanosatellites. It can readily mount inside the ESPA ring, feeding the tether through the Lightband separation ring, thereby maximizing the volume available for payloads. Using a method similar to that shown in Figure 21, but modified to accommodate the Lightband interface to the nanosats, this module could boost several nanosatellites on a single launch. A mass estimate for the ESPA-NanoTHOR system is shown in Table 2. The total module mass is under 37 kg.

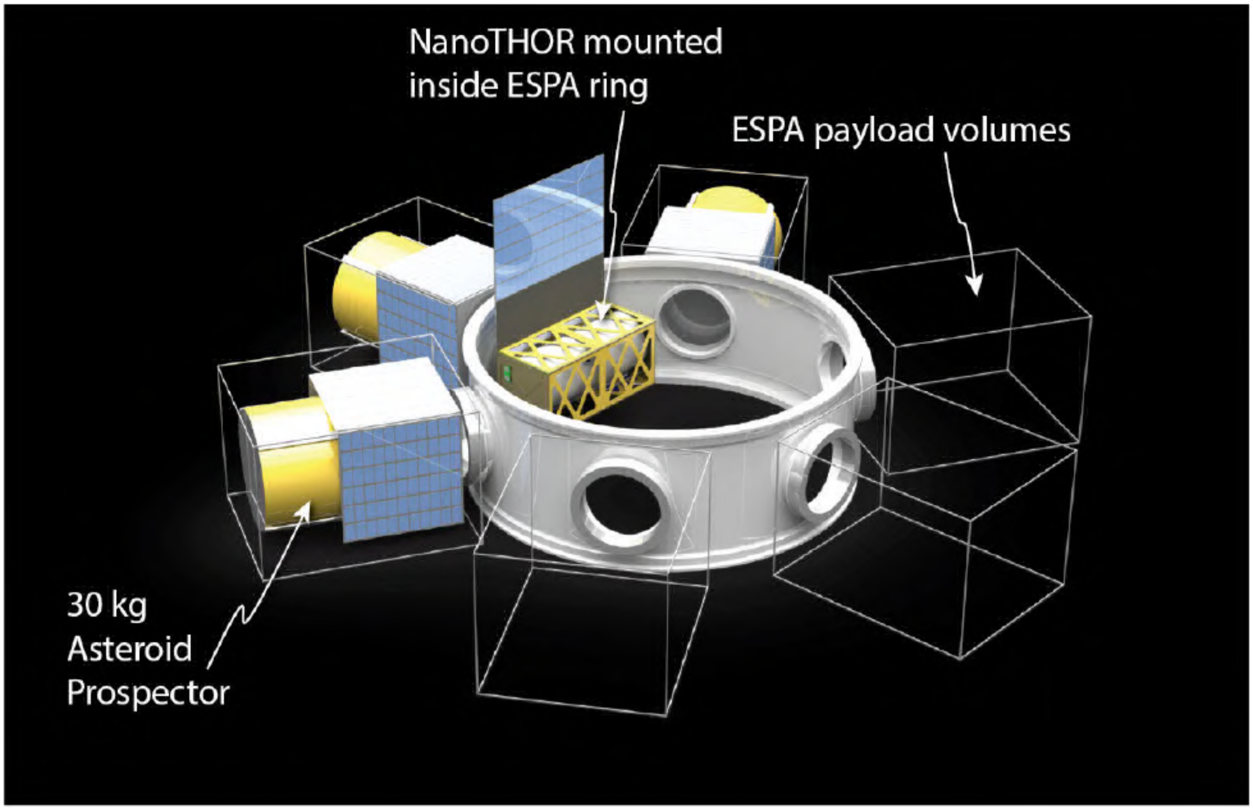


Figure 22. ESPA-NanoTHOR module concept design. *NanoTHOR can integrate inside the ESPA ring to maximize available volume for the nanosat payload.*

Table 2. Mass Breakdown for the NanoTHOR Module sized for 30kg NanoSats.

Component	Mass, kg (CBE)
Structure & Mech.	11
Avionics	2.3
Motors	0.4
Tether	23.0
TOTAL	**36.7 kg**

4. THE VALUE PROPOSITION FOR NANOTHOR

We have so far established that it is technically feasible to use a relatively simple high-strength tether and winch to boost nanosatellite payloads from GTO ride share launches to escape trajectories. But investing in developing an unconventional technology such as a momentum-exchange tether only makes sense if it provides a distinct advantage over established high-TRL technologies. In this section, we discuss three aspects of the NanoTHOR concept that can provide significant advantages relative to conventional propulsion technologies.

4.1 CREATING OPPORTUNITIES FOR LAUNCHING NANOSATELLITES TO DEEP SPACE

Likely the most important advantage of the NanoTHOR system is the one that is most difficult to quantify: that because it does not require any stored energy on launch, it can open up new, affordable opportunities for delivering nanosats to deep space destinations. Currently, to launch a small satellite beyond Earth orbit requires either purchasing a dedicated launch vehicle, finding a secondary payload ride on an interplanetary mission, or securing a secondary payload slot on an Earth-orbit launch and then using a rocket to inject the nanosatellite into an escape trajectory. For CubeSat and nanosat-scale systems, purchasing a dedicated launch vehicle is not cost effective because there are no rockets optimized to launch these very small systems to escape. Secondary payload slots on interplanetary missions are exceedingly rare. ULA does occasionally perform launches of a military payload to polar orbit in which they use only a fraction of the launch mass capability, and as a result they can dispose of the upper stage by boosting it to escape.[7] Secondary rides on these launches would be feasible, but infrequent. Using a rocket to boost the nanosatellite from a secondary payload delivery to Earth orbit is currently the most affordable option. However, primary payload customers have little incentive to accept secondary payloads that could pose a threat to their satellite, and the cost of qualifying a nanosatellite chemical rocket system to a zero threat level is prohibitive for most small satellite programs.

4.2 RAPID TRANSFER TIMES

It could be feasible to launch a secondary payload nanosat with an electric propulsion (EP) thruster that would have no stored energy upon launch. Several EP technologies are being developed for CubeSat-scale systems, including pulsed plasma thrusters (PPTs) and electrospray thrusters. However, these EP thrusters are limited by physics to providing extremely low thrust levels, and boosting a nanosatellite from a LEO or even GTO drop-off would require many months of spiraling out through the Van Allen radiation belts. The longer operations duration and the cost of hardening avionics to survive multiple transits through the radiation belts result in a significant impact to the program cost.

The NanoTHOR system acts like an electric propulsion technology in that it uses electrical power generated on-orbit to provide orbital energy to the nanosatellite, but it acts much more like a chemical thruster in that it provides the thrust impulse to the nanosatellite very quickly, scavenging orbital energy from the upper stage and delivering it to the nanosat within about three days. Consequently, relative to EP technologies the NanoTHOR system can enable significant reductions in lifecycle cost by reducing mission duration and mitigating radiation doses due to radiation belt transits.

4.3 HIGH EFFECTIVE ISP

The third advantage of the NanoTHOR tether system is that it is reusable, and taking advantage of that reusability can enable it to deliver multiple nanosatellites to escape trajectories with total mass less than rocket-based propulsion technologies. Figure 23 and Figure 24 show the effective specific impulse of the CubeSat and ESPA NanoTHOR systems as a function of the number of payloads they boost; the more payloads the tether boosts, the higher its effective Isp. In calculating these 'effective Isp' values,

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[7] Szatkowski, J., "ULA Orbital Debris Mitigation," *Improving Space Operations Workshop*, April 25, 2012, Pasadena CA.

we assumed that a rocket-based system designed to provide the same ΔV to a nanosatellite would have a 30% tankage/thruster parasitic mass on top of the propellant mass. For 10-kg CubeSat payloads, a NanoTHOR system boosting 3 or more nanosatellites will require less total mass than a monopropellant (hydrazine) propulsion system. The ESPA NanoTHOR system boosting 30-kg nanosatellites is mass-advantageous for 2 or more payloads.

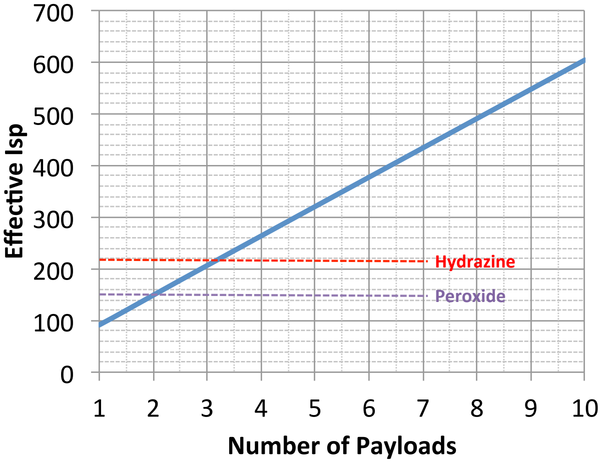

Figure 23. Effective Isp of the CubeSat Nano-THOR. *NanoTHOR is mass-competitive with monopropellants for ≥ 3 10kg, 6U-CubeSats.*

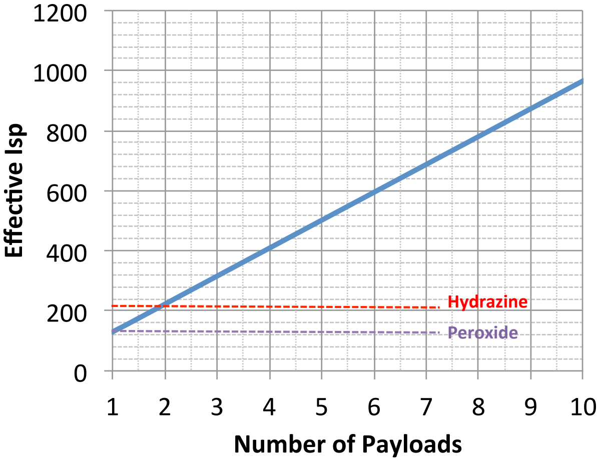

Figure 24. Effective Isp of an "ESPA" Nano-THOR for 30 kg nanosats. *NanoTHOR is mass-competitive with monopropellants (~220s Isp) for ≥ 2 30-kg nanosats.*

4.4 COST

Table 3 presents a breakdown of estimated recurring costs for the hardware, testing, launch, and operations of a NanoTHOR system to deliver a 6U, 10 kg nanosatellite to Earth escape. The total estimated recurring costs are under $3.2M. We can compare this with the launch costs for secondary payloads on the ULA polar launches that perform disposal of the upper stage by injecting to escape. The cost for a recent 3U CubeSat secondary payload on such a launch was $2.1M, not including integration and qualification. If the cost scales with mass, the cost for a 6U CubeSat on such a launch, including integration and qualification, would likely be on the order of $5M. Thus, from a recurring cost perspective, NanoTHOR appears to be competitive from a cost perspective with existing capabilities, and will be even more so if a single NanoTHOR module is used to toss multiple nanosats.

Table 3. ROM Recurring Cost for NanoTHOR Delivery of 6U CubeSat to Escape.

Component	Est. Recurring Cost ($K)	BOE
Tether	22	$900/kg Dyneema cost + Braider Time
Winch	400	scaled MXER-1 deployer
RelNav	75	RelNav Price
Avionics	200	Andrews Space CORTEX Stack Price
Solar Panel	150	SunMill Array Price
Structures	50	scaled MXER-1 structure cost
Qual Testing	14	5K shake & thermal vac + 2 man months
GTO Launch & Deployer	2,100	Est. based on ULA & SpaceFlight Svcs pricing
NanoTHOR Operations	150	6 man months for mission planning & ops
Total Recurring Cost (Est.)	**3,139**	**$K**

5. CONCEPT MISSION - "HAMMERSAT" AND THE ASTEROID PAYLOAD EXPRESS

To provide a mission context for evaluating the benefit of the NanoTHOR technology, we developed a concept 6U CubeSat system intended to be tossed into heliocentric orbit in order to deliver payloads to Near Earth Objects (NEOs). We performed a preliminary design and SWaP analysis of this "HAMMERsat" in order to quantify the amount of useful payload a NanoTHOR system could deliver to candidate NEOs.

5.1 HAMMERsat Concept Design

The "Hurled Asteroid Mapping, Mining, Exploration, & Rendezvous Satellite" (HAMMERsat) packages the power, propulsion, communications, and ADCS components necessary for a mission to a NEO into a 6U CubeSat form factor, leaving at least 1.75U and up to 4U of volume free for a scientific payload. A preliminary concept design for the HAMMERsat is shown in Figure 25. To provide up to 3 km/s of additional ΔV to enable the HAMMERsat to transfer from the minimum-energy Earth-escape trajectory provided by NanoTHOR to a NEO intercept or rendezvous trajectory, the HAMMERsat will use the HYDROS Propulsion System TUI is currently developing for CubeSat applications under a Phase II NASA SBIR. The HYDROS Thruster uses electrolysis to process water propellant into gaseous oxygen and hydrogen for high-thrust, 350s-Isp propulsion as well as cold-gas attitude control. To enable communications between the nanosatellite and ground stations over the AU-scale distances required for a survey of NEOs, the system will use the SWIFT-HPX radio and Ka-band high-gain antenna technologies TUI is developing under a NASA/GRC SBIR. Power for the system will be provided by two solar wings derived from the SunMill deployable, steerable array we developed under SMDC SBIR funding. Table 4 presents a summary of the mass breakdown of the system concept, with 1 kg available for scientific payloads if the CubeSat is loaded with a full 3.3L of water propellant.

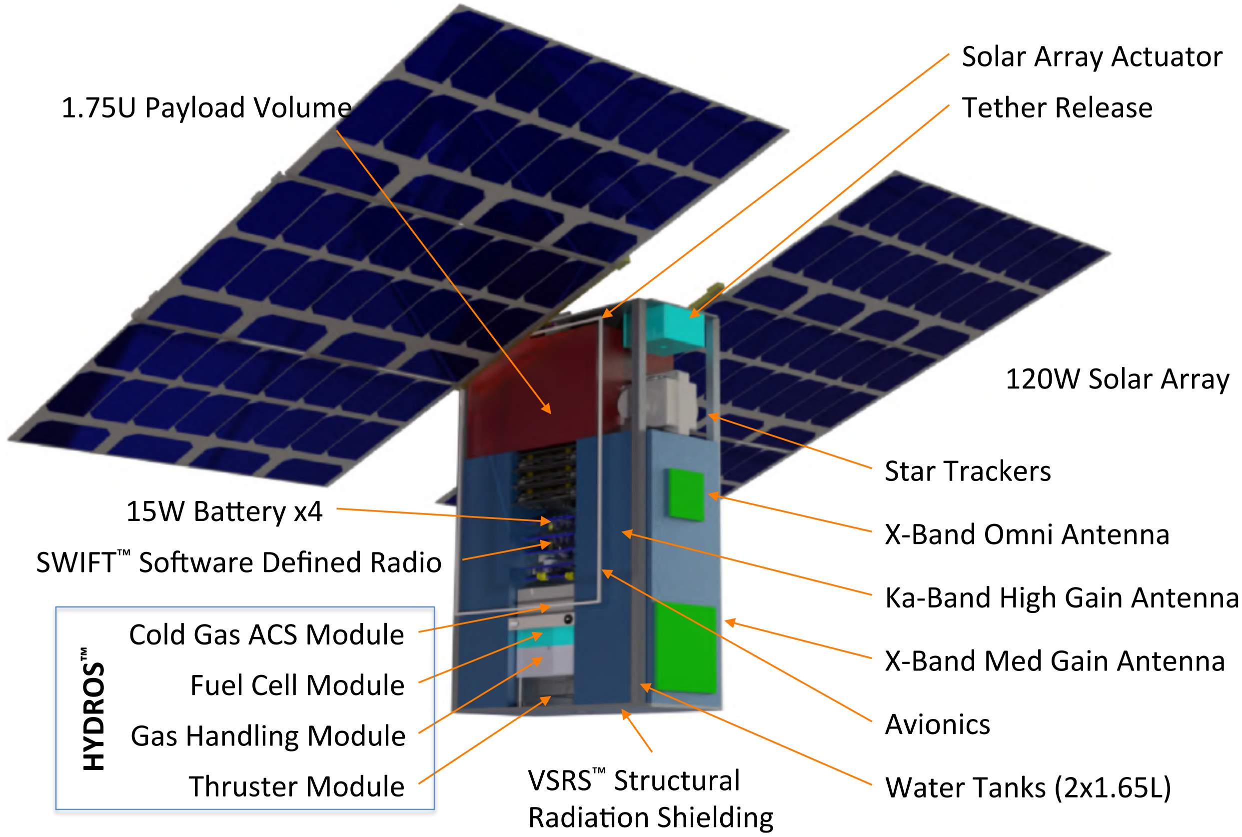

Figure 25. Configuration for a 10 kg, 6U "HAMMERsat" asteroid prospector that could be tossed into heliocentric orbit by NanoTHOR. *The HAMMERsat is a concept payload for NanoTHOR assembled using technologies available commercially or currently in development at TUI.*

Table 4. Projected mass allocation for the HAMMERsat.

Part	Mass (kg)
Arrays with Cells	1.25
Array Actuator Mechanism	0.20
Thruster Module	0.90
Avionics	0.30
Batteries	0.40
StarTrackers	0.10
Tether Release Mechanism	0.15
Antennas	0.20
Structure	1.50
Waters Tanks with Water	3.50
Misc. Hardware and Wiring	0.50
Total:	**9.00**
Available Payload Mass:	1.00

5.2 ASTEROID PAYLOAD EXPRESS PERFORMANCE ANALYSIS

The combination of NanoTHOR serving as an in-space upper stage and the HAMMERsat as a maneuverable platform can enable affordable, rapid delivery of small payloads to near-Earth objects using rideshare launch opportunities. In ***Appendix A: Asteroid Payload Express***, we present this system concept in more detail. Figure 26 shows the trade-off between required water volume and the available payload

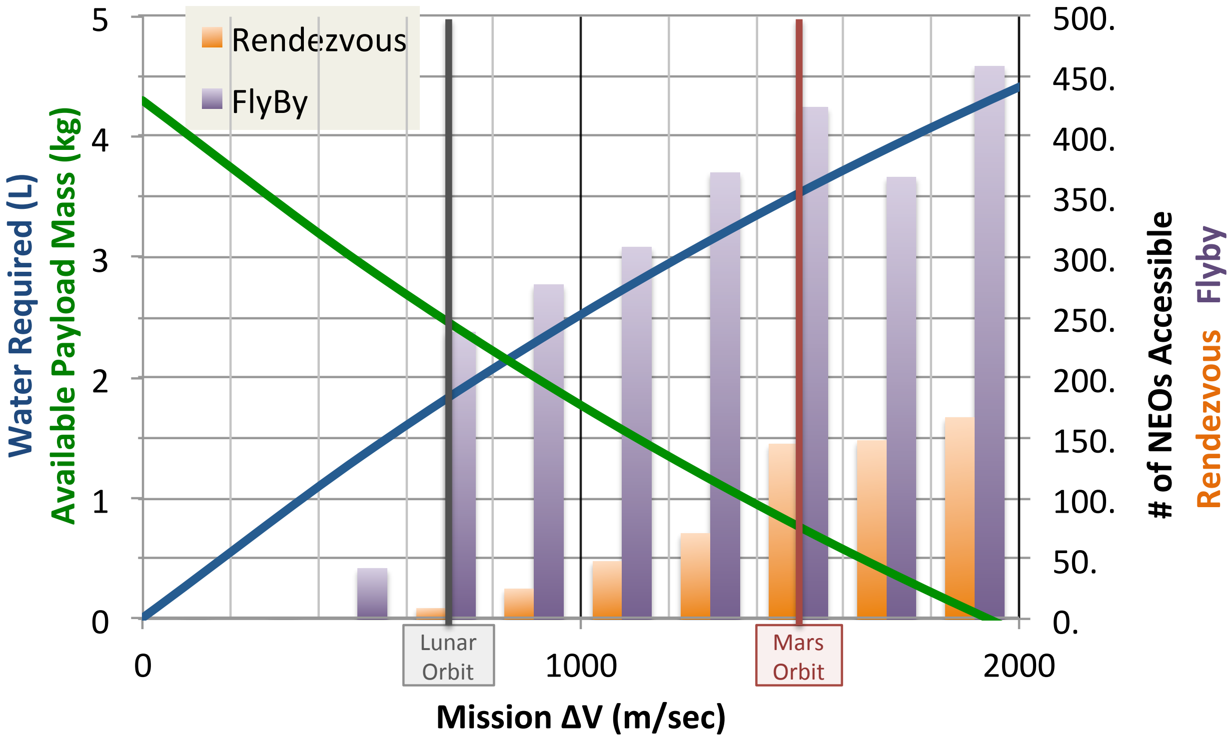

Figure 26. Available payload mass and water propellant volume required as a function of mission ∆V for a 6U HAMMERsat using a HYDROS thruster, and a histogram of the number of NEOs accessible within 200 m/s bins. *NanoTHOR can act as a re-usable, high-effective thrust propulsion "stage" to enable small, low-cost nanosatellites to access a large number of NEOs.*

mass allocation with the ΔV the thruster must provide to the HAMMERsat to reach a NEO after the NanoTHOR tether tosses the satellite to an escape trajectory. Also shown in the graph is the number of known NEOs the HAMMERsat could access within 0.2 km/s bins of ΔV capability. Columns are shown for either performing a flyby of the NEO or making rendezvous with the NEO. These ΔVs were calculated using data on known NEOs from the IAU Minor Planet Center.[8] With a full 3.3 L of water propellant, the HYDROS thruster can provide 1.3 km/s of ΔV after the NanoTHOR has tossed it to escape, and with this ΔV capability it could deliver 1 kg of payload to rendezvous with 110 known NEOs, and could perform a flyby of 1046 of the known NEOs. Furthermore, with 1.3 km/s of ΔV capability after NanoTHOR tosses it to escape, a single HAMMERsat could perform a flyby 'grand tour' of roughly 15 NEO objects within a 2.5 year mission. Table 5 shows ΔV's required to maneuver a satellite in the ecliptic plane to fly past a number of NEOs as they make nodal crossings.

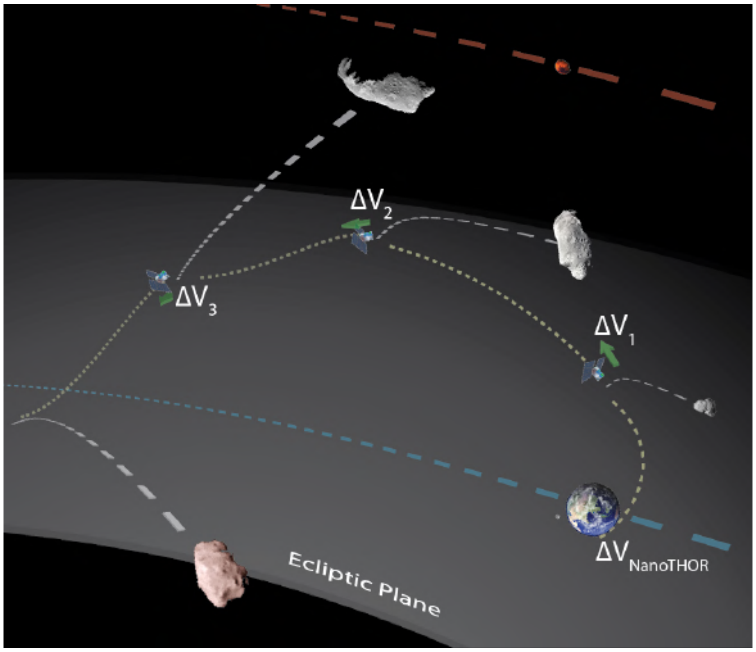

Figure 27. Grand Tour of NEOs by a NanoTHOR-tossed HAMMERsat maneuvering in the ecliptic plane to intercept NEOs as they make nodal crossings. *NanoTHOR can act as a reusable propulsion stage to enable a small nanosat to visit many NEOs.*

Table 5. Estimated Post-Earth-Escape ΔV's for a NEO Grand Tour.

	Object	ΔV	Cum. ΔV
1	(2012 UR18)	102.64	102.64
2	(2012 XA)	97.91	200.55
3	(2004 QB3)	19.72	220.27
4	(2009 UY17)	16.29	236.56
5	(2000 RD53)	98.54	335.1
6	(2003 WJ98)	26.63	361.73
7	(2007 PF2)	64.18	425.91
8	(2012 DR32)	65.44	491.35
9	(2004 VD17)	79.44	570.79
10	(2012 QV2)	41.25	612.04
11	(2004 RO111)	94.3	706.34
12	(2008 FO)	24.64	730.98
13	(2012 UX68)	247.2	978.18
14	(1998 QA1)	33.86	1012.04
15	(2007 RY19)	242.33	1254.37
16	(2000 WJ107)	222.12	1476.49
17	(2007 YF)	205.43	1681.92
18	(2011 DD5)	43.45	1725.37
19	(2011 KW15)	274.35	1999.72
20	(2012 QD8)	0	1999.72

These evaluations of the capabilities of a NanoTHOR-tossed HAMMERsat demonstrate that by acting as a re-usable propulsion 'stage' to boost nanosatellites from GTO to escape, NanoTHOR can enable a small satellite system to perform significant exploration of near Earth objects using an affordable launch architecture. Without the nearly 800 m/s of ΔV provided by NanoTHOR, a 6U CubeSat with a 350 Isp HYDROS thruster would not have sufficient ΔV capability to get from a GTO drop-off to a rendezvous with a NEO. A CubeSat with a much higher Isp Hall or Ion propulsion system might be able to generate sufficient ΔV, but the low thrust capability of such EP systems would require a long duration spiral out to escape, and likely would not provide the thrust authority necessary to accomplish rendezvous after an intercept transit. NanoTHOR thus could serve as a key enabling component of a low-cost program to survey multiple NEOs in preparation for robotic or manned missions by NASA or commercial enterprises to explore and utilize near Earth asteroid resources.

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[8] www.minorplanetcenter.net

6. EVALUATION OF TECHNICAL MATURITY AND RISKS

6.1 COMPONENT TECHNOLOGY TECHNICAL MATURITY

Table 6 lists the key component technologies necessary for the NanoTHOR system, along with their Technology Readiness Level (TRL) and a summary of the justification for the TRLs assigned. On the balance, the hardware necessary for a NanoTHOR system is "mid-TRL". Several prior contract efforts conducted by TUI have developed and tested relevant tethers, deployers, and sensors, and suitable flight-qualified avionics are commercially available. The key aspect of the concept that requires the most attention to mature it to flight readiness are the algorithms and software necessary to control deployment and winching of the tether to accomplish a controlled spin-up of the system and accurate toss of a nanosatellite payload. Additionally, methods for integrating the NanoTHOR system onto a host vehicle, coordinating the spin-up of the tether and vehicle, and ensuring safety of flight of the host must be developed. The work performed in this Phase I effort has established the basic feasibility of the control methods by demonstrating them in a simple, open-loop implementation. Further work will be necessary to implement them in a robust closed-loop control manner and validate them to a high level of fidelity.

Table 6. Technology Maturity of NanoTHOR 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 • Same tether material survived 10 years on orbit in TiPS mission
Deployer/Winch	4	• Orbital Winch prototyped & tested in lab environment in contract NNM04AA10C
Relative Position Sensing	5	• RelNav sensor demonstrated with prototype hardware using ISM S-Band frequencies in contract W31P4Q09C0272
Avionics	6	• Candidate avionics have been flight qualified
Host Integration	3	• SEDS tether systems were successfully integrated and demonstrated on Delta-II upper stages • NanoTHOR system requires coordinated control of spin-up of tether and stage
Flight Software	3	• The necessary tether control algorithms have been demonstrated in simulation (TetherSim, Matlab, Excel)

6.2 TECHNICAL RISKS

In the following subsections we discuss the key technical risks to the success of a NanoTHOR mission and detail methods to mitigate these risks in future efforts.

6.2.1 Tether Deployment Failure

As with any technology involving on-orbit deployables, deployment is the most significant risk for the success of a NanoTHOR system. Most in the space community are familiar with the Tethered Satellite System experiment flown twice on the Shuttle (TSS-1 and TSS-1R), and the fact that both times it flew, anomalies during deployment terminated the experiment prematurely. As a result of those failures, tethers have earned a reputation as a problematic technology. However, the fact is that over 75% of prior space tether experiments have successfully deployed their tethers and completed all of their mission goals, including: SEDS-1, SEDS-2, Plasma Motor Generator, OEDIPUS-A, OEDIPUS-C, TiPS, AeroCube-3, and the JAXA T-REX experiment. Furthermore, the failures of the TSS-1 and TSS-1R missions have both been tied to failures of the engineering process, not to a fundamental physics problem with tethers. As with any hardware operating in the space environment, a tether system must be properly engineered and tested if it is to function with high reliability.

To mitigate risks associated with deployment of the tether, the NanoTHOR system will use a combination of methods that have been proven in prior missions to enable reliable, controllable deployment of the tether. First, the initial portion of the deployment, at least several hundred meters of the tether, will be performed by ejecting the nanosatellite from its carrier on the launch vehicle and using its momentum to pull tether off the end of a small spool located on the payload. This simple "end-off" deployment method has been demonstrated successfully on several prior missions, including SEDS-1, SEDS-2, PMG, and TIPS. As that initial deployment is nearing its end, the NanoTHOR winch will begin paying out tether at a controlled rate, and will used control of the deployment rate to minimize the dynamic behavior of the tether as was accomplished in the SEDS-2 and TiPS experiments.

6.2.2 Contact Between Tether and Host Vehicle

An additional risk to the success of a NanoTHOR mission is the potential for the tether to contact the host vehicle and either become snagged on the vehicle or be severed due to abrasion against the vehicle. This risk results primarily because ensuring the tether does not contact the host requires that the the host vehicle's rotation always remain well synched to the tether's rotation. The host vehicle will have a large moment of inertia, and the relatively low tension on the tether during the initial phase of the spin-up maneuver will induce small torques on the host vehicle, which may not be sufficient to force the host's rotation to follow the tether's rotation. The most straightforward solution to this risk from a technical standpoint would be to use the NanoTHOR's RelNav sensor to track the relative position of the nanosat at the tether's tip, communicate that relative position to the host vehicle, and have the host vehicle use its ADCS to maintain its orientation constant with respect to the nanosat. However, from a practical standpoint this solution may be less practical, because most of the candidate launch vehicles use cold gas for attitude control, and likely do not have sufficient cold gas reserves for three days of operation. A second potential solution is to use a boom or 'fishing rod' structure extended from the deployer to move the tether attachment point further from the host vehicle's center of mass, increasing the torque the tether tension will apply to the host vehicle. A third potential solution is to vary the rate of tether deployment or reeling so as to vary the tether tension and thereby control the rotation of the host vehicle.

6.2.3 Collision Risks

Because the NanoTHOR concept involves the use of a multi-kilometer long tether deployed in orbit, the potential for collision between the tether and other spacecraft must be considered. The Area-Time Product, the collisional cross section of a satellite integrated over its time in orbit, enables a rough comparison of the collision probability represented by a satellite to other spacecraft. We can evaluate the Area-Time Product for the NanoTHOR tether by integrating its collisional cross section during its operation:

$$ATP = \int \bar{r}_{rso} L(t)\, dt, \tag{4}$$

where $\bar{r}_{rso}$ is the average diameter of the population of resident space objects. For the three days the NanoTHOR requires to deploy and toss a nanosatellite, its ATP is 150 m^2years. When compared to the ATP of a typical satellite deployed in a 700 km orbit, which is nearly 14,000 m^2yr,[9] the ATP of the NanoTHOR system, and thus its collision risk, is almost negligible. Furthermore, of the 3 days the tether is deployed, only a total of 100 minutes of that time is spent at LEO altitudes where the density of operational satellites and orbital debris is high, further reducing collision risks.

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[9] Nock, KT, Aaron, KM, McKnight, D., "Removing Orbital Debris with Less Risk," *J. Spacecraft and Rockets*, 25Jan13.

To mitigate risks of the tether colliding with active satellites during its operation, the CONOPS can be modified so that the upper stage performs a small apogee burn to raise its perigee above 2,000 km, so that the tether never encounters the dense traffic in LEO.

To eliminate any collision risks after the NanoTHOR module has tossed its payload, the tether can either be fully retracted, or cut away from the host vehicle while the system is near apogee and when the tether is swinging 'backwards' relative to the hosts orbital motion. This will drop the tether into a sub-orbital trajectory, and it will re-enter and burn up in the upper atmosphere within 6 hours.

6.2.4 MM/OD Impact Risks

The NanoTHOR's very thin but very long tether will be exposed to both the micrometeoroid flux present in cislunar space and the orbital debris flux present in Earth orbit. Calculating the probability that the NanoTHOR tether will not be severed by a MM/OD impact during its operational lifetime requires determining the average flux of MM/OD particles in the NanoTHOR's GTO orbit which have a diameter large enough that their impact will sever the tether, and integrating this flux over the duration of the mission. Unfortunately, neither the NASA/JSC ORDEM-2K debris model nor the ESA MASTER-2005 software cover orbit apogees above 2,000 km, and both are significantly out-of-date considering the ASAT tests and multiple debris-generating events that have occured since their release. NASA/JSC has developed a new version of their tool, ORDEM-2010, but it is still under review for release and is not available. Consequently, to estimate the probability of tether survival in a NanoTHOR mission, we have used ORDEM-2K to calculate fluxes of particles in a 300 km LEO orbit, and used these fluxes to estimate the probability the tether will be cut during the approximately 100 minutes it spends below 2,000 km in altitude during its mission.

The majority of the tether length is a 2-ply 44-Tex Dyneema yarn. The total tether length is 32.5 km, but the average deployed length during the mission is approximately 10 km, because it is deployed and retracted during the mission. Each ply of the yarn is approximately 0.25 mm in diameter when lightly loaded, and will present an average cross-sectional area to the MM/OD flux of approximately 2.5 m^2. Assuming a lethality coefficient of 3, each ply can be cut by an impactor of diameter 0.083 mm or larger, and both plys would need to be cut to cause the tether to fail. Integrating the flux distribution calculated by the ORDEM-2K model, the total rate of cuts by of lethal particles to each ply in the yarn is 4e-4 per m^2 per minute. The probability of survival of the 2-ply yarn tether for the 100 minutes of exposure to the LEO MM/OD population is

$$S(t) = (1-(1-e^{-ct})^2) \approx 99.9998\%. \tag{3}$$

This is only a crude estimate, and more detailed survivability analyses integrating the particle flux around the tether's full orbit will be performed once NASA/JSC releases ORDEM-2010.

To increase the survivability of the tether, we can again use the method of having the upper stage perform an apogee burn to raise its perigee above 2,000 km. This will isolate the tether from the dense orbital debris flux in LEO, reducing the impactor risk to that posed by the lower micrometeorite fluxes in mid-Earth-orbit (MEO) altitudes.

6.2.5 Analysis of Toss Timing Sensitivity

In the NanoTHOR system concept, the tether that tosses the nanosatellite payload from GTO to escape must rotate relatively quickly in order to provide the nearly 800 m/s ΔV required. At the end of the spin-up maneuver, the baseline design tether is rotating at over 8 degrees per second, or one revolution every 41 seconds. Proper timing of the release of the nanosatellite is thus important to achieving the C_3 required for hyperbolic escape. In order to evaluate the sensitivity of the nanosatellite's trajectory to timing release errors, we used TetherSim to calculate the payload's orbit over a range of release times around the optimal point. Figure 28 shows the variation in the nanosatellite's C_3 with release time (a C_3 of ≤0 is required to escape the Earth's gravity well). This graph shows that for this baseline system design, which was sized to get the nanosatellite just barely to escape, there is a roughly 2-second window for payload release within which the nanosatellite will be tossed to escape. This timing is well within the capabilities of a number of typical release mechanisms, such as pyros and SMA-based non-explosive actuators (NEAs). Any trajectory dispersion resulting from off-nominal release timing can readily be corrected using a very small amount of ΔV as the nanosat leaves the Earth's sphere of influence.

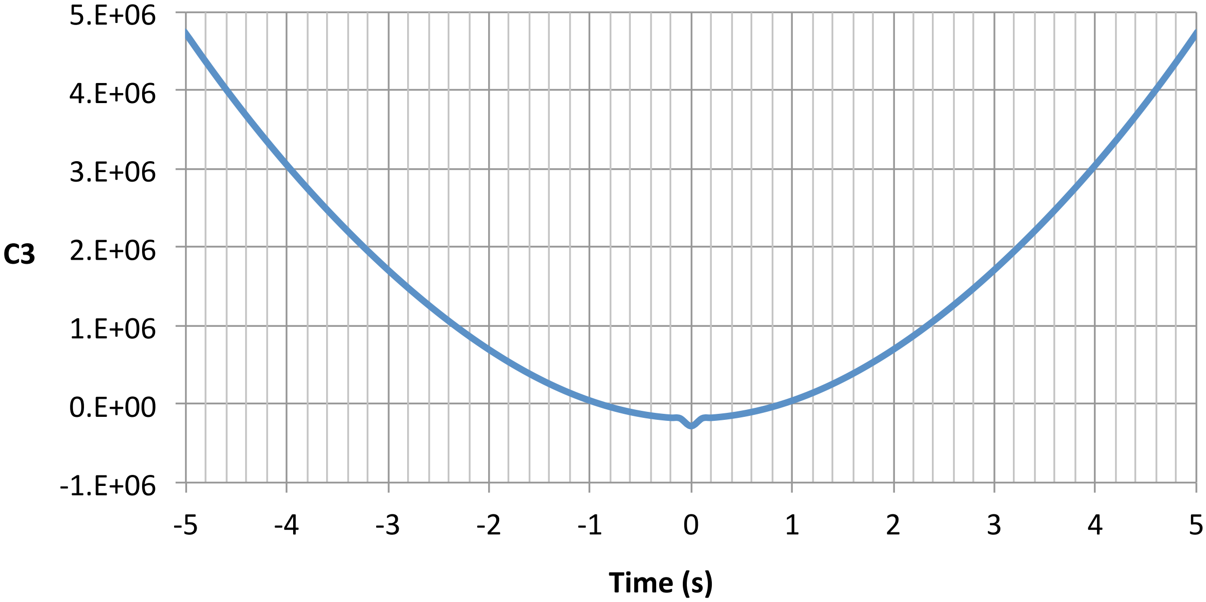


Figure 28. Sensitivity to release timing. *A NanoTHOR system designed to toss a payload just barely to escape would have a release window of approximately 2 seconds to achieve a payload C_3=0.*

7. TECHNOLOGY MATURATION PLAN

As summarized in Figure 6, most of the component technologies required for a NanoTHOR system are already at 'medium' Technology Readiness Levels. The key technology risk that must be addressed before this technology can be considered for flight validation are the overall control of the system, most importantly being control of deployment and retraction to ensure dynamic stability of the tether, upper stage, and nanosatellite payload during spin-up. Additionally, we must develop methods for integrating the NanoTHOR system onto a host vehicle while ensuring safety of flight for that host.

Figure 29 illustrates our proposed technology maturation plan for the NanoTHOR technology. The Phase II NIAC effort will focus upon advancing the flight control methods and software, the methods and designs for integration with the host vehicle, and the tether and winch hardware to the mid-TRL maturity where it will be suitable for implementation and flight-testing under NASA's Game Changing Development and Small Satellite Technology programs. This flight demonstration would validate the NanoTHOR technology to TRL-7, readying it for direct infusion into the critical path for future NASA flight missions. It will also enable TUI to begin providing the Asteroid Payload Express service to commercial, government, and academic organizations, opening thousands of near-Earth objects to affordable exploration and development.

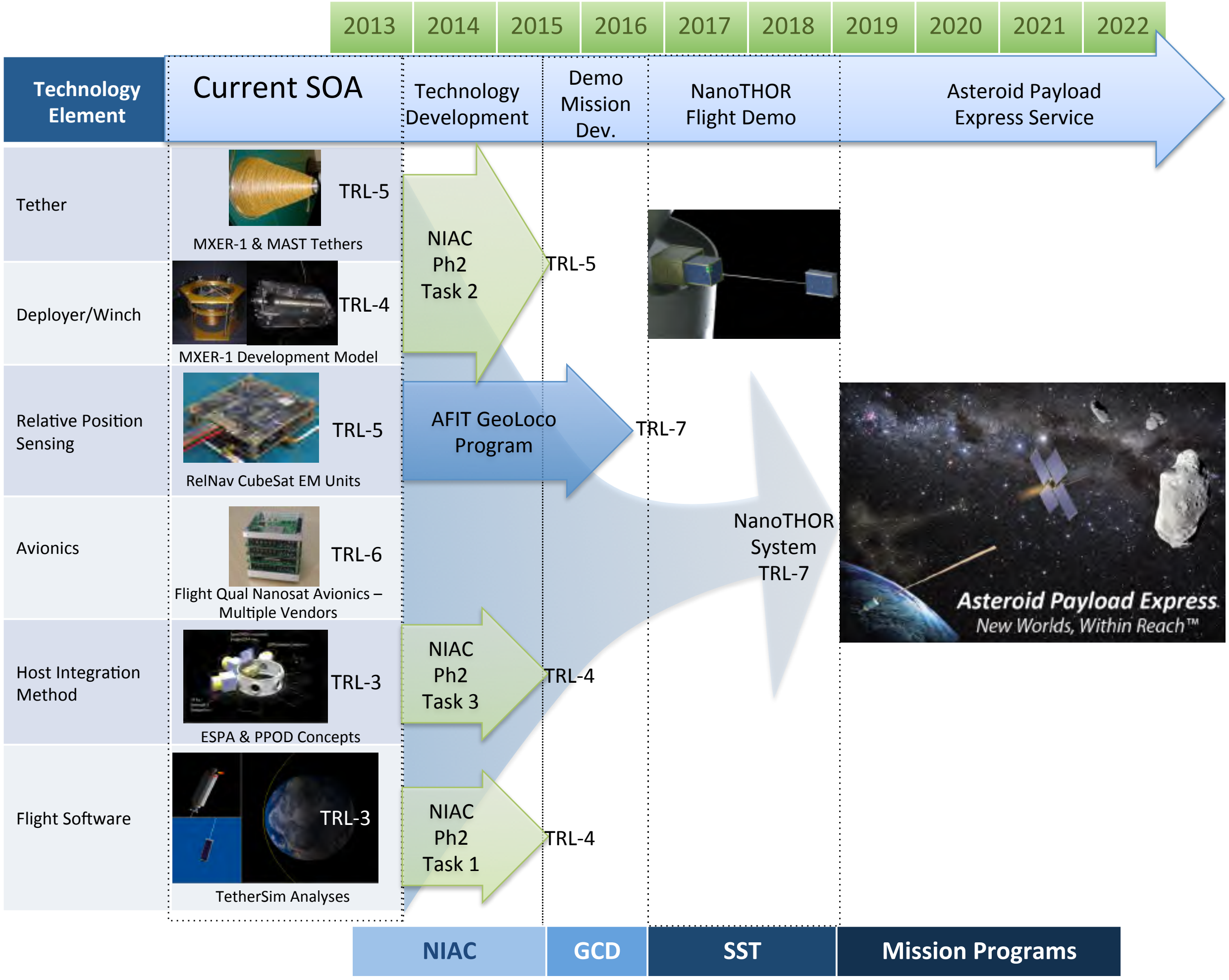


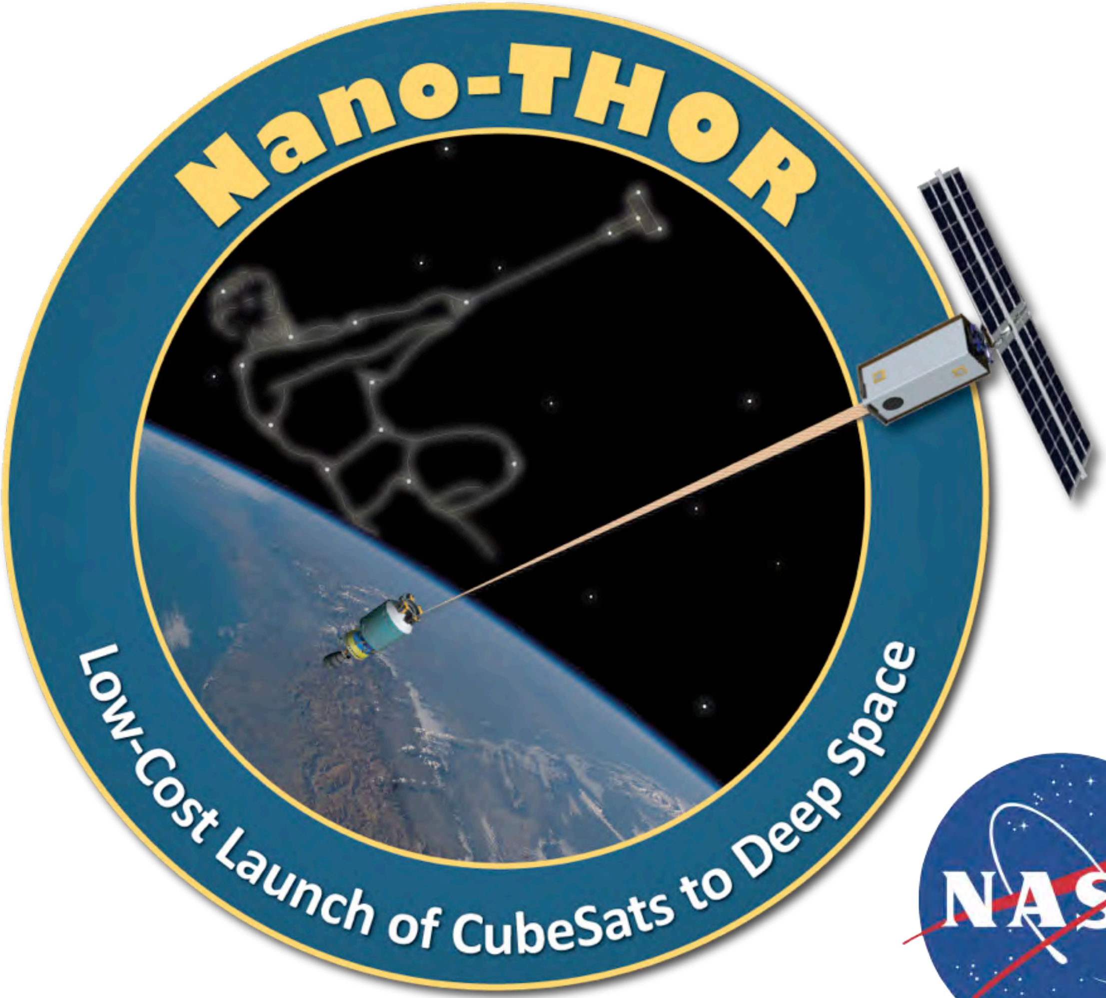
Figure 29. NanoTHOR Technology Maturation Plan. *Phase II NIAC efforts will mature the low-TRL component technologies to mid-TRLs, readying NanoTHOR for flight demonstration and transition to operational missions.*

8. CONCLUSIONS

In this Phase I effort, we have investigated the technical feasibility and value proposition for using a simple momentum-exchange tether system to scavenge orbital energy from an upper stage in geostationary transfer orbit in order to boost nanosatellites to Earth escape. We developed and simulated methods to enable a NanoTHOR module to accomplish rapid transfer of a nanosatellite from a GTO rideshare to an Earth-escape trajectory by deploying the nanosat at the end of a long, slender, high-strength tether and then using winching in the Earth's gravity gradient to convert orbital angular momentum into rotational angular momentum. These simulations demonstrated the feasibility of providing delta-Vs on the order of 800 m/s with a simple, low-mass tether system. We developed concept designs to enable the NanoTHOR tether to act as a reusable in-space upper stage, boosting multiple nanosatellites on a single launch and doing so with a mass requirement lower than that of conventional rocket technologies. Combining the NanoTHOR system to provide Earth-escape injection with a water-electrolysis based thruster for maneuvering in heliocentric orbit, we developed a concept for an "Asteroid Payload Express" service, which enables a 6U CubeSat to deliver small payloads to Mars orbit, lunar orbit, and rendezvous with at least 110 of the known near-Earth asteroids. Evaluation of the technology readiness of the components required for NanoTHOR indicate that the hardware required is all mid-TRL, and the lower-TRL controls and integration components can be advanced to mid-TRL with modest investment. By scavenging orbital energy from upper stages without any stored energy or propellant requirements, NanoTHOR permits deep-space nanosat missions to launch on rideshare opportunities, enabling NASA and commercial ventures to conduct affordable and frequent missions to explore deep space destinations.

NanoTHOR

Low-Cost Launch of Nanosatellites to Deep Space



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NASA

NIAC
NASA Innovative Advanced Concepts

NanoTHOR

- **Challenge Addressed:**
  - Emerging nanosatellite and CubeSat technologies could enable NASA to perform Exploration missions at lower cost, but ride-share opportunities to Earth escape are very rare
  - Restrictions on secondary payload stored energy limit opportunities to use conventional rockets to boost nanosats
  - Electric propulsion requires a long spiral out through the radiation belts

NanoTHOR Concept

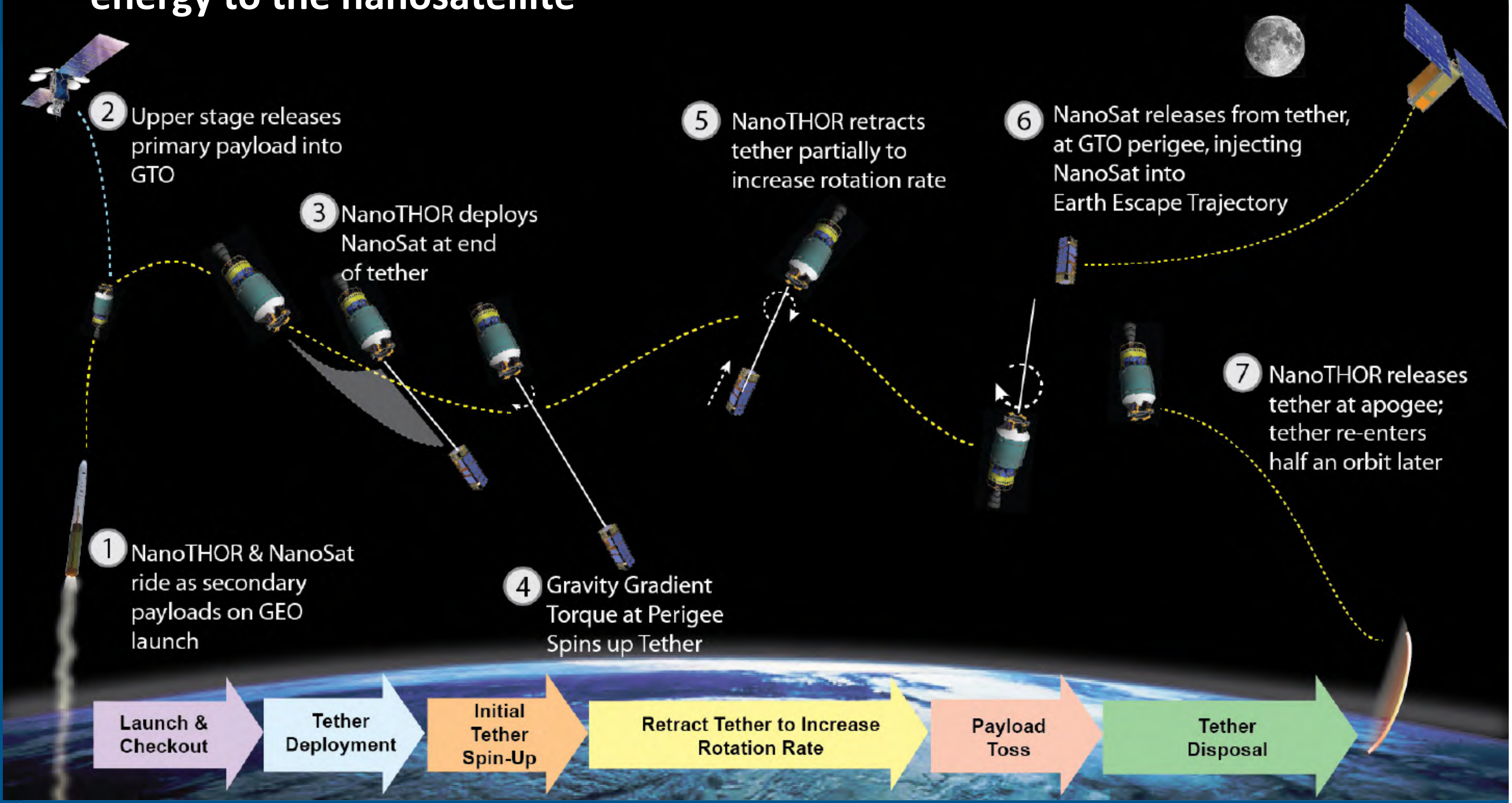
- **Proposed Solution:**
  - Launch nanosatellite as ride-share on GEO satellite launch
  - GTO=>Escape requires ΔV of 770 m/s
  - The "Nanosatellite Tethered High-Orbit Release" (NanoTHOR) system will use a simple high-strength tether to ***scavenge the orbital momentum*** of GEO upper stages to 'sling' multiple nanosatellites to Earth-escape
  - NanoTHOR enables *fast* (e.g. few hours or few days) transfer of multiple nanosats to escape trajectories with effective specific impulse comparable to EP thrusters that would require many months

NanoTHOR Concept

- **Benefits**
  - Enables fast delivery of secondary payloads to deep space trajectories without requiring chemical rockets that would pose a risk to the primary payload
  - NanoTHOR tether is re-usable, and can boost multiple nanosatellites with a lower total required mass than rocket technologies

CONOPS

- **Nanosat & NanoTHOR ride as secondary payloads on GEO satellite launch**
- **NanoTHOR uses slender, high-strength tether to transfer stage's orbital energy to the nanosatellite**



① NanoTHOR & NanoSat ride as secondary payloads on GEO launch

② Upper stage releases primary payload into GTO

③ NanoTHOR deploys NanoSat at end of tether

④ Gravity Gradient Torque at Perigee Spins up Tether

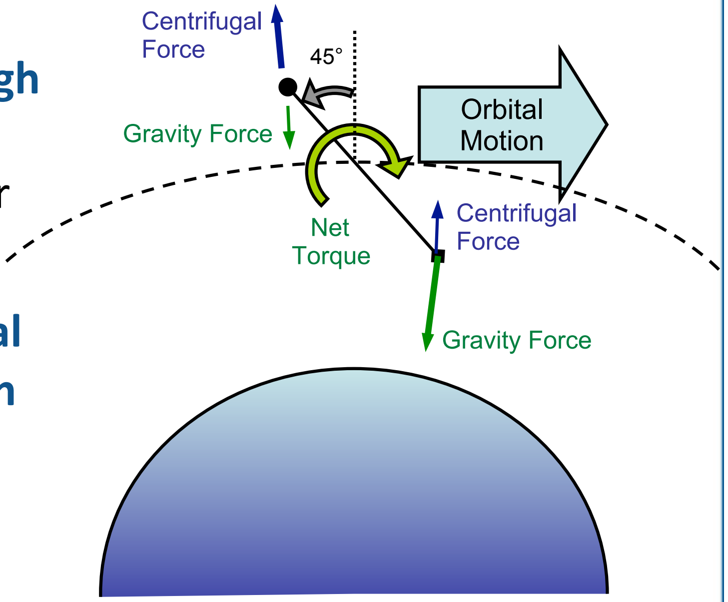
⑤ NanoTHOR retracts tether partially to increase rotation rate

⑥ NanoSat releases from tether, at GTO perigee, injecting NanoSat into Earth Escape Trajectory

⑦ NanoTHOR releases tether at apogee; tether re-enters half an orbit later

Tether Spin-Up CONOPS

- **Getting tether deployed and 'spun up' in highly elliptical GTO orbit is a significant dynamics control challenge**
- **In elliptical orbit, the tether spin angular momentum and orbital angular momentum are coupled**
- **Tether spin gets a 'kick' every time it passes through perigee**
  - Direction of kick depends upon phasing of tether rotation w.r.t. orbit
- **Once tether is spinning fast enough to rotate several times during a perigee pass, the angular momentum exchange becomes small**
- **Proposed Solution:**
  - First, to start tether spinning:
    - Control tether deployment over several orbits to maximize transfer of orbit angular momentum to spin angular momentum
  - Once a stable spin is established:
    - Retract tether to increase spin rate (via conservation of angular momentum) until required tip velocity is reached



Tether Spin Equations of Motion

Rate of change of tether rotation rate w.r.t. true anomaly

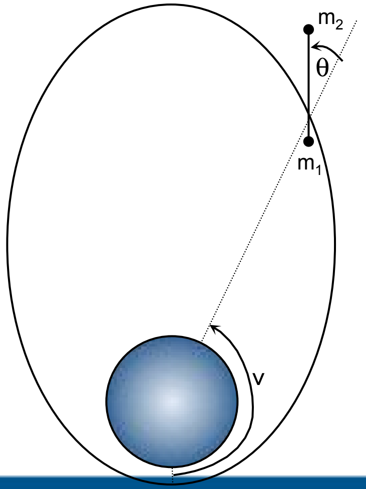
Effect of tether deployment

$$\theta'' = 2(\theta'+1)\left[\frac{e\sin\nu}{1+e\cos\nu} - M^{*}\frac{\Lambda'}{\Lambda}\right] - \frac{3}{1+e\cos\nu}\sin\theta\cos\theta$$

$$\Lambda'' = \frac{2e\sin\nu}{1+e\cos\nu}\Lambda' - M^{**}\frac{(\Lambda')^2}{\Lambda} + M^{***}\Lambda\left[(\theta'+1)^2 + \frac{3\cos^2\theta - 1}{1+e\cos\nu}\right] - T^{*}$$

Rate of change of tether deployment rate w.r.t. true anomaly

Normalized tether tension



$( )' = \frac{d( )}{d\nu}$

$\nu =$ true anomaly

$e =$ eccentricity

$\theta =$ in-plane libration angle

$\Lambda = \frac{\ell}{L} =$ normalized tether length

$\ell =$ deployed tether length

$L =$ total tether length

$T^{*} = \frac{T}{m_1\dot{\nu}^2 L(m_2+m_t)/(m_1+m_2+m_t)} =$ normalized tether tension

$\mathrm{M}^{*} = m_1\left(m_2+\frac{m_t}{2}\right)\Big/\left[m^{*}m\right]$

$\mathrm{M}^{**} = (2m_1-m)\frac{m_t}{2}\Big/\left[m_1(m_2+m_t)\right]$

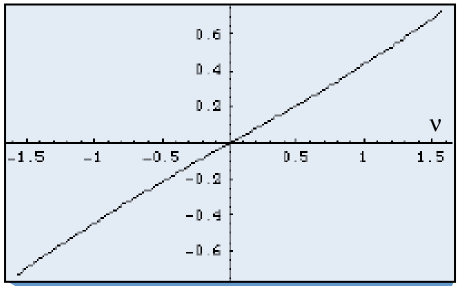
$\mathrm{M}^{***} = \left(m_2+\frac{m_t}{2}\right)\Big/(m_2+m_t)$

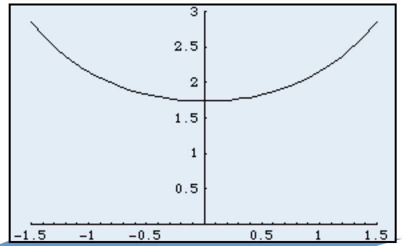
$m = m_1+m_2+m_t$

$m^{*} = \frac{\left(m_1+\frac{m_t}{2}\right)\left(m_2+\frac{m_t}{2}\right)}{m} - \frac{m_t}{6} =$ reduced mass of system

Spin Equation Analysis

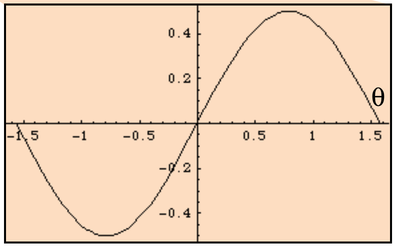
- Tether deployment always slows rotation
- Tether retraction increases rotation rate





$$\theta'' = 2(\theta'+1)\left[\frac{e\sin\nu}{1+e\cos\nu} - M^{*}\frac{\Lambda'}{\Lambda}\right] - \frac{3}{1+e\cos\nu}\sin\theta\cos\theta$$

No dependence on θ and symmetric about periapse, so contribution minimal



<u>Solution:</u> Control tether deployment rate so that tether passes perigee with ~ -30° in-plane libration angle while keeping tension always > 0

We want θ to be ≈ -30° to maximize spin-up of tether during perigee pass

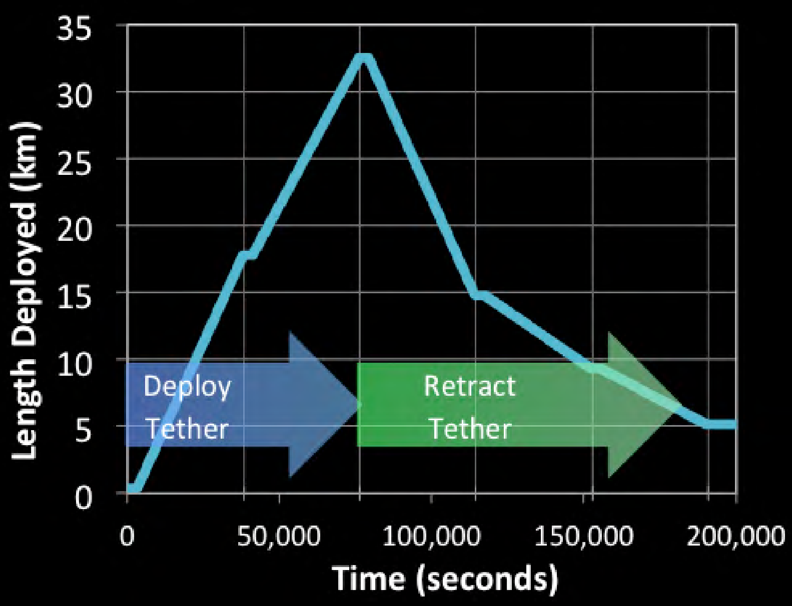
e.g. keep: $\Lambda'' < \frac{2e\sin\nu}{1+e\cos\nu}\Lambda' - M^{**}\frac{(\Lambda')^2}{\Lambda} + M^{***}\Lambda\left[(\theta'+1)^2 + \frac{3\cos^2\theta - 1}{1+e\cos\nu}\right]$

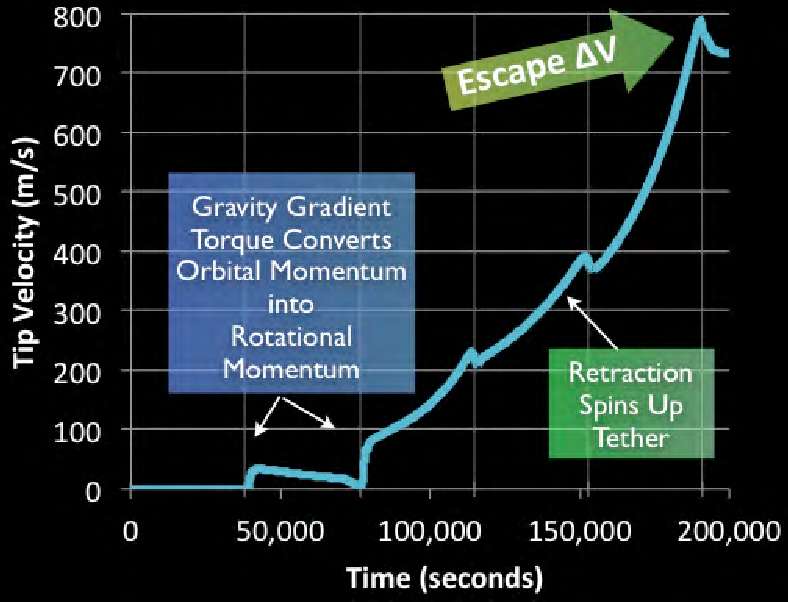
Tether Spin-Up in GTO

TETHERS UNLIMITED

Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

- **Deploy tether over 2 orbits at ~50 cm/s**
- **Vary deployment rate so that tether is ~30° behind vertical when approaching perigee**
- **Gravity gradient provides torque to get tether spinning**
- **Retract tether at ~25 cm/s to increase spin rate**



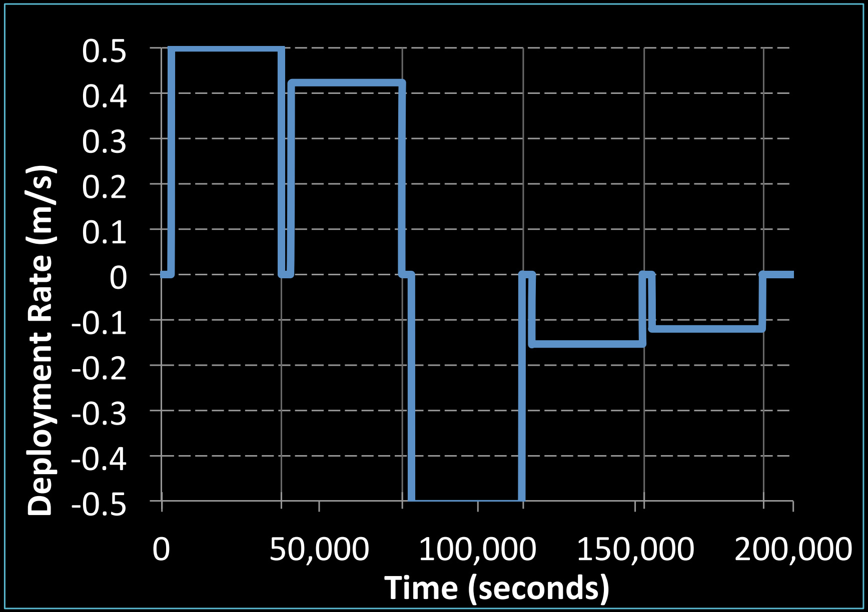


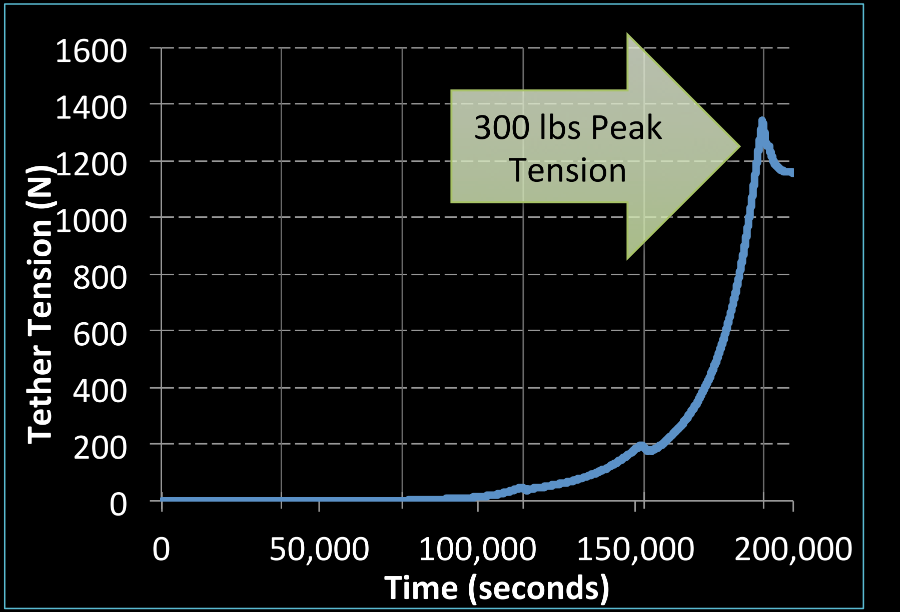
We can use tether reeling in the Earth's gravity well to spin up the tether

Tether Spin-Up Reeling

Advanced Propulsion, Power, & Comm.
for Space, Sea, & Air

For 10 kg Nanosat:

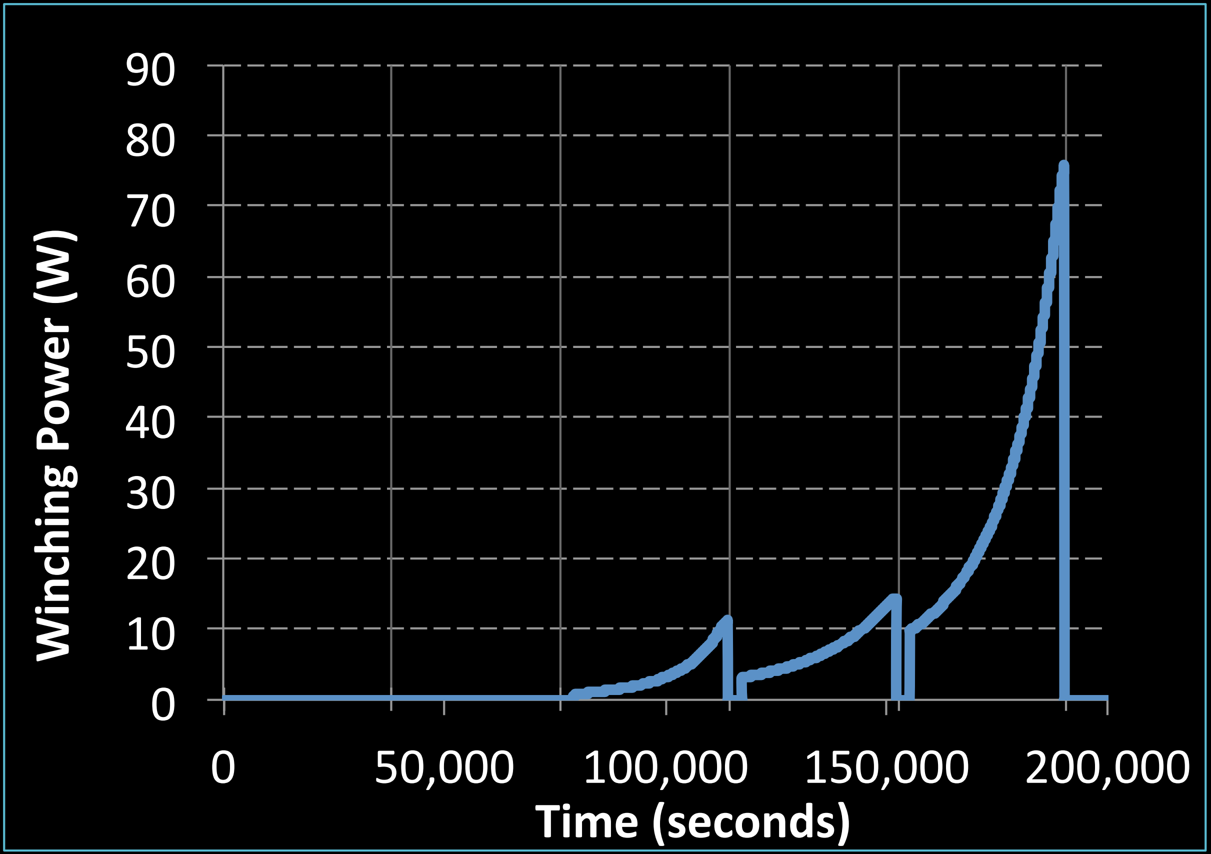


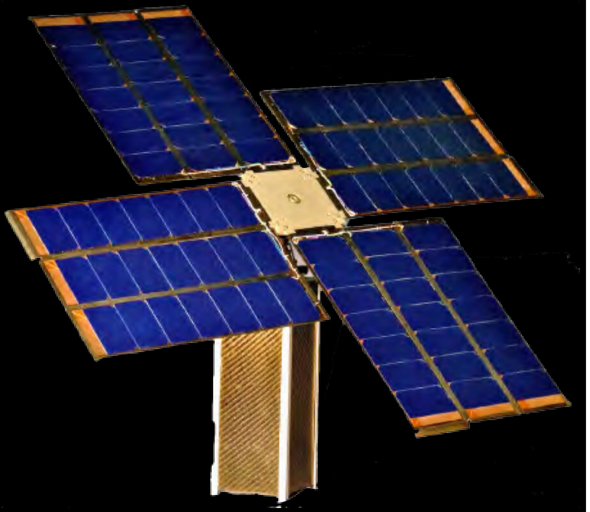


300 lbs Peak Tension

Reeling Rates and Tether Tension are Reasonable

Winch Power Required





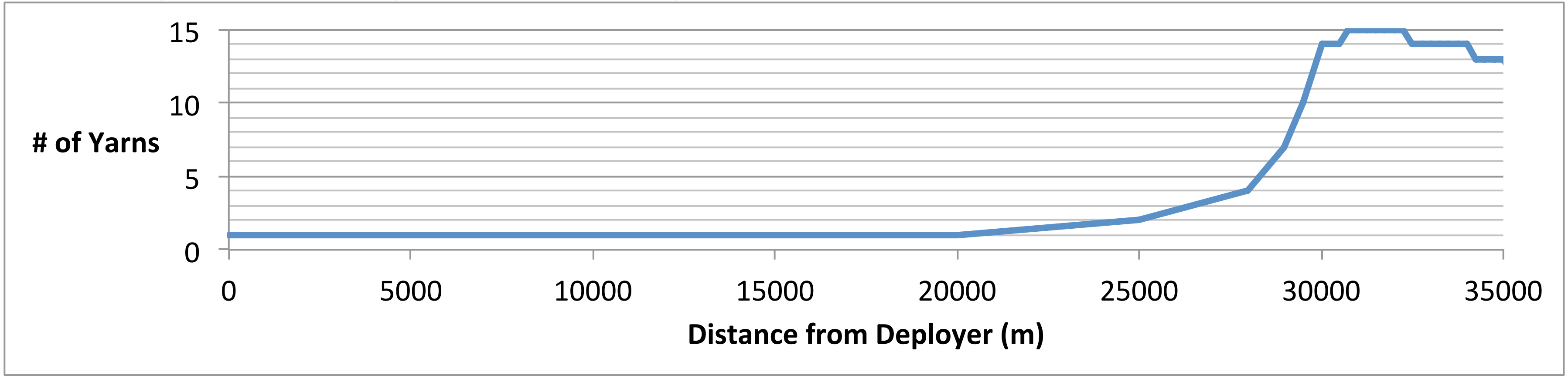
80W SunMill™
Deployable Array
for CubeSats

Power Required for Spin-Up Reeling Is Feasible Within a Small, Low-Cost System

Tether Design & Mass

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

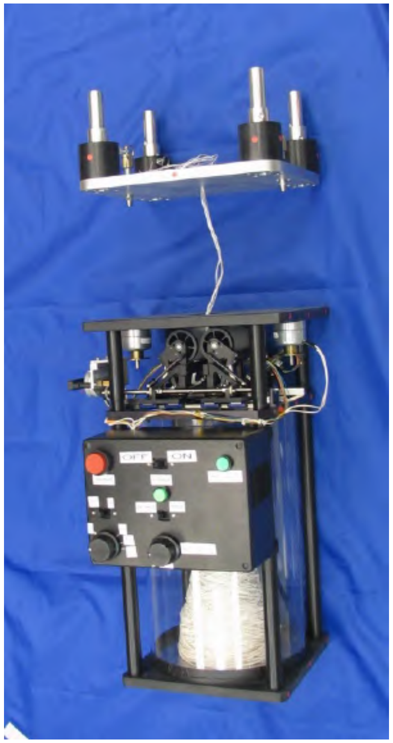
- Material: Dyneema/Spectra (HMWPE)
- Braided tape of 88-Tex yarns (think dental floss)
- Stepwise-tapered to optimize mass

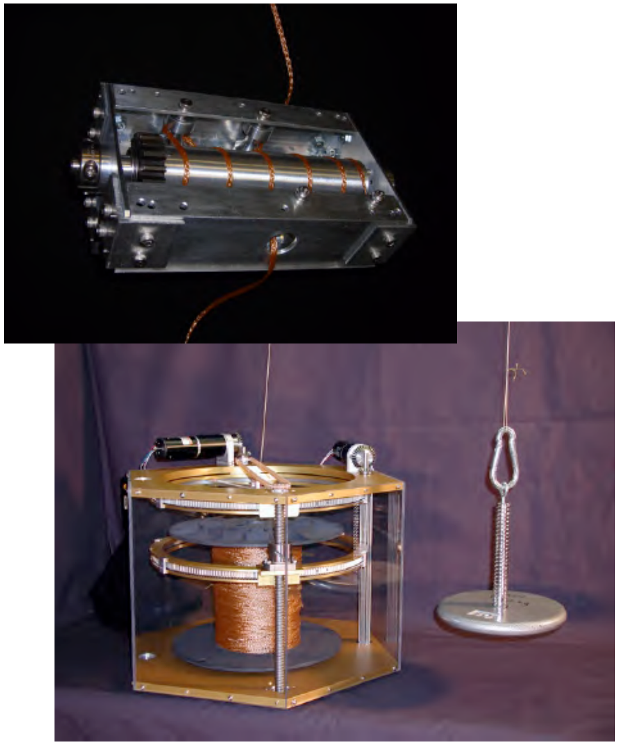


- Total tether mass: **12 kg** ← for a 10 kg payload
- Tether mass is > solid propellant mass to provide the same ΔV, but tether is re-usable for multiple payloads

Orbital Winch™

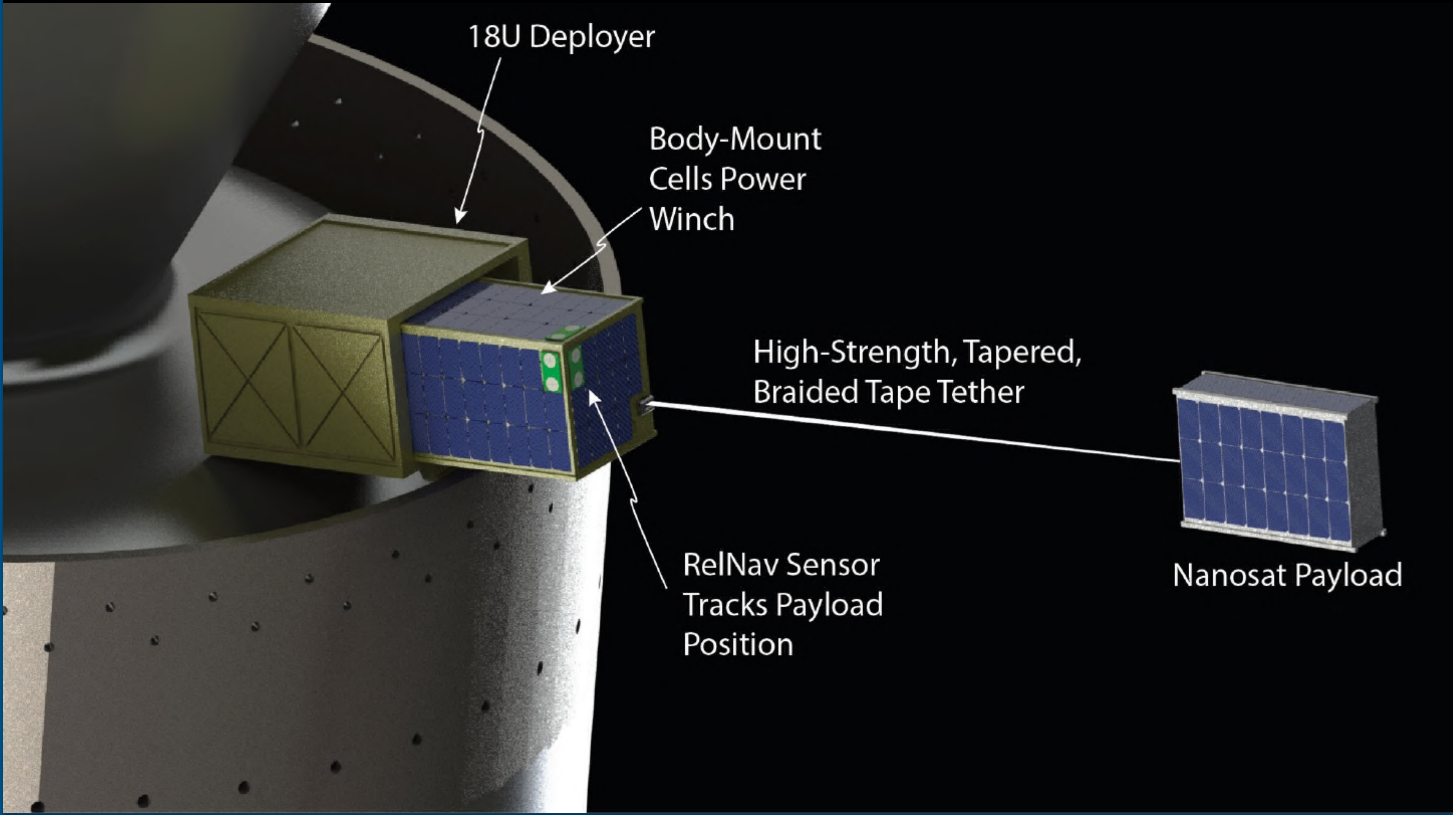
- **NanoTHOR leverages tether deployment/retraction mechanism technology developed under NASA and DARPA funding**
  - Deployer component matured to TRL-5 by microgravity testing
  - High-load retraction capability demonstrated to TRL-4



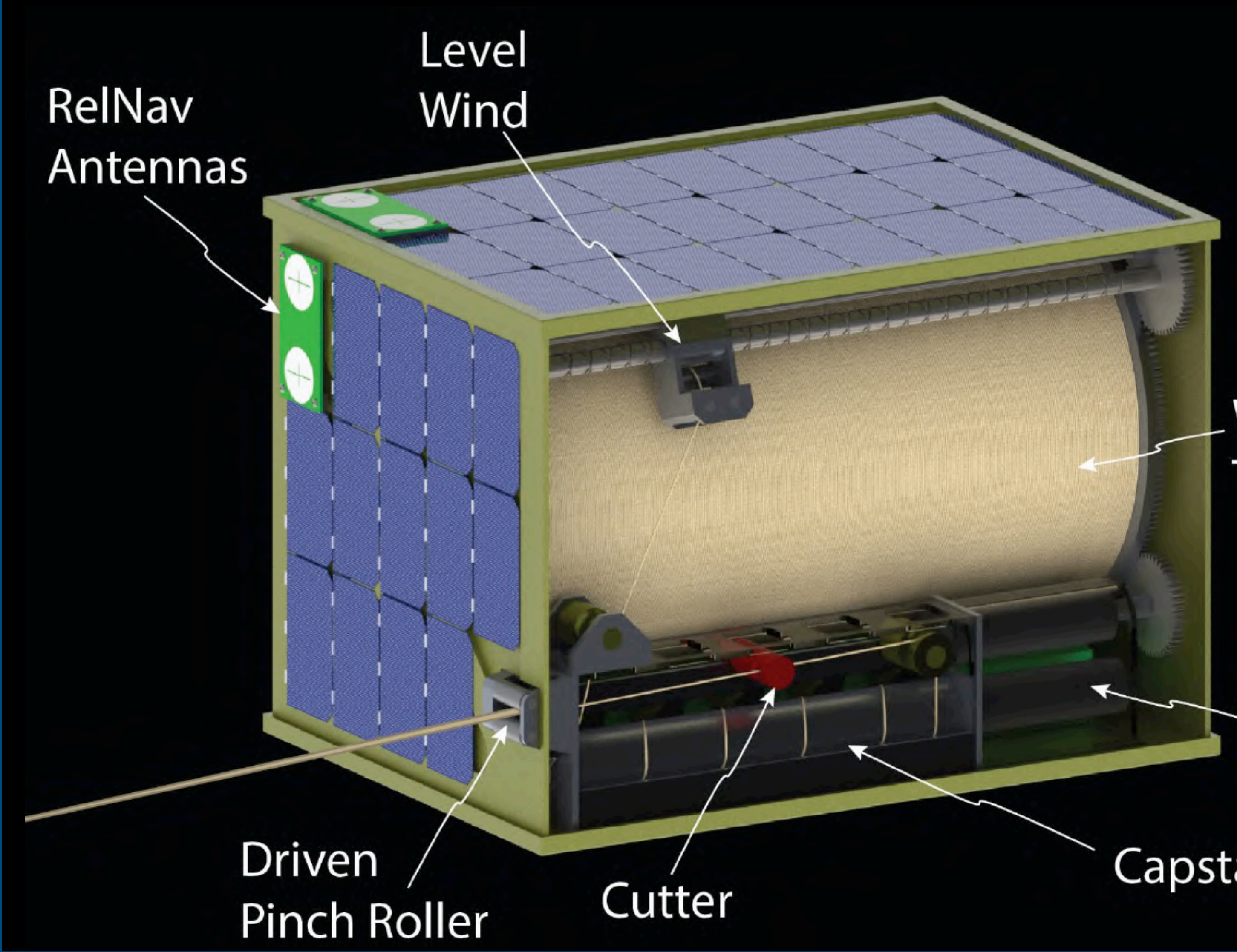


Concept Design

- **6U Nanosat Payload and Winch fit within 18U Deployer**



Winch Design



Component	Mass, kg (CBE)
Structure & Mech.	4.7
Avionics	2.3
Motors	0.4
Tether	12.0
TOTAL	**19.4 kg**

NanoTHOR Value Proposition

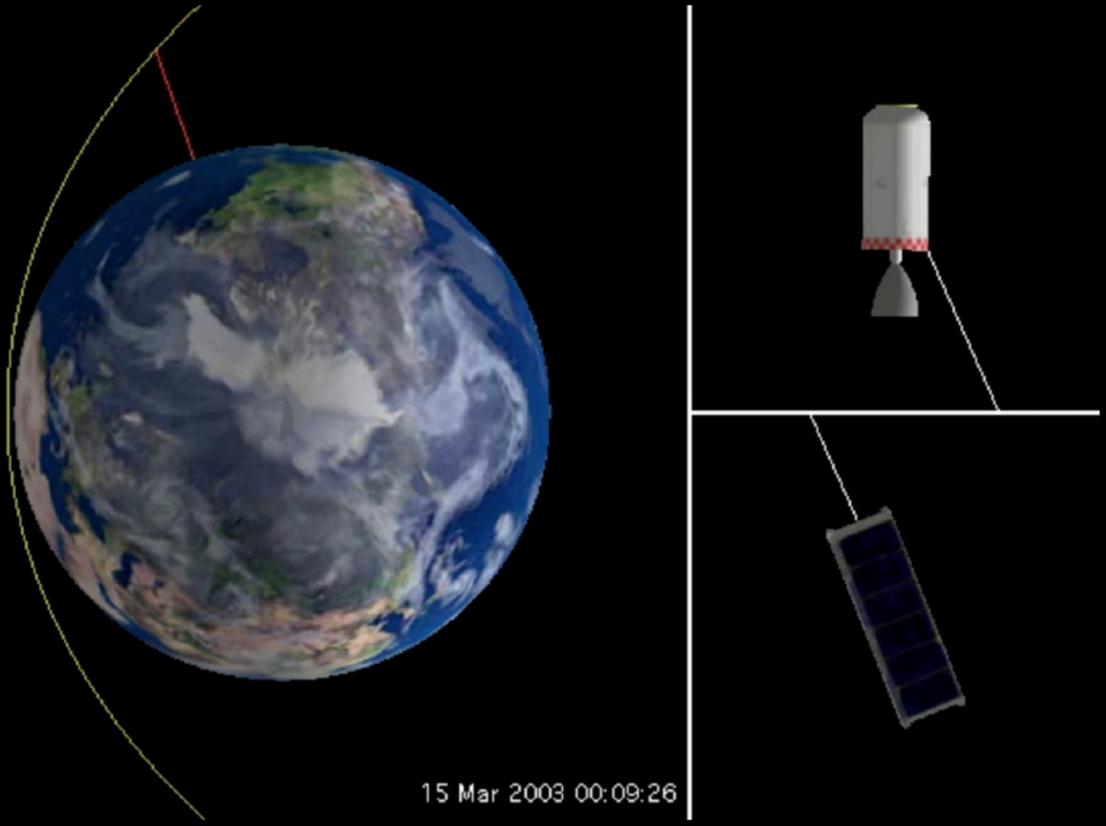
- **Cost comparison based on published commercial secondary payload launch costs:**
  - Conventional:
    - To directly launch a single 10 kg, 6U nanosat to escape would require either a dedicated launch or booking an entire secondary payload manifest **=>~$24M**
  - NanoTHOR
    - Launch of 12U Tether module + 6U nanosat: $ 2.5M
    - Tether module hardware & Ops *recurring* cost: ~$ 1.5M

$ 4M

- **~6X launch cost savings enabled by NanoTHOR**

Ongoing Work

- Modeling of tether, spacecraft, and orbital dynamics during spin-up maneuver
- Evaluate methods for coordinating spacecraft attitude with tether rotation to prevent tether contact with spacecraft



Summary

- **NanoTHOR "harvests" orbital energy from spent upper stage to boost nanosat payloads**
- **Control of tether deployment and retraction can enable ΔV's sufficient for GTO->Escape boost**
  - Boosting multiple nanosats per mission is feasible
- **Leverage recent multi-$M investments by NASA & DoD in tether tech maturation to enable near-term validation**
- **NanoTHOR enables frequent and low-cost delivery of nanosats to Earth-escape trajectories**

TETHERS UNLIMITED

Advanced Propulsion, Power, & Communications
for Space, Sea, & Air

Asteroid Payload Express

Architecture for Low-Cost and Frequent Prospecting of NEOs

Dr. Rob Hoyt
Jeffrey Slostad, Lenny Paritsky, Nestor Voronka, Todd Moser, Greg Jimmerson
Tethers Unlimited, Inc
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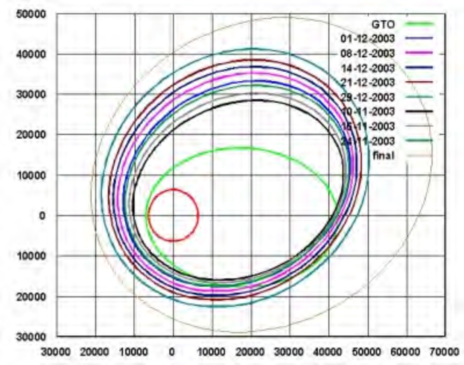
NASA Innovative Advanced Concepts

Challenges for NEO Exploration

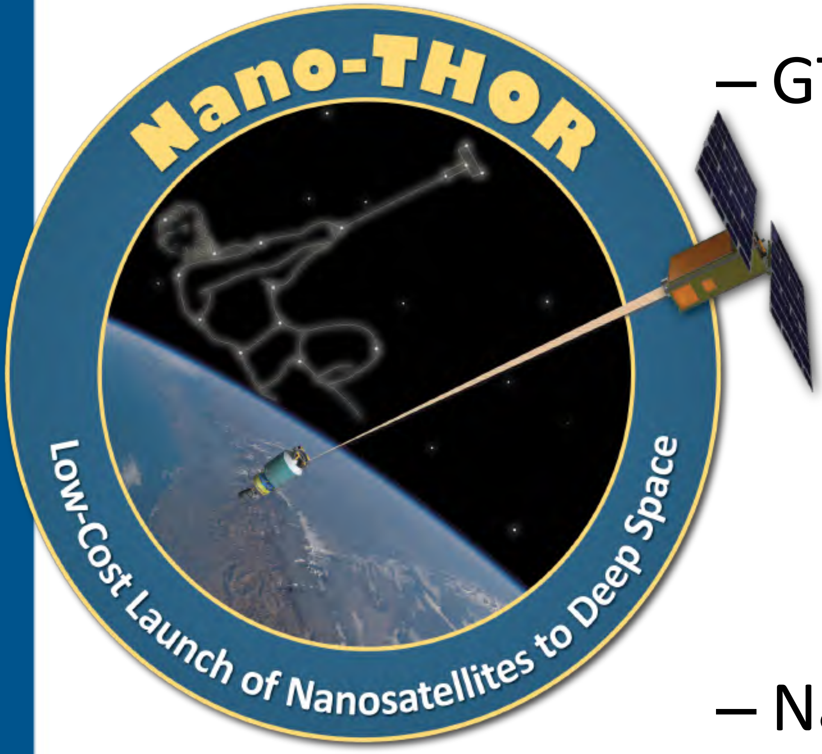
- Emerging nanosatellite and CubeSat technologies could enable affordable missions to NEOs
- BUT: ride-share opportunities to Earth escape are very rare
- Restrictions on secondary payload stored energy limit opportunities to use rockets to boost nanosats
- Electric propulsion requires a long spiral out through the radiation belts



Asteroid Payload Express

- **Combines two advanced space technologies to enable rapid, affordable delivery of small payloads to NEOs:**
  1. Uses "momentum scavenging" to boost nanosat from GTO Rideshare to Escape
  2. HYDROS™ Electrolysis Thruster provides high-Isp, high-thrust propulsion & pointing with safe, storable, non-toxic propellant: Water!

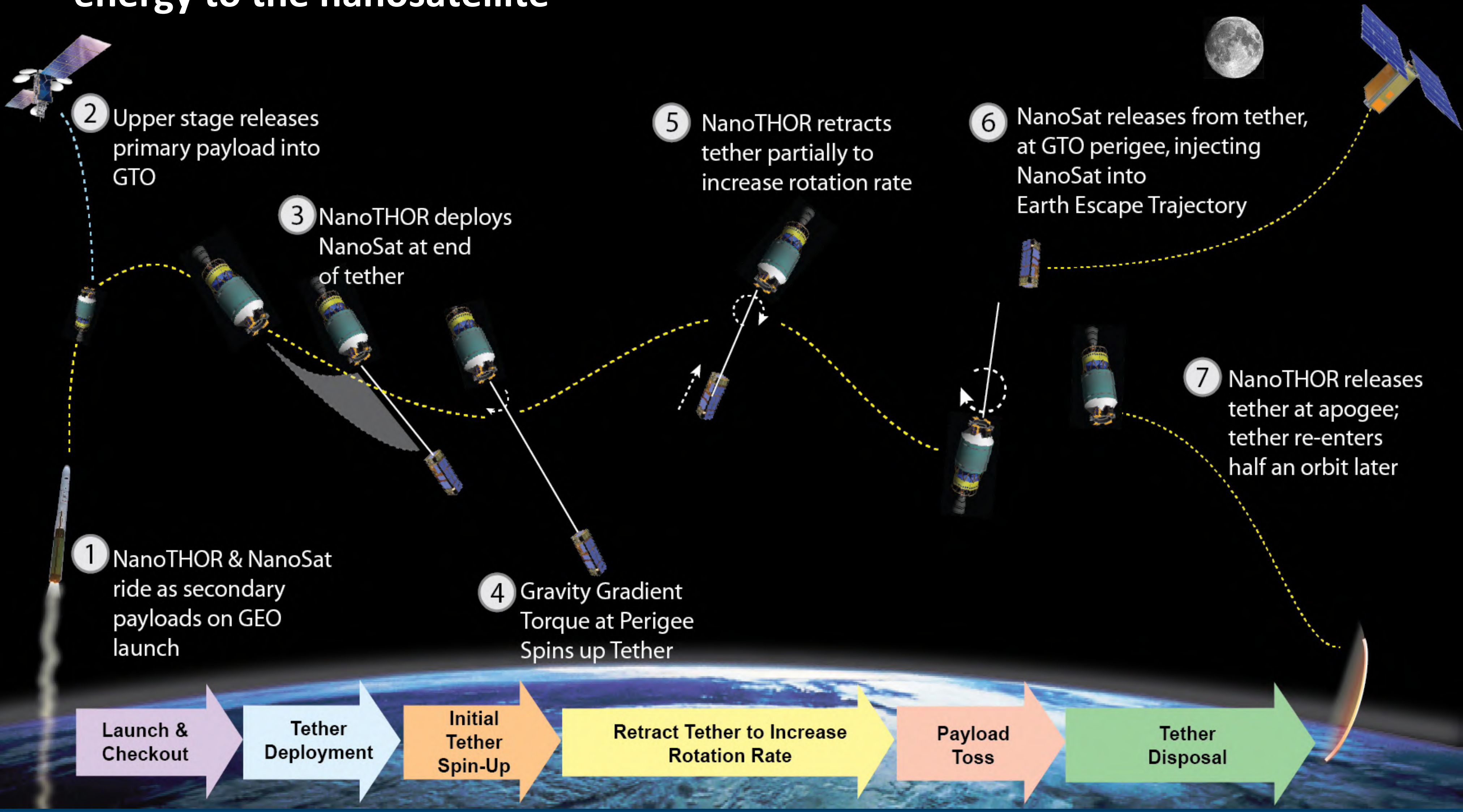
NanoTHOR



- Launch nanosatellite as ride-share on GEO satellite launch
- GTO=>Escape requires ΔV of 770 m/s
  - The “Nanosatellite Tethered High-Orbit Release” system uses a simple high-strength tether to ***scavenge the orbital momentum*** of GEO upper stages to ‘sling’ nanosatellites to Earth-escape
- NanoTHOR enables *fast* (e.g. few days) transfer of multiple nanosats to escape trajectories

NanoTHOR CONOPS

- **Nanosat & NanoTHOR ride as secondary payloads on GEO satellite launch**
- **NanoTHOR uses slender, high-strength tether to transfer stage's orbital energy to the nanosatellite**



① NanoTHOR & NanoSat ride as secondary payloads on GEO launch

② Upper stage releases primary payload into GTO

③ NanoTHOR deploys NanoSat at end of tether

④ Gravity Gradient Torque at Perigee Spins up Tether

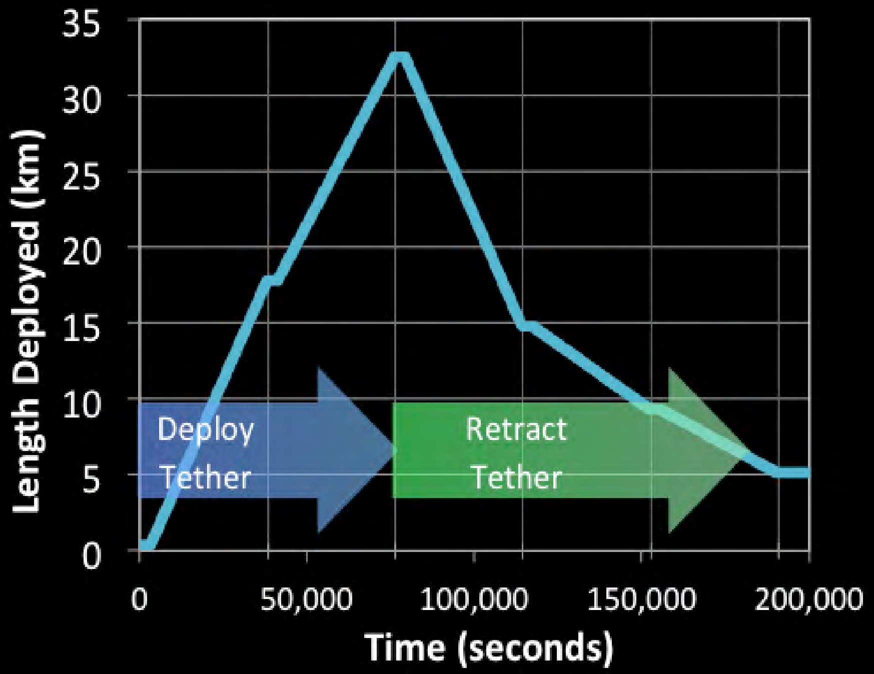
⑤ NanoTHOR retracts tether partially to increase rotation rate

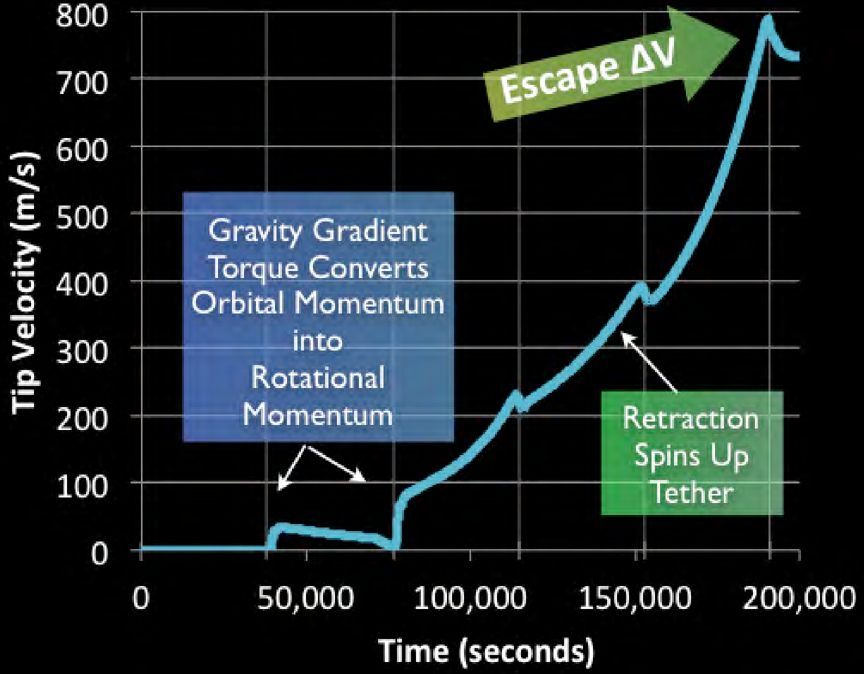
⑥ NanoSat releases from tether, at GTO perigee, injecting NanoSat into Earth Escape Trajectory

⑦ NanoTHOR releases tether at apogee; tether re-enters half an orbit later

Tether Spin-Up in GTO

- Deploy tether over 2 orbits at ~50 cm/s
- Vary deployment rate so that tether is ~30° behind vertical when approaching perigee
- Gravity gradient provides torque to get tether spinning
- Retract tether at ~25 cm/s to increase spin rate

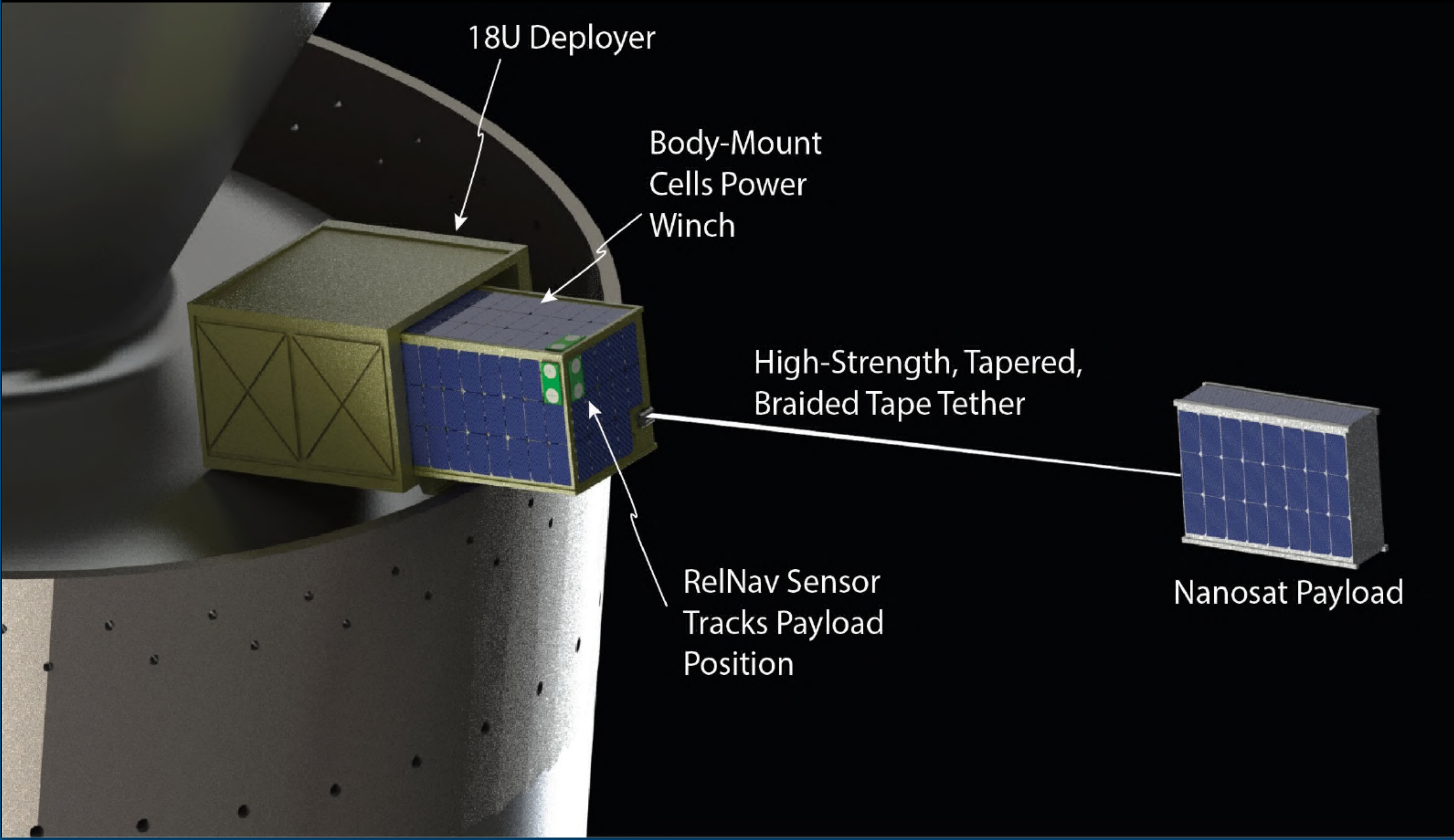




We can use tether reeling in the Earth's gravity well to spin up the tether

Concept Design

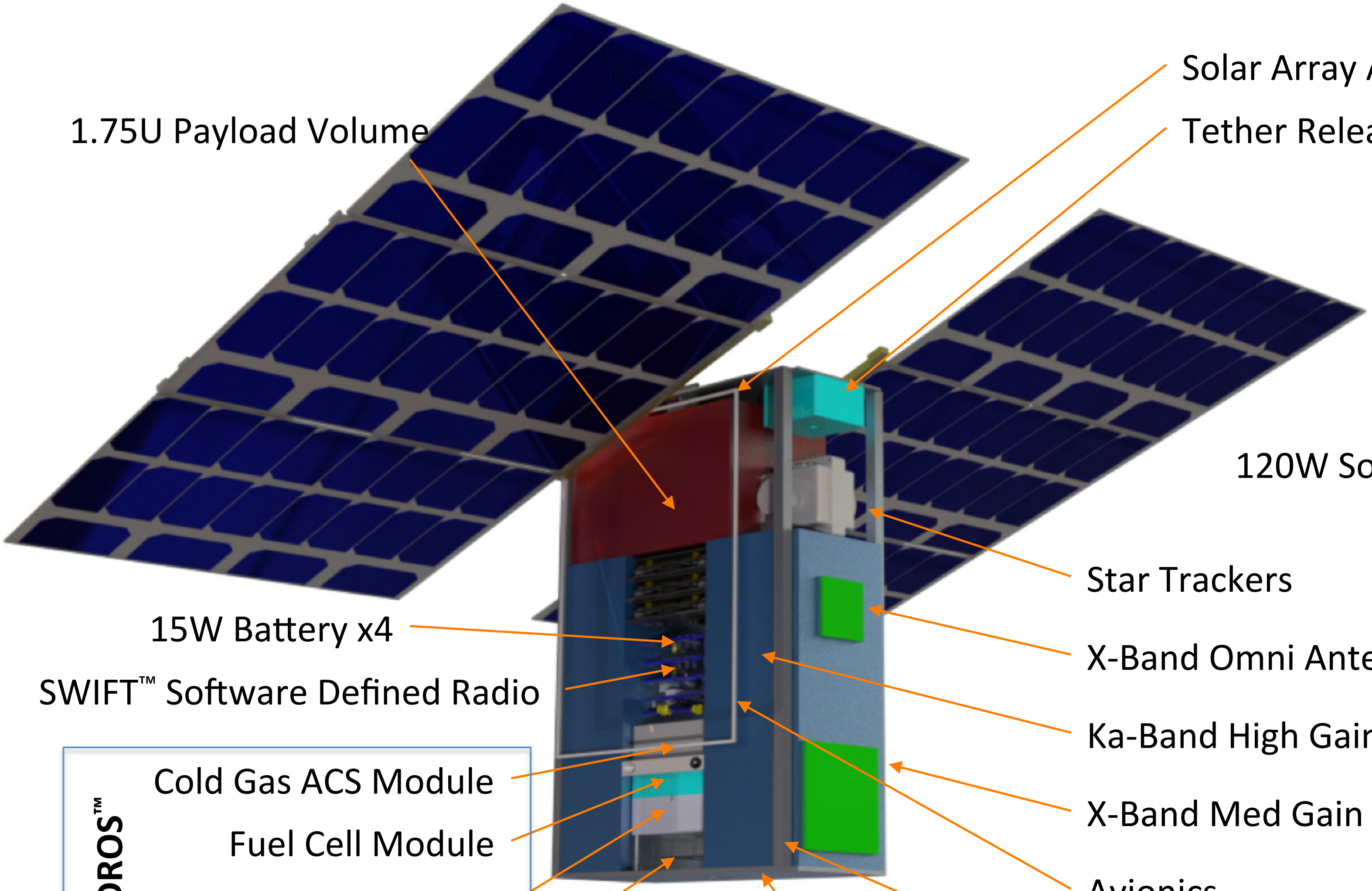
- **6U Nanosat Payload and Winch fit within 18U Deployer**



And What Does NanoTHOR Throw?

HAMMERsat

- Hurled Asteroid Mapping, Mining, Exploration, & Rendezvous Satellite



1.75U Payload Volume

15W Battery x4

SWIFT™ Software Defined Radio

HYDROS™

- Cold Gas ACS Module
- Fuel Cell Module
- Gas Handling Module
- Thruster Module

VSRS™ Structural Radiation Shielding

Solar Array Actuator

Tether Release

120W Solar Array

Star Trackers

X-Band Omni Antenna

Ka-Band High Gain Antenna

X-Band Med Gain Antenna

Avionics

Water Tanks (2x1.65L)

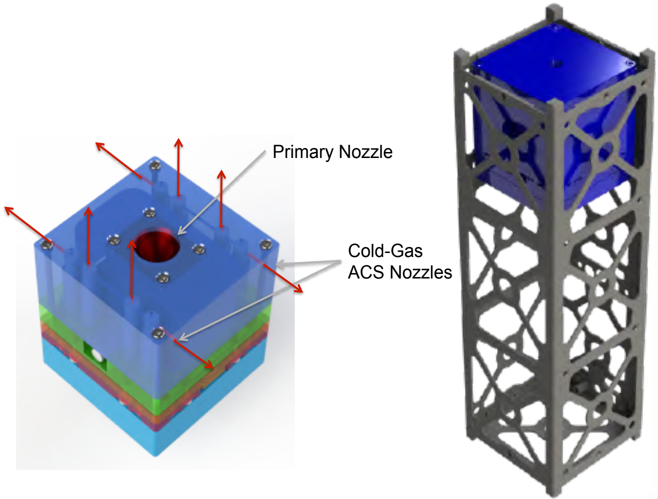
HYDROS™
Water Electrolysis Propulsion System

HYDROS Water Electrolysis Propulsion

- **Allows secondary payloads to launch with a *safe, storable, low-pressure, non-toxic* propellant: WATER**
- **Fuel cell electrolyzes water into oxygen and hydrogen once on-orbit**
- **High performance bipropellant thruster provides up to 1 N of thrust at 300 seconds of specific impulse for:**

  Orbit raising, plane changes, precision pointing, large delta-V maneuvers

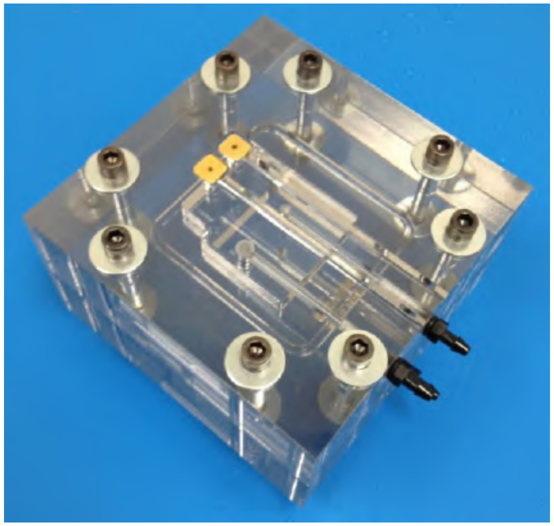
- **Total propulsion system volume <1U, including electronics**
- **Available in in two configurations, including one that utilizes 3U+ volume**



Fuel Cell

- **HYDROS™ fuel cell is designed to generate and pressurize gaseous oxygen and hydrogen up to 100 psia**
- **Designed for zero-g operation**
  - Hydrogen and oxygen are inherently separated and released through isolated output ports
  - No need for spacecraft spinning or other complex mechanics to enable gas separation
- **Fueled by deionized water**
- **Produces gas at efficiencies up to 85%**
- **Consumes 0.5 – 10 W depending on desired gas generation rate**

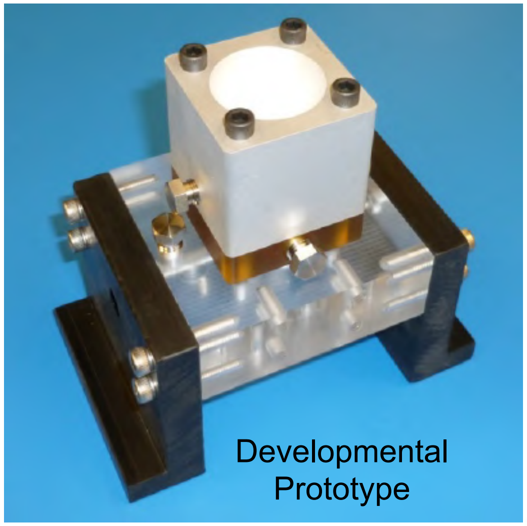
Developmental Prototype



Thruster

- Bipropellant microthruster designed for integration into CubeSats
- Gas flow is controlled via two lightweight, low power, and isolated propellant valves
- Features reliable and repeatable spark igniter design
- Provides both high Isp and good thrust authority to enable rapid rendezvous with NEOs
- Cold gas thrusters enable precise attitude control

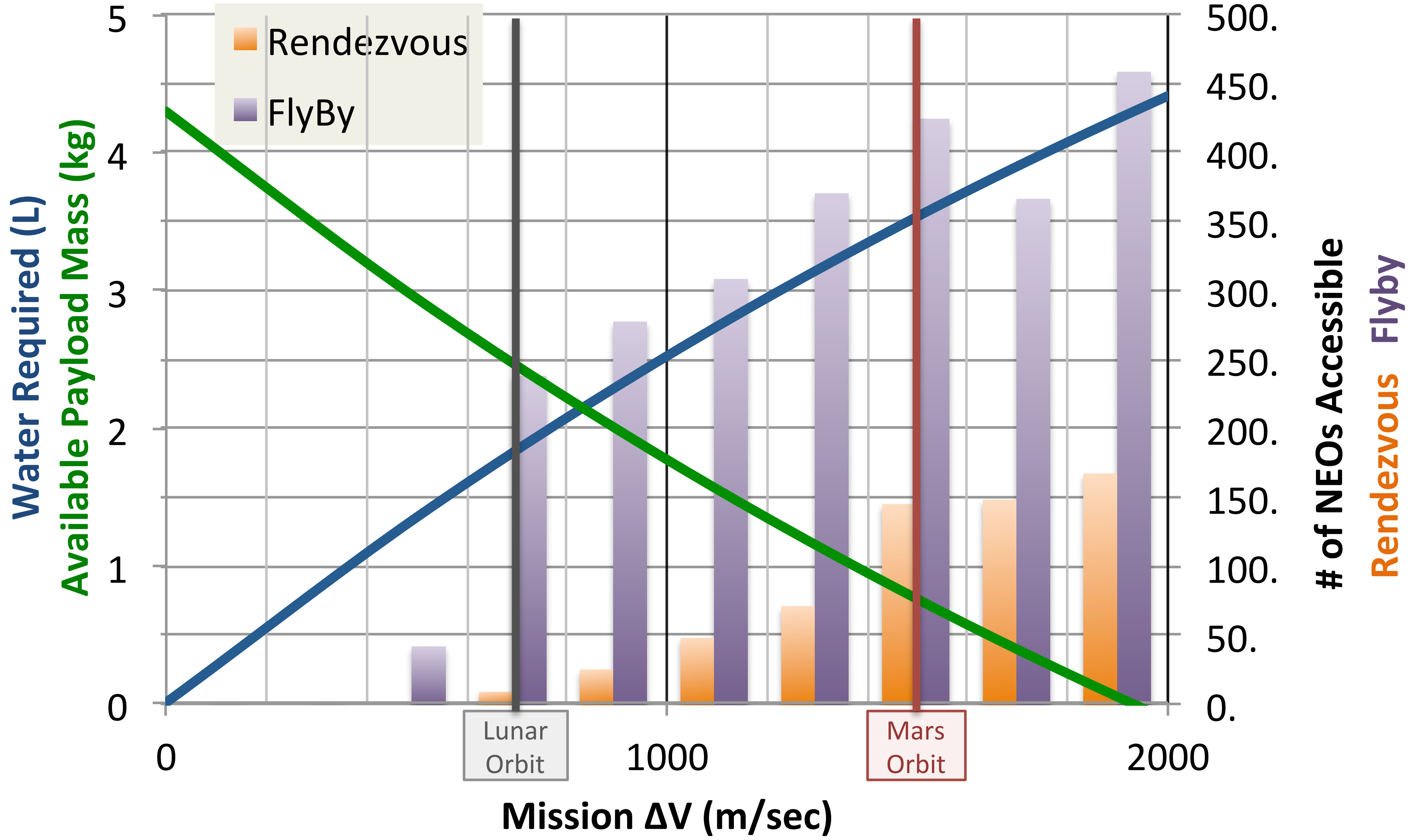
Performance Metric	Goal	Demonstrated To-Date
Thrust (Max)	1 N	0.8 N
Minimum Bit Impulse	0.1 mN-s	< 0.75 mN-s
Specific Impulse	300 s	300 s



Developmental Prototype

APX Payload Capability

Tethers Unlimited
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air



Asteroid Payload Express Can Deliver 1 kg Payload to 110 Known NEOs And Perform Fly-By of 1046 Known NEOs

Summary

- NanoTHOR “harvests” orbital energy from spent upper stage to boost nanosat payloads to escape
- HYDROS thruster provides secondary payloads high-Isp, high-thrust propulsion without risk to primary payloads
- Asteroid Payload Express service can deliver small payloads to 100’s of NEOs

Asteroid Payload Express

New Worlds, Within Reach™

www.tethers.com