A MODULAR
MOMENTUM-EXCHANGE/ELECTRODYNAMIC-REBOOST TETHER SYSTEM ARCHITECTURE

Robert P. Hoyt, Jeffrey T. Slostad, Scott S. Frank
Tethers Unlimited, Inc.
www.tethers.com

Abstract
The Momentum-Exchange/Electrodynamic-Reboost (MXER) Tether Boost Facility concept has the potential to achieve significant reductions in launch costs for a number of space missions. In this document, we investigate the design of the MXER Tether Boost Facility and develop a highly modular architecture that will enable the system to be designed, built, launched, operated, and maintained at low cost. Using this modular approach, we develop a concept design for a MXER Tether Boost Facility optimized for boosting 2,000 kg payloads from a 250 km drop-off orbit to geostationary transfer orbits. To enable it to boost multiple payloads, the system incorporates a propellantless electrodynamic tether reboost system that enables it to restore the orbital energy transferred to each payload within a period of 45 days. Based upon this concept design, we have developed a mass estimate preliminary configuration design, and found that this modular MXER Tether Boost Facility will have a mass and stowed volume that will enable it to be launched by a SeaLaunch Zenit-2 rocket. Once the system has been deployed on-orbit, its modular design enables its capacity to be expanded in a "bootstrap" manner.

INTRODUCTION
The Momentum-Exchange/Electrodynamic-Reboost (MXER) Tether Boost Facility has the potential to provide a fully-reusable in-space propulsion infrastructure that can dramatically reduce propulsion costs for many space missions.\(^1\)\(^2\) The MXER concept, however, must compete with conventional rocket-based transportation solutions which, although expensive, are already developed and flight qualified. Consequently, in order for the MXER System to realize its full potential for significant mission cost savings, it must be architected so that it can be designed, fabricated, tested, deployed, operated, and maintained with costs low enough that the net cost savings compared to conventional rocket-based propulsion options are still significant enough to justify the up-front investments required for development and launch of a MXER Tether Boost Facility. Achieving these low costs for such a large, complex, many-ton space system will require an innovative approach to designing the overall system. In this paper we propose an architecture and development plan that takes advantage of the fact that, unlike rocket-based propulsion systems, tether-based systems are amenable to a highly modular design and assembly approach. This modular architecture enables a few small components to be designed, prototyped, and tested, and then fabricated in quantity and combined to create a large MXER Tether Boost Facility. Moreover, this modular architecture is highly amenable to on-orbit refurbishment and expansion of the capabilities of the system. We will describe a concept design for a MXER Tether Boost Facility sized to boost one 2,000 kg payload from low Earth orbit (LEO) to geostationary transfer orbit (GTO) every 45 days. This MXER system has a total mass and volume that enable it to be launched using a single Zenit-2 SeaLaunch rocket. The modularity of the system can then enable the capability of the tether system to be increased incrementally over time in a "bootstrap" manner. This bootstrapped expansion will enable the system to grow into a much larger MXER Tether Boost Facility that will have the capability of picking 5,000 kg payloads up from a suborbital launch vehicle and boosting them to GTO.

Background
Momentum-Exchange Tethers
In a momentum-exchange tether system, a long high-strength tether is deployed from a facility in orbit and set into rotation around a central body. The tether system is placed in an elliptical, equatorial orbit and its rotation is timed so that the tether is oriented vertically below the central facility and swinging backwards when the system reaches perigee. At that point, a grapple mechanism located at the tether tip can rendezvous with and capture a payload moving in either a lower orbit. Half a rotation later, the tether can release the payload, tossing it into a higher energy orbit. This concept is termed a momentum-exchange tether because when the tether picks up and tosses the payload, it transfers some of its orbital energy and momentum to the payload, resulting in a drop in the tether system’s apogee.
Electrodynamic Reboost
In order for the tether system to boost multiple payloads, it must have the capability to restore its orbital energy and momentum after each payload transfer operation. If the tether system has a solar power supply, and a portion of the tether contains conducting wire, then the power supply can drive current along the tether so as to generate thrust through electrodynamic interactions with the Earth's magnetic field. By properly controlling the tether current during an orbit, the tether system can reboost itself to its original orbit, as illustrated in Figure 1. The tether system essentially serves as a large "orbital energy battery," enabling the system to convert solar energy into orbital energy gradually over a long period of time and then rapidly transfer that energy to the payload.

MXER Design Reference Mission
To maximize the economic returns from a MXER Tether Boost Facility it is desirable to size it so that it can be deployed with a single launch vehicle. NASA’s In-Space Propulsion Program has defined a “Design Reference Mission” (DRM) for a MXER System, which is to boost 2,000 kg payloads from LEO to GTO. Consequently, in this effort we have focused on developing a point design for this DRM MXER System.

Prior MXER Design Efforts
The MXER Tether Boost Facility concept originated in the early 1990’s and has evolved through design efforts carried out by several researchers. The concept of combining momentum-exchange and electrodynamic reboost to create a propellantless system capable of boosting multiple payloads from LEO to higher orbits was originated by Hoyt in 1991 and later studied briefly as a part of a Phase I SBIR conducted by Forward Unlimited in 1992. In 1997, John Mankins of NASA-HQ funded a study by Hoyt and Forward that performed a rudimentary analysis of the MXER concept (at that point it was called the “High-strength Electrodynamic Force Tether [HEFT] System). In 1998 a NASA funded study performed by the Smithsonian Astrophysical Observatory and Boeing investigated the feasibility of a momentum-exchange tether facility for LEO to GTO payload transfer. The MXER concept began to gain momentum through two studies funded by NASA’s Institute for Advanced Concepts (NIAC), one of which investigated the design of a LEO to GTO MXER tether boost facility and the other investigated a Hypersonic-Airplane Space-Tether Orbital Launch (HASTOL) System architecture. All of these studies focused on a “monolithic” system architecture, in which the tether deployers, power systems, and other components are integrated into a single large control station that is located either at the tether system’s center of mass or at the end of the tether opposite to the grapple assembly.

Limitations of Prior Design Architectures
While conceptually simple, the monolithic system architecture investigated in prior efforts has several drawbacks. The first is the size of the components involved. The tether in a MXER system with the capability to boost a payload by several km/s will have a total mass several times that of the payloads it can boost. For a two-ton payload, the tether will mass on the order of 10 metric tons. Designing, building, integrating, and testing such a tether as well as a deployment system able to handle such a massive structure would be a very complex and expensive undertaking. The same applies for the power system needed to drive the electrodynamic tether component of the MXER system. The MXER System will require the ability to drive several hundred kilowatts through the tether in order to reboost the tether’s apogee. A single

Figure 1. The Momentum-Exchange/Electrodynamic Reboost Tether Launch Assist Concept.
solar panel array and power processing unit capable of collecting sufficient solar energy during the orbit and then applying it to the tether during the perigee passes would exceed any space power system yet fielded, and its design, assembly, and testing would be a significant challenge. Additionally, for reboost efficiency it is desirable for the electrodynamic tether system to drive current along the majority of the tether length; if the power supply for the electrodynamic reboost system is located at one position along the tether, the voltages that must be applied to the tether will be quite large, in excess of 20 kV. Furthermore, the monolithic architecture does not lend itself well to easy repair/refurbishment, nor to expansion of the system’s capabilities.

THE MODULAR MXER TETHER BOOST FACILITY ARCHITECTURE

Overview
Fortunately, it is possible to take a different approach in designing the architecture of the MXER Tether Boost Facility, one in which the multi-ton tether is constructed of a large number of small, identical components, or “modules”. In this approach, illustrated in Figure 2, the MXER Tether Boost Facility will be built out of five basic building blocks:

- A high strength tether module;
- A conductive electrodynamic tether module;
- A deployer reel assembly able to deploy and retract both kinds of tether modules;
- A power module; and
- A truss structure that supports the deployer and power modules at each junction.

In addition to these four building blocks, the MXER system will also require two additional components. The first is ballast mass, and the second is a grapple assembly.

The proposed architecture is illustrated in Figure 2. The 100 km tether structure will be divided into 10 sections, each 10 km long. Each 10 km section of the tether is composed of several parallel pairs of 5 km tether modules (attached back-to-back to form a 10 km length as illustrated on the right hand side of Figure 2). In between each section of the tether, a truss structure will support the tether deployer modules. As shown in Figure 2, in eight of these junctions, power modules will supply the high-voltage power needed to perform electrodynamic reboost. The upper stage used to launch the MXER Tether Boost Facility will be retained to serve as ballast mass at one end of the tether, and at the opposite end of the tether the payload capture/grapple mechanism will hang below the last set of tether deployers.

Constructing the 10 km segments of the tether structure out of two 5-km tethers enables us to place tether deployment/retraction mechanisms at both ends of the tether segments. This is important because it enables us to ensure that if a tether segment were to be severed, both halves of the tether can be retracted, preventing the generation of orbital debris and stowing the broken pieces to facilitate replacement.

Advantages of Modularity
Reducing the size of the components that must be developed for the MXER Tether Boost Facility will greatly reduce the requirements for the manpower and facilities needed to design, fabricate, and flight-qualify the overall system. Smaller components will require less complex and less expensive tooling and equipment for handling and testing. Furthermore, economies of scale in manufacturing can significantly reduce the cost of fabricating the entire system if many identical units are produced rather than one large system. Quality assurance will be made significantly easier, as well. For example, when constructing a 100 km long structure, if a materials, manufacturing, or handling problem resulted in a weak section of tether, a modular design where one must simply swap out one 5 km module will be far preferable to a non-modular design where one might have to refabricate the entire 100 km tether. An additional cost-saving advantage is the significant reduction in costs for engineering models and flight spare units. As discussed in a later section, modularity of design also will enable the MXER tether system to be expanded in capability over time.

Figure 2. Conceptual layout of the modular MXER Tether architecture.
High-Strength Tether Modules
The baseline tether module design is illustrated in Figure 4 and Figure 3. The high-strength tether component of the MXER system will be composed of a total of 136 tether modules, each of which will be a 5 km length of a Hoytether™ structure constructed using Zylon® yarn. The Hoytether™ structure will be a flat tape consisting of 8 primary lines that are interconnected by 14 secondary lines. Each primary line is a 3-braid constructed with 3000 denier Zylon® yarns, and each secondary is a 3-braid constructed with 1000 denier Zylon® AS yarns. Each tether module will have a tensile capacity of 3 tons.

To provide capability for high-strength termination of the tethers, the braiding program will be varied so that short sections at both ends of the tether module will be constructed with additional yarns to form a flat tape segment that has much higher strength than the bulk of the tether and can withstand deployment and retraction under high loads. To ensure that the individual lines in the tether structure remain spread apart, perpendicular spreaders will be constructed in the tether, spaced every 100 meters. Each tether module will have a mass of 66 kg, which includes a 5% mass penalty for AO and UV resistant coatings. These modules will be combined in parallel and series to form a stepwise-tapered tether structure that closely approximates the ideal tapering described by Moravec’s tether taper equations. In the Phase I effort, we have fabricated prototype samples of a Hoytether™ structure with 2 primary lines using a computerized braiding process. Winding tests with these prototypes indicate that the tether can be wound with a package density of approximately 750 kg/m³, so each tether module will require a deployer canister able to contain 0.088 m³.

Electrodynamic Tether System
To enable propellantless reboost of the tether’s orbit after it has transferred a payload, the system will also incorporate conductive tethers and devices for making electrical contact with the ionospheric plasma.

Insulated Tethers
Along the seven tether segments in between Power Module 1 and Power Module 8, insulated conducting tether modules will be deployed in parallel with the high-strength tethers. As with the high-strength tethers, two 5-km modules will be deployed back-to-back to span the distance between the power modules. These electrodynamic tether modules will be constructed using thin aluminum wires in a cylindrical Hoytether™ configuration. Each insulated tether module will have a mass of 30 kg, and they are sized to fit in the same deployer modules as the high-strength tether modules. The total mass of the electrodynamic tether modules is 500 kg. The electro-
dynamic tether is not run along the sections of tether nearest the tether tip assembly because the mass of the power equipment required for the electrodynamic tether would cause too large an impact on the total tether mass if they were located at the tether tip.

**Tether Anode**

At the end of the tether system that is positively biased relative to the ambient environment, the system will require an anode technology that will enable it to collect electrons from the ionospheric plasma. Several technologies can provide this function, including plasma contactors, Nobie Stone's GridSphere concept, or a bare-wire tether. Because plasma contactors require expenditure of propellant, and because the GridSphere concept may require significant additional mass to enable it to maintain its shape under the 2-gees of acceleration it will experience near the tether tip, we currently favor the bare wire tether approach. The baseline MXER Tether Boost Facility design thus incorporates two 5-km sections of bare wire tether, constructed in a cylindrical Hoytether™ configuration, one located outboard from Power Module 1 and the other deployed outboard from Power Module 8. These cylindrical tether structures will be constructed so that they can deploy with a diameter of a meter or more, enabling them to act like a very elongated version of the GridSphere. These bare wire anodes will be switched in and out of the tether circuit as needed to modulate the direction of current flow in the system as the tether rotates.

**Field Emission Array Cathodes**

At the negatively biased end of the electrodynamic tether, the system will require a mechanism to emit electrons into the ionospheric plasma. Again, several technologies exist that could perform this function, including plasma contactors, thermionic emitters, and field emission array cathodes (FEACs). FEACs are currently the most promising candidate because they can emit electron currents with very low power and mass requirements. A challenge for incorporating FEACs into the MXER Tether Boost Facility is the large currents (10-15 A) that must be emitted into the ambient plasma, because space-charge limitations on current density will restrict the amount of current that can be emitted from a given area. To mitigate this issue, multiple redundant FEAC devices will be suspended "below" (outboard from the system's center of mass) Power Modules 1 and 8 to enable the system to emit electrons across a wide area. These FEAC arrays will be switched in and out of the tether circuit in opposition to the bare wire anodes to enable the tether system to carry current in the desired direction.

**Deployer Modules**

Each of the 5-km lengths of high-strength tether and conductive electrodynamic tether will be deployed by its own deployer module. A preliminary concept design for a deployer module is shown in Figure 5. These deployer modules must have the capability to stow 0.1 cubic meters of wound tether, to deploy and retract the tethers under low tension, and to securely terminate the high strength tethers prior to system spin-up. The primary component in the deployer modules is the tether spool, nominally sized with a spool diameter of 5 cm, an outer diameter of 38 cm, and a length of 72 cm. Preliminary tests with prototype Zylon® Hoytethers™ indicate that the tether modules can be wound with a packing density of at least 800 kg/m³, so these spools will be able to hold the 5-km high-strength tether modules with room to spare.

In this system design we chose to place a deployer at both ends of the 10 km segments in between the power modules so that the system has the capability to retract a tether segment from either end of the tether. This will ensure that if a tether segment were to be cut by an impact with a large piece of orbital debris, the tether system will have the capability to retract both halves of the tether so as to facilitate replacement or repair.

**Truss Structure**

Each assembly of deployer modules will be affixed to the exterior of a 10-sided truss structure. This truss structure will also house the power modules. Because the deployer modules can be designed to transfer their loads directly from one deployer module to the next, this truss structure does not need to have exceptional strength for the operational phases of the MXER Tether Boost Facility. However, the truss structures will provide the primary load-bearing path for the launch configuration of the system, and thus they need to be designed with sufficient strength for that purpose. In this study, we have used an estimate
of 50 kg for these trusses, based upon masses of trusses used for launches of stacked satellites.

**Control Station/Ballast Mass**

When the MXER Tether Boost Facility catches and tosses a payload, it transfers some of its orbital energy to the payload, and thus the tether’s orbit will drop. In order to ensure that the orbit of the tether does not drop so much that the tether dips too deeply into the upper atmosphere, it is necessary for the MXER System to have a mass that is roughly ten times that of the payload it is boosting, and the more mass it has, the better its performance. Since the tether system must be launched into orbit, it is logical to consider retaining the upper stage of the rocket used to launch it to serve as the ballast mass. For the modular MXER Tether Boost Facility design presented here, we have selected the SeaLaunch Zenit-2 launch vehicle as the most optimum choice, for two reasons. First, it is most desirable to place the MXER Tether Boost Facility into an equatorial orbit, and since SeaLaunch can launch from a floating platform on the equator, it can provide excellent performance. Second, the Zenit-2 rocket uses a second stage vehicle that has a dry mass of approximately 8,367 kg, which can provide a large ballast mass for the MXER Tether. After the Zenit-2 second stage has carried the MXER Tether Boost Facility into a low Earth orbit, its remaining fuel will be used to boost the apogee of the tether system as high as possible, and then the stage will be safed. When the tether system deploys, the first set of deployer modules will remain affixed to the upper stage, as illustrated in Figure 6.

The assembly at this end of the tether will also include the master avionics for the MXER Tether Boost Facility, communications hardware, and a solar panel PowerMast to drive the avionics and deployer mechanisms. The mass allocation for this “Control Station” module is 1,275 kg, including deployer modules. This mass includes 1,000 kg of mass held as margin for the overall system; this 900 kg margin represents 6% of the total launch mass (not including the upper stage mass).

**Power Modules**

As illustrated in Figure 2, the MXER Tether Boost Facility will have eight power modules spaced along the length of the tether. The choice of several power supplies distributed along the tether, rather than a single power system at one position on the tether, is driven primarily by the desire to maximize thrust efficiency and to minimize the peak voltages applied to the tether. In that task, we investigated the factors influencing the thrust efficiency of the electrodynamic tether reboost system and concluded that in order to maximize the thrust efficiency of the system, current should be driven along as much of the length of the MXER tether as possible. In order to do so, however, we must either apply very large voltages (≥20 kV!) at one end of the tether, or distribute power systems along the tether. In order to avoid the issues associated with very high voltages, we then developed a modular power architecture designed to enable the DRM MXER Tether Boost Facility to restore its orbit within 45 days, and performed sizing estimates using realistic projections for the technologies that will be available in the 5-10 year timeframe in which a MXER Tether system might be fielded. This modular design enables the peak tether voltages to be kept under 6 kV, which, while still a challenge, will be significantly less challenging than 20 kV. Figure 7 shows the profile of the tether and ambient plasma voltages along the tether at a moment when the tether is swinging below the center of mass of the system and the electrodynamic reboost system is operating at an input power level of 366 kW. The tether current was 11.5 Amps, and the peak relative voltage between the tether and the surrounding environment is 5 kV. Table 1 presents a summary of the power specifications and the mass estimates for the power modules.

Each power module will have a 12 kW solar panel array. To enable these panels to track the sun continuously while the tether rotates, we propose to utilize a space-rated version of the HighPower™ system developed for high-altitude, long duration balloon systems by Global Aerospace.10 This design provides sun-tracking capabilities
with very low mass and eliminates the need for rotating electrical connections. Figure 9 illustrates the manner in which the solar panel array would hang below the power module due to the centrifugal forces (the direction of deployment of the solar panel array would depend upon the location of the power module with respect to the system’s center of rotation).

Figure 8 shows a close-up view of the proposed configuration of the power module. Each 10-km section of the tether structure would be joined to the next through a 10-sided truss structure. The batteries, high voltage power supplies, avionics, and other components of the power modules would be housed inside this truss. The sizing of the power module components leaves room for the HighPower™ solar array to fit within the truss when it is in its stowed configuration. The tether deployer modules will be attached to the sides of the truss. The entire assembly has a diameter of 3.2 meters, and a height of 0.8 m.

Accounting for eclipse periods and pointing inaccuracies, the eight power modules will collect a total average power of 60.5 kW over the course of each orbit. During the perigee passes, when the tether is within the ionospheric plasma and can perform electrodynamic thrusting, the power modules expend this power at the rate of 366 kW total, or 46 kW each. Extensive simulation and analysis indicates that this power level will be sufficient to enable the MXER Tether Boost Facility to reboost its orbit within 45 days.

Payload Capture Mechanism
To enable the MXER Tether Boost Facility to capture payloads for orbital transfer, the system will include a payload grappling mechanism. This grappling mechanism has a number of very challenging requirements. First, it must be capable of securing a 2,000 kg payload with docking times time periods measured in a few seconds and positional error tolerances of ± 5 m in all three dimensions. It must be able to support the mass of the payload at up to 6 gees of acceleration (2 gees nominal acceleration due to tether rotation, plus 50% due to capture dynamics, multiplied by a safety factor of two). Because the mass of the tether in the MXER System scales linearly with the mass located at the end of the tether, it is critical to minimize the mass of the payload grappling mechanisms.

Several capture techniques have been proposed for momentum-exchange tether systems, including “harpoon and net” and “heavy-duty Velcro™” approaches, as well as

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### Table 1. MXER Power Module Sizing

<table>
<thead>
<tr>
<th>Power Sizing:</th>
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<tbody>
<tr>
<td>Total BOL Panel Power</td>
<td>12 kW</td>
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<tr>
<td>Orbit Averaged Power†</td>
<td>7.5 kW</td>
</tr>
<tr>
<td>Energy Collected over Orbit</td>
<td>19.5 kW hr</td>
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<tr>
<td>Battery Capacity (28 V)</td>
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</table>

<table>
<thead>
<tr>
<th>Masses:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Mast Mass</td>
<td>30 kg</td>
</tr>
<tr>
<td>HVPS</td>
<td>29 kg</td>
</tr>
<tr>
<td>Batteries/Flywheels</td>
<td>105 kg</td>
</tr>
<tr>
<td>Thermal Mgmt/Radiators</td>
<td>35 kg</td>
</tr>
<tr>
<td>Cabling</td>
<td>3 kg</td>
</tr>
<tr>
<td>Avionics</td>
<td>3 kg</td>
</tr>
</tbody>
</table>

| Power Module Mass: ‡               | 204 kg |

† Orbit averaged power is the average power collected during the orbit, accounting for pointing factors as the tether rotates as well as for the fraction of the orbit where the system is in the sunlight.

‡ The power module mass list does not include a structures mass item because these components are supported by the interstage truss, so the structure mass for the power modules is booked elsewhere.
mechanical and electromagnet-based docking mechanisms. We have conducted an analysis of these and other concepts, and identified a new capture method as having the best combination of large tolerance to positional error and low grapple mass. The “Grapple, Retrieve, And Secure Payload for Momentum Exchange” (GRASP-MX™) concept is illustrated in Figure 10, and a proof-of-concept demo is shown in Figure 11. This device will essentially provide a large volume net “box” into which the payload will coast, and provides a simple means of closing that box to capture the payload. In the proposed configuration, a small Grapple Control & Power unit at the tether tip will deploy several lightweight deployable booms. These booms will spread and support a large-volume net structure that initially has an open bottom. This box can be 10 meters or more on a side. To achieve capture, the payload will maneuver to enter the box. When sensors on the GRASP-MX™ device detect that the payload has entered the box, the device will activate a “drawstring” mechanism to rapidly close the bottom of the net. This approach is conceptually similar to a purse-seine net used in the commercial fishing industry to haul tens of tons of fish out of the ocean. The net and support booms will be designed so that as the payload begins to contact the bottom of the net, the booms will pivot to enable the high-strength cables composing the net to support the load of the payload; this will allow the booms to be constructed of relatively lightweight materials, because they serve only to spread the net, not to carry the load of the payload.

To release the payload, the GRASP-MX™ system will simply loosen the drawstring and allow the payload to slide out of the net. Preliminary testing with a simple proof-of-concept prototype indicates that this release method will be reliable and controllable. If, however, further testing on full prototypes indicates that this net-release method does not provide sufficient timing control on the release for MXER application, the system could accommodate a robotic arm that would slide down the center of the net and latch onto a small recessed grappling feature on the payload shroud. The system would then loosen and retract the net, and use the latching mechanism on the robotic arm to release the payload with high precision.

Figure 10. Concept of operations of the GRASP-MX™ payload capture system.

Figure 11. Proof-of-concept demo of the GRASP-MX™ Concept.
The advantages of the GRASP-MX™ concept include:

- **Passive Payload:** In the GRASP-MX™ concept, the payload can be entirely passive during the final phase of the capture maneuver. The only hardware requirements on the payload are that it have a lightweight shroud to prevent the net and payload from damaging each other. This shroud needn’t be solid or massive; an open cage structure of aluminum tubing would suffice to protect the payload components from the net. Having a passive payload minimizes the complexity and expense of any expendable components that must be flown with each payload. The use of a standardized shroud or “payload capsule” for all payloads will significantly simplify integration on the launch vehicle.

- **No Expendables on Tether:** The GRASP-MX™ approach requires no expendables on the tether side of the system. On the payload side, it will require the mass of the lightweight shroud and the propellant used to guide the payload into the capture “box.”

- **Large Capture Volume with Low Mass:** The deployable-net approach can achieve a large capture volume with very low mass. The components of the system that will bear the mass of the payload can be constructed of high strength-per-weight materials such as the Spectra, Zylon, or Kevlar materials that would be used in the tether itself.

- **Only One Active Component:** The only active mechanical component required to achieve the capture is the “drawstring” mechanism. Providing redundancy for this component can be achieved very easily with low mass penalty.

- **Minimizes Shock Loading on Tether:** As the payload falls into the bottom of the net, the pivoting support beams and design of the net will enable the net to “sag” as it begins to support the payload. This will enable the GRASP-MX™ system to minimize the tension gradient experienced by the tether.

- **Distributed Load-Bearing:** Rather than concentrate the loads at one point as do some of the other grappling concepts, the mass of the payload will be supported by a net structure that distributes the loads over many tension-bearing members. This will enable the structure to be built with a low total mass while eliminating risks of single-point failures.

**Grapple System Mass:**

Because the grapple system rides at the end of the rotating tether, its mass strongly influences the mass of the overall tether system. Currently, several concept payload capture mechanisms, including the GRASP-MX™ system and others, are the subject of ongoing research and development. Their mass characteristics, however, are not yet well defined. In the present system design, we have assumed a payload capture mechanism mass of 175 kg.

**Impacts of Modular Architecture on Reliability**

In comparison with a more monolithic system architecture – i.e., one in which there is just one very larger deployer, rather than 136 – the modularity of the proposed architecture presents both advantages and drawbacks to the system reliability. The primary drawback is obvious: in order to successfully deploy the entire tether facility, 136 deployer modules must successfully deploy their tether modules, rather than just one for a monolithic architecture. However, the modularity of the system improves the capability of the system to handle deployer component failures. In a monolithic system, if the single large deployer jams, as happened with the TSS-1 mission, the entire mission is a failure. With a modular system design, if one of the deployers fails to fully deploy its tether, the system can either remove that tether module from the system and operate at a slightly lower load capacity (or the same load capacity but at a lower safety factor), or adjust the length of the other tether modules on that segment of the tether structure and operate with a shorter total length.

A very significant advantage of the proposed modular architecture is that the tether structure has an overall diameter of more than 3 meters, as illustrated in Figure 8. This means that the tether will be very robust against collisions with even large pieces of space debris.

**MXER Tether Boost Facility Design Reference Mission Point Design**

Using the designs presented above for the tether, deployer, and power modules as well as the payload capture mechanism and the control station/ballast mass assembly, we have developed a point design for a MXER Tether Boost Facility optimized for the Design Reference Mission. This design is summarized below in Table 2. The total MXER Tether Boost Facility mass is 22,448 kg, or over 11 times the mass of the 2,000 kg payloads it is designed to transport. Because it utilizes the second stage of the rocket used to launch it, however, the true “launch mass” of the MXER system is just over 14 metric tons. This launch mass is compatible with the capabilities of the SeaLaunch Zenit-2 for delivery to a 300 km circular equatorial orbit. The system is optimized for picking up payloads from 250 km circular holding orbits and boosting them into GTO trajectories.
Table 2. MXER Tether Boost Facility Design Summary

<table>
<thead>
<tr>
<th>Payload Mass</th>
<th>2,000 kg</th>
<th>Tether Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tether System Masses</td>
<td></td>
<td></td>
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<tr>
<td>Total Tether Mass</td>
<td>9,370 kg</td>
<td>Tether mass, Zylon 8,870 kg</td>
</tr>
<tr>
<td>Deployer Modules</td>
<td>1,360 kg</td>
<td>Tether mass, Copper 500 kg</td>
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<tr>
<td>Power Modules</td>
<td>1,631 kg</td>
<td>Tether Length 100,000 m</td>
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<tr>
<td>Module Truss Structures</td>
<td>450 kg</td>
<td>Tether mass/Payload Mass 4.69</td>
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<tr>
<td>Control Module Mass</td>
<td>1,095 kg</td>
<td>Tether tip velocity at catch 1,265 m/s</td>
</tr>
<tr>
<td>Grapple System Mass</td>
<td>175 kg</td>
<td>Tether tip velocity at toss 1,161 m/s</td>
</tr>
<tr>
<td>Total Launch Mass</td>
<td>14,081 kg</td>
<td>Tether angular rate, inertial frame -0.0166 rad/s</td>
</tr>
<tr>
<td>Ballast Mass (Zenit-2 2nd Stg)</td>
<td>8367 kg</td>
<td>Gravity at Control Station 0.67 g</td>
</tr>
<tr>
<td>Total Control Station Mass</td>
<td>9,462 kg</td>
<td>Gravity at payload 2.13 g</td>
</tr>
<tr>
<td>Total MXER System Mass</td>
<td>22,448 kg</td>
<td>Rendezvous acceleration 2.32 g</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Positions &amp; Velocities</th>
<th>Pre-Catch</th>
<th>Joined System</th>
<th>Post-Toss</th>
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<tr>
<td>apogee velocity m/s</td>
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<td>4,461</td>
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<td>CM dist. From Station m</td>
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<td>23,966</td>
<td>17,161</td>
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<tr>
<td>CM dist. To Grapple m</td>
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<td>76,034</td>
<td>82,839</td>
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<tr>
<td>ΔV to Reboost m/s</td>
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</table>

Concept of Operations of the MXER Tether Facility

Designing a MXER Tether System requires planning for several different operational phases, including launch, deployment, orbital placement, operation, servicing, and retirement.

Launch

For launch, the MXER Tether Boost Facility will be stowed and stacked as illustrated in Figure 12. The sizing of the power modules and the deployer modules has been chosen so that the entire assembly will fit within the dynamic envelope for the 3.9m SeaLaunch Fairing. The Zenit-2 will then be used to launch the MXER Tether system into an equatorial LEO orbit. The MXER Tether Boost Facility has been sized so that the Zenit-2 can deliver it into at least a 300 km circular orbit. Any propellant remaining in the second stage after reaching this altitude will be used to raise the apogee as far as possible.

Deployment, Orbit Raising, & Spin-Up

After the Zenit-2 and the MXER Tether Boost Facility reach orbit, the system will deploy the first 10 km section of tether (in between the stage and the first power module), resulting in a tethered configuration with 10 metric tons on one end (the upper stage and the Control Station) and approximately 12 metric tons on the other (the rest of the power modules and tether deployers). It will then deploy the solar arrays on Power Module 1, and use electrodynamic tether propulsion to raise the system’s orbit. Only one tether section is deployed initially because the system must first raise its orbit before deploying the full tether to ensure that the bottom end of the tether will not experience excessive aerodynamic drag when the system is fully deployed. As the system climbs, it will periodically deploy additional segments of the tether structure as well as the solar arrays associated with those segments in order to increase the system’s power and thrust level. Once fully deployed, it will then continue to raise the apogee of its orbit up to the operational altitude of 8200 km. This orbit-raising period will require approximately 6 months. Towards the end of its orbit-raising, it will begin modu-
lating the tether current so as to achieve both orbit-raising and spin-up of the tether structure, until its tip reaches the full 1,265 m/s velocity relative to the system’s center of mass. It will then deploy the payload capture mechanism.

Operational Service
At this point the MXER Tether Boost Facility will be ready to enter operational service. The system is sized to capture 2,000 kg payloads from a 250 km circular orbit and toss them into a GTO trajectory. With each payload boost operation, the apogee of the tether system will drop to approximately 6,000 km. The MXER system will then use its electrodynamic tether component to reboost its apogee. The system’s power capacity is sized to accomplish this reboost within 45 days.

Reconfiguration, Repair, & Expansion of the MXER System
The MXER Tether Boost Facility design presented here is optimized for the task of boosting 2,000 kg payloads from LEO to GTO. Because the MXER Tether Boost Facility’s architecture is designed in a modular manner, it can be reconfigured to enable it to serve other purposes. For example, the system can be reconfigured into a 50 km long tether optimized for providing 545 m/s of launch assist ΔV to 5,000 kg payloads carried up by a reusable launch vehicle (RLV). Although 545 m/s is only a small fraction of the total ΔV needed to place a payload in orbit, reducing the ΔV the RLV must provide to the payload would roughly double the launch capacity of the RLV. Conversely, the system could be configured to provide larger ΔV’s to smaller payloads, tossing 1-ton spacecraft to interplanetary trajectories.

The modularity of the system will also make it possible to increase its payload capacity by adding additional tether and power modules to the structure. Additionally, although the Hoytether™ design used to construct the tether structure will provide high reliability for a number of years in the Earth-orbit micrometeoroid and orbital debris (M/OD) flux, the reliability of the tethers will eventually begin to decrease after extensive exposure to the M/OD environment, and they will need to be replaced.

Additional modules for expansion or repair of the MXER Tether Boost Facility could potentially be carried up to the tether system one or two at a time along with the payloads it transports. This would enable the tether system to essentially “bootstrap” itself, because these additional modules could ride as “ballast mass” along with payloads that do not fill the entire 2 ton capacity of the system. Transporting the modules along the tether and integrating them into the structure while it is spinning would require additional system complexity such as a grappling arm and an “elevator” car that could ride up the structure. Alternatively, an additional launch of a rocket could be used to transport a large number of additional modules up to the facility’s orbit.

To facilitate the repair/expansion of the system, the tether would use electrodynamic thrusting to de-spin itself into a gravity-gradient stabilized orientation. In its de-spun state, each of the tether modules will be under only about 10 kg of tension, and so they can be reeled back in with very low power requirements. The MXER Tether Boost Facility will retract all of the tether segments, returning to its original stacked configuration. A lightweight robotic arm can then be used to swap out degraded tether modules for new ones and add additional tether modules to the structure. To optimize the MXER Tether Boost Facility for a larger payload or a higher ΔV capability, the number of tether modules on each level will be reconfigured to achieve the desired structural tapering for the new mission.

Retirement
Ideally, the MXER Tether Boost Facility will never need to be retired, as it does not consume propellants that would run out, and it is designed so that new tether modules can be added to replace old ones as well as to increase the capacity of the system. If at some point it should become necessary to retire the system, however, the electrodynamic tether system will first be used to de-spin the system. The deployer reels will then be used to retract all of the tether except for the the bare wire tether segments so as to minimize its collisional cross-section. Using electrodynamic drag, the tether system will then lower its own orbit until it reenters the Earth’s atmosphere.

Conclusions
Achieving the MXER Tether Boost Facility concept’s potential for dramatic reductions in launch costs will require an innovative development approach that will minimize the cost of designing, fabricating, testing, launching, and operating the system. We have developed a modular architecture that seeks to enable this low-cost development. This modular architecture enables a limited set of small tether, deployer, and power components to be developed and qualified for space operations at a relatively low cost. We have developed preliminary concept designs and performed sizing estimates for these components. Once these components have been developed and qualified, they can be produced in quantity, achieving economies of scale in mass-production. These modules can then be integrated to create a MXER Tether Boost Facility that can be launched with a single SeaLaunch Zenit-2 rocket and will be capable of providing 2,000 kg payloads with a 2.4 km/s ΔV boost that will transfer them from LEO to GTO. The modularity of the system archi-
Architecture will also enable this initial facility to be expanded to handle larger payloads and larger ΔV’s. Furthermore, because the MXER Tether Boost Facility can begin generating revenue almost immediately after the launch of the first system, it can fund its own expansion. This “bootstrap” development will enable a large MXER Launch Assist Tether Boost Facility to be deployed with very low up-front launch costs. This Launch Assist Tether Boost Facility would enable a MXER Tether-RLV combination to achieve launch costs as low as $500/kg.

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