

# Electrodynamic Tether as a Thruster for LEO Mission Applications

G. V. Khazanov\*

NASA Marshall Space Flight Center, Huntsville, Alabama, AL 35805, USA

E. N. Krivorutsky†

National Space Science & Technology Center, Huntsville, Alabama, AL 35805, USA

and L. Johnson‡

NASA Marshall Space Flight Center, Huntsville, Alabama, AL 35812, USA

The efficiency of an electrodynamic tether (ED) system with a grid-sphere anode is considered, when the system operates as a thruster. A developed approach is applied to the analysis of the problems of the International Space Station (ISS) and Momentum-exchange/Electrodynamic Reboost (MXER) facility reboost. The difference in their trajectories resulted in different operational regimes; a requirement of minimal ISS center of mass shift due to attached tether system, the total length of the MXER facility, and restrictions on the power source voltage and currents are taken into account. It is found that for both missions the efficiency of an ED tether system with a grid-sphere anode is about 30% - 50% smaller than the efficiency of an ED thruster with a partly insulated tether.

## Nomenclature

$d$ = tape width	$r_b$ = boundary radius
$e$ = elementary charge	$s$ = tether cross-section
$E_m$ = induced electric field along the tether	$T$ = temperature
$F$ = thrust	$t_i$ = flight time through a layer
$h$ = tape thickness	$v$ = satellite velocity
$I$ = current	$W$ = electrical power
$I_0$ = thermal current	$W_t$ = thrust power
$K_t$ = thrust work per revolution per module	$\alpha$ = grid-sphere transparency
$k$ = Boltzmann constant	$\beta$ = source mass per unit power (energy)
$L$ = tether length	$\eta$ = electrical efficiency
$L_b$ = bare segment length	$\eta_t$ = tether efficiency
$L^*$ = normalization length	$\eta_i$ = electrical efficiency for a layer
$l_b$ = normalized bare segment length	$\lambda_D$ = Debye length
$m$ = electron mass	$\rho$ = tether density
$M$ = mass dedicated to the thrust	$\rho_{gsp}$ = grid-sphere density
$M_t$ = tether mass	$\sigma$ = tether conductivity
$n_\infty$ = undisturbed electron density	$\tau$ = mission duration
$p$ = tether perimeter	$\varphi$ = grid-sphere bias
$R$ = grid-sphere radii	

\* Research Scientist, Science and Exploration Office, VP62, 320 Sparkman Dr., Huntsville, AL 35805.

† Research Scientist, Science and Exploration Office, VP62, 320 Sparkman Dr., Huntsville, AL 35805.

‡ Manager, Science Programs and Projects Office, VP50, MSFC, Huntsville, AL 35812.

## I. Introduction

The concept of electrodynamic tether propulsion has a number of attractive features and has been widely discussed for different applications. Electrodynamic propulsion based on the interaction of a conducting tether with the background magnetic field can be implemented across a range of system designs. Bare tethers,<sup>1, 2</sup> bare and insulated tethers with a balloon termination,<sup>3, 4, 5</sup> and insulated tethers with a grid-sphere termination<sup>6</sup> have been suggested for different applications. An electrodynamic tether as a thruster is currently proposed for the Momentum-eXchange/Electrodynamic Reboost (MXER) tether facility that has the potential to provide a fully-reusable in-space propulsion infrastructure and dramatically reduce propulsion cost for many space missions.<sup>7,8</sup> Partly insulated tethers and tethers with a grid-sphere contactor have been proposed as thrusters also for the ISS reboost.

The choice of tether design for a specific mission is based on the analysis of tether system performance for the specific mission conditions and requirements. We present the analyses of efficiency of a tether system with grid-sphere contactor as a thruster and consider the possible application of such a design for the ISS and MXER facility reboost. We also compare the performance of such a system with the performance of a partly insulated tape tether for these applications.

## II. Grid-sphere current collection and system efficiency

To analyze the tether performance the current collected by a grid-sphere contactor is needed. This current depends on the grid-sphere radius and transparency, the bias of the electrode, satellite motion, and plasma parameters. The current calculation for grid-sphere in the broad range of system parameters, in particular for large grid-sphere radii, is presented in Ref. 9:

$$I = 2.372I_0(1 - 0.5\alpha^2 - 0.5\alpha^4) \frac{r_b^2}{R^2}, \quad I_0 = \pi R^2 n_\infty e \sqrt{8kT/\pi m} \quad (1)$$

Here:  $R$  is the grid-sphere radius,  $\alpha$  is the grid-sphere transparency (the ratio of the sphere surface without mesh to its total surface) assumed to be high, and  $I_0$  is the random electron current. Parameter  $r_b/R$  from their Table 3 can be approximated as

$$\frac{r_b}{R} = 1 + 0.012 \frac{(e\phi/kT)^{0.65}}{\sqrt{1 + 10^{-4} R^2/\lambda_D^2}} \quad (2)$$

where:  $\phi$  is the sphere bias, and  $\lambda_D$  is the Debye length. The accuracy of such approximation is presented in Fig. 1 for the grid-sphere potentials 0.1kV and 1 kV. Eqs. (1) and (2) are valid also for a solid sphere contactor, i. e. for transparency  $\alpha = 0$ .

For plasma density  $n_\infty = 3 \cdot 10^{11} m^{-3}$ , temperature  $T = 1eV$ , and transparency  $\alpha = 0.9$  a grid-sphere with the radii  $R = 2.5m$  collects currents of 0.18A and 0.42A for the potentials  $\phi = 0.1KeV$  and  $\phi = 1KeV$  respectively, whereas for  $R = 10m$  and the same potentials the respective currents are 2.2A and 2.9A. So the dependence of the collected current on the grid-sphere bias for large radii is weak.

Tether performance can be characterized by the ratio of the system mass dedicated to the thrust,  $M$ , and the product of thrust,  $F$ , and thrust duration  $\tau$ ,  $(M/F\tau)$ . This characteristic has been discussed for partly insulated electrodynamic tethers and tethers with solid sphere contactors in Refs. 4 and 10. In the following, their approach will be adopted for this problem. The electrical and thrusting powers,  $W$  and  $W_t$ , needed for this ratio calculation can be found from Eqs. (4).<sup>4</sup>

$$W = I \left[ \phi + E_m L + I \frac{L}{\sigma s} \right] \quad (3)$$

$$W_t = Fv = IE_m L$$

Here:  $L$ ,  $\sigma$ ,  $s$  is the tether length, conductivity and cross-section respectively,  $E_m$  is the projection of the induced electric field on the tether direction, and  $v$  is the tether velocity.

The mass dedicated to the thrust consists of two terms (neglecting the mass of the cathode contactor and its propellant)

$$M = \beta W + \kappa M_t \quad (4)$$

The first term depends on the specifics of the mission. If the energy source is solar panels, the dedicated mass (solar panels and batteries) for ISS and MXER facility are essentially different. In the latter case, the energy is produced and stored during the flight outside the ionosphere (about 3hr.) and consumed at the time of the transition through it (~10min), whereas for the ISS these times are of the same order of magnitude. The second term in Eq. (4) is the sum of the tether and grid-sphere masses, and  $\kappa = 2.25$  accounts for dedicated masses (packing canister, deployer, and inflation system).<sup>6</sup>

Equation 5 follows from Eqs. (3) and (4):

$$\frac{M}{F\tau} = \frac{v\beta}{\tau\eta_t}, \quad \frac{1}{\eta_t} = \frac{1}{\eta} + \gamma \frac{R^2}{I} \left( \frac{s}{R^2} + \frac{4\pi\rho_{g sph}}{\rho L} \right) \quad (5)$$

$$\frac{1}{\eta} = \frac{W}{W_t} = 1 + \frac{I}{\sigma s E_m} + \frac{\varphi}{E_m L}$$

Here:  $\gamma = \rho\kappa/\beta E_m$ ,  $\rho$  is the tether material density,  $\rho_{g sph} = (1-\alpha)/1.4 \text{ kg/m}^2$  is the grid-sphere density,<sup>6</sup>  $\eta$  and  $\eta_t$  are the electrical and tether efficiency respectively. The tether efficiency increases with the growth of the tether length, as can be found from these equations and Eqs. (1) and (2) for the collected current. The second terms in the tether efficiency ( $\eta_t$ ) and the electrical efficiency ( $\eta$ ) are inversely dependent on the current and cross-section ratio and therefore, the tether efficiency has a maximum as the function on this ratio.<sup>10</sup> The available tether efficiency depends on the specific operational requirements and restrictions of the mission.

### III. Application to ISS reboost

The drag of the rest gas atmosphere in the relatively low orbit causes a permanent deceleration and decay of the ISS and periodic reboost to maintain its orbit is required. The propellant costs associated with keeping ISS in the designated orbit with the help of the bi-propellant rocket thruster and tankage system which must to be refueled via some launch vehicle is extremely high. Various electric propulsion systems<sup>11</sup> and electrodynamic tethers (partly insulated,<sup>12,13</sup> and with a grid-sphere anode<sup>14</sup>) have been discussed as thrusters able essentially to reduce the amount of required propellant. The drag force acting on the ISS depends on the year with the average magnitude 0.6 N, and a thrust about 0.8N is desirable. It is also required that the added thruster mass does not shift essentially the ISS center of mass.

Below we will analyze the efficiency of the Tether Reboost System (TRS) design with the grid-sphere anode<sup>14</sup> and compare it with the performance of a partly insulated tether thruster.<sup>12</sup> The TRS has a triangle configuration with the ISS Truss forming the base and a pair of tethers meeting at the power supply satellite, based on the DS1 technology, to form the apex. The tethers have a mechanical connection to the truss with a 100-m nonconducting tether segment before transitioning to a grid-sphere charge collector and insulated conducting tether.

Tether efficiency,  $1/\eta_t$  (black curves), and electrical efficiency,  $\eta$  (red curves), for grid-sphere potentials ( $\varphi$ ) 100V and 500V as functions on the grid-sphere radii (R) are presented in Figs. 2(a) and 2(b) respectively. Different curves correspond to different tether cross-sections,  $s$  (in  $\text{mm}^2$ ). These plots are calculated with the help of Eqs. (1), (2) and (5) under two additional restrictions. The tether length in Eq. (5) has been defined by the required thrust ( $F = 0.4N$ ) from the equation

$$Fv = E_m IL \quad (6)$$

that relates the tether length with the grid-sphere radii. Blue and green curves in Fig. 2(a, b) present the tether length and collected current as the function on grid-sphere radii under condition (6). We also restricted the domain of possible tether system lengths by the assumption that the source voltage can not exceed 5kV. System parameters are as follows: plasma density  $n_\infty = 3 \cdot 10^{11} m^{-3}$ , temperature  $T = 1eV$ , induced electric field  $E_m = 0.12V / m$ ,  $\beta = 0.06kg / W$ ,<sup>4</sup>  $v = 7.7km / s$ , transparency  $\alpha = 0.9$ ; aluminum is used as the tether material.

As can be seen from the Fig. 2 the tether efficiency weakly depends on the tether cross-sections, if they are larger than  $1.2mm^2$ . For the given grid-sphere radii, there exists a cross-section maximizing tether efficiency, but the tether efficiency - cross-section dependence near the maximum is flat. Whereas the tether efficiency of about 0.5 ( $1/\eta_t = 2$ ) can be obtained with small grid-sphere radii (about 6-8m), for the proposed design with two grid-spheres it will require unacceptably long tethers. Larger potentials worsen the system performance, whereas the required tether length diminishes weakly for large grid-spheres, as can be found from Fig.2 (a) and (b). The tether length can be reduced by reducing the grid-sphere transparency, as can be seen in Fig. 2(c), but the efficiency diminishes. Here the transparency is 0.8, whereas other parameters are the same as in Fig. 2(a).

A thruster with a partly insulated tether as anode also has been considered for ISS reboost.<sup>12</sup> Calculation of the performance of such a system can be found in.<sup>4,15</sup> Fig.3 presents the tether efficiency (black curves) and electrical efficiency (red curves) as functions on a dimensionless length,  $l_b$ , of the tether bare segment. The normalization length is

$$L^* = \left( \frac{m_e E_m}{2e} \left( \frac{3\pi\sigma_s}{4epn_\infty} \right)^2 \right)^{1/3}, \quad l_b = \frac{L_b}{L^*} \quad (7)$$

where  $p$  is the tape perimeter. The number at the curve is the ratio of insulated and bare segment lengths. The bias at the end of the bare segment is zero. Additional conditions on the thickness,  $h$ , and the width of the tape,  $d$ , imposed by the OML theory validity, is taken as  $h + d = 6\lambda_D$ .<sup>4</sup> Fig. 4(a, b) presents the system parameters for a triangle configuration similar to that considered above, and Fig. 5(a, b) describes the design with one tether. Other parameters are the same as in the calculations for the tether with the grid-sphere anode. Note that the tether efficiency (Fig. 3) is independent on the system configuration and remains unchanged for the same normalized lengths,  $l_b$ , and insulated and bare segment length ratios.

As can be seen from Fig. 2(a-c) and Fig. 3, systems with the ratio of partly insulated and bare segments lengths in the range of 2-5 and bare segment normalized length,  $l_b$ , of about one, can provide tether efficiencies about 50% larger than tethers with a grid-sphere anode. The required tether length is also shorter for systems with partly insulated tethers. A configuration with one partly insulated tether requires the tether length to be about 8km with approximately two times larger tape cross-section, and the shift of the system center of mass will be larger than for both triangle designs (Fig. 5(a, b)).

#### IV. Application to MXER facility reboost

The MXER facility will consist of a rotating, ~100km long tether with components distributed along its length. MXER is to be operated in an elliptical trajectory, where a payload in a low circular orbit is caught by the rotating tether, accelerated by its tension and released with a velocity about 2.4km/s greater than the initial one. An electrodynamic tether system can be used to restore the facility kinetic energy lost to the boosted payload. In order for the tether system to boost multiple payloads, it must have the capability to restore its orbital energy and momentum as rapidly as possible after each payload transfer operation.

It is expected that the MXER tether would operate in an equatorial elliptical orbit with perigee in the altitude range of 300-500km and apogee in the range of 5000-10000 km.<sup>8</sup> The specific orbit chosen would be a function of the tip velocity of the tether, which is in turn a function of the orbital transfer desired and the limitations of material tensile strength. We will consider a trajectory with perigee at 300 km altitude and an apogee of 8500 km. The angle between the satellite velocity and the Earth's magnetic field was 90°. The orbital period of the facility motion is 3.06

hours and it rotates with the period about 400s.<sup>7</sup> Following Refs. 7 and 16, the payload capability is taken as 2500kg with the energy needed to restore the facility orbit after the payload launch equal to 54GJ. The thrust work needed to restore the position of the MXER facility within 100 days after launch is 68.9 MJ per facility revolution.

In contrast to the previous case the tether system should produce and store energy during the main part of the revolution (~3 hours), and then release it during the facility transition through the ionosphere (~15 min). Two other factors that should additionally be taken into consideration are the changing environmental parameters (plasma density and magnetic field) during transition through the ionosphere and tether rotation. A detailed description of the calculation of tether performance for MXER project is presented in Ref. 15, where the partly insulated ED tethers have been considered. Following this reference electrical power and tether efficiencies can be introduced as

$$\eta = \frac{\sum \langle E_{mi} \rangle I_i L t_i}{\sum \langle E_{mi} / \eta_i \rangle I_i L t_i} \quad \frac{M}{\sum \langle F_i t_i \rangle} = \frac{v \beta}{\eta_t}, \quad \frac{1}{\eta_t} = \frac{1}{\eta} + \frac{\kappa (\rho L s + 4 \pi \rho_{gsp} R^2)}{\beta \sum \langle E_{mi} \rangle I_i L t_i} \quad (8)$$

Here instead of power as used in Eqs. (3-5), the tether work during the transition through the ionosphere is introduced. This work is calculated as the sum of the works performed by the tether during the flight through the ionosphere layers (i) with approximately constant parameters;  $t_i$  is the time of flight through a layer, and the angle brackets indicate the averaging over the tether rotation.<sup>15</sup>  $\eta_i$  is calculated according to Eq. (5) for the corresponding layer and specific angle between the tether and the vertical. The performance of the tether system with modular architecture<sup>7,16</sup> has been considered for a different number of elements. The choice of this number defines the work per element,  $K_t$  (with total work 68.9MJ per revolution) and the required tether length as a function of the grid-sphere radii:

$$K_t = L \sum \langle E_{mi} \rangle I_i t_i \quad (9)$$

with the restriction that the source voltage can not exceed 5kV. Because of this constraint, the needed current for a system with two modules exceeds 50A. The system performance is presented below for the designs with 5 and 10 elements (Fig. 6(a, b)). Grid-sphere bias is taken as 100V, the transparency is 0.9,  $\beta \approx 6.7 \cdot 10^{-3} \text{ kg / kJ}$ <sup>7,16</sup> and other constants are taken as shown in the calculations for the ISS above. Numbers near the curves present the tether cross-sections in mm<sup>2</sup>. As can be seen in these figures, for both cases there exists a grid-sphere radius and corresponding tether cross-section providing approximately equal maximum tether system efficiency (minimums on the black curves). It can be found that higher grid-sphere bias leads to smaller tether efficiency. For example, for the bias 1kV and a system that contains 10 modules the best achievable efficiency is ~15% less than for 0.1kV bias (Fig. 6(b)). The system efficiency is practically the same if the grid-sphere transparency is changed from 0.9 (Fig. 6) to 0.8. It should be noted that for the 10 module system, whereas the grid-sphere radius for the maximum efficiency is smaller than for 5 modules, the total length of 10 tethers is about the length of the MXER facility (~100km).

Fig. 7 presents the system characteristics for partly insulated tethers with cylindrical and tape cross-sections for the MXER project from Ref.15. The notations here are the same as in Fig.3. The green curve presents the tether length permitted by the 5kV restriction on the source voltage. As can be seen from Fig. 6 and 7 the partly insulated tether with the ratio of insulated and bare segment lengths of about five has the efficiency about 25% higher than the tether with the grid-sphere anode.

## V. Conclusion

We have considered the efficiency of ED tether systems with a grid-sphere anode and partly insulated tethers as thrusters for the ISS and MXER project. It has been assumed that the electric source voltage is limited by 5kV. Because of the restriction on the shift of the ISS center of mass and, therefore, restriction on tether length, the maximum possible efficiency for the tether system with the grid-sphere anode is not available. The partly insulated tether efficiency is about 50% greater than the efficiency of a tether with the grid-sphere anode. Required tether length is also shorter for partly insulated tethers for a system with a triangle configuration. For the MXER project, in spite of the restriction on the tether length due to the limited source voltage, the maximum efficiency of the system with a grid-sphere anode can be obtained starting with three modules. For tether systems containing 5-10 modules the grid-sphere radii are in the range 7 – 10m and the currents did not exceed 15A. The efficiency of such systems is

about 25% lower than the efficiency of systems with partly insulated tethers. Lower grid-sphere bias and higher transparency act in favor of the efficiency for the considered tether systems with large grid-sphere radii.

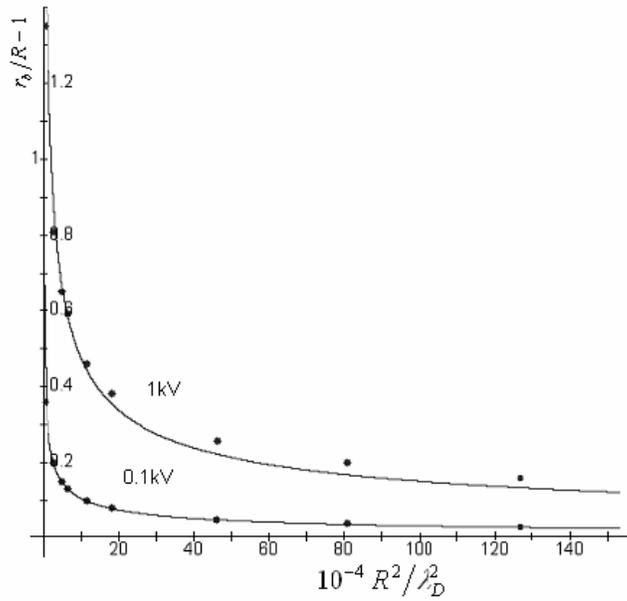
Results presented for this ISS and MXER project can be used for the preliminary analyses of the tether performance and the choice of the preferable thrust technology for these missions.

### Acknowledgments

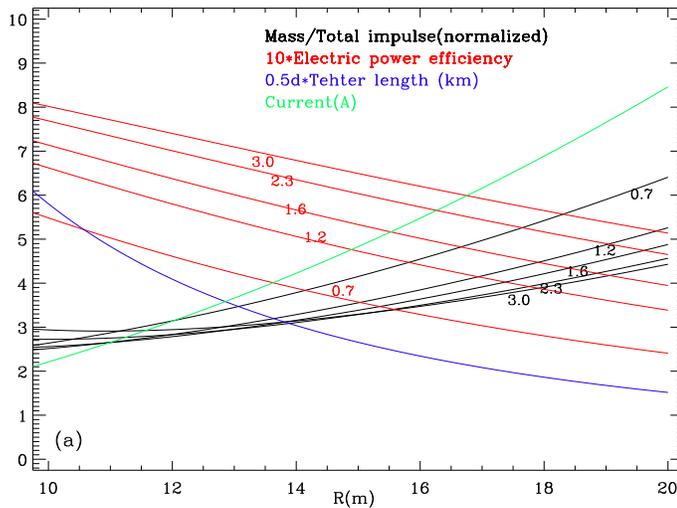
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**Figure 1. Approximation of data in Ref. 9 Table (3) by Eq. (2) for grid-sphere bias 0.1kV and 1kV**



**Figure 2 (a, b, c). Tether system parameters for ISS as functions on the grid-sphere radii R for different tether cross-sections (mm<sup>2</sup>).**  
**(a) Grid-sphere bias 100V, transparency 0.9.**

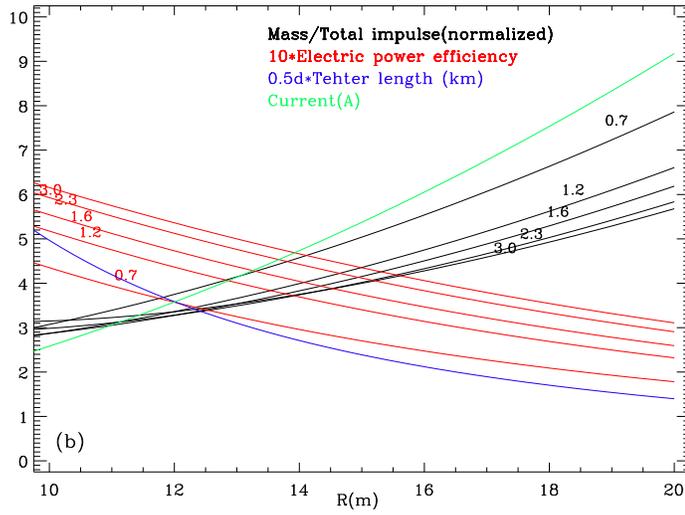


Figure 2 (b). Grid-sphere bias 500 V.

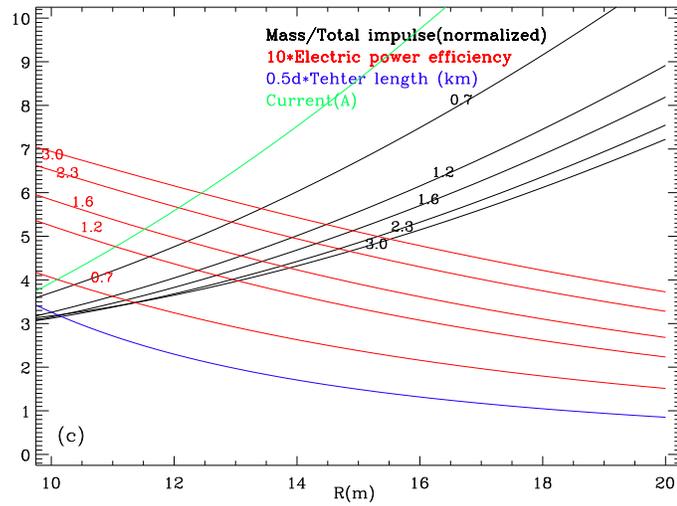
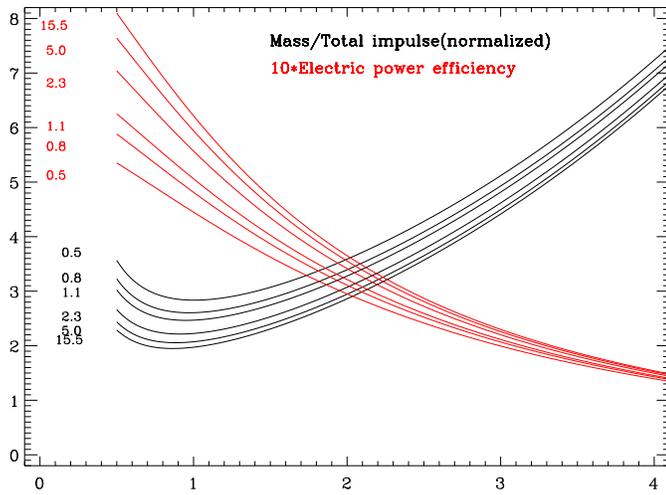
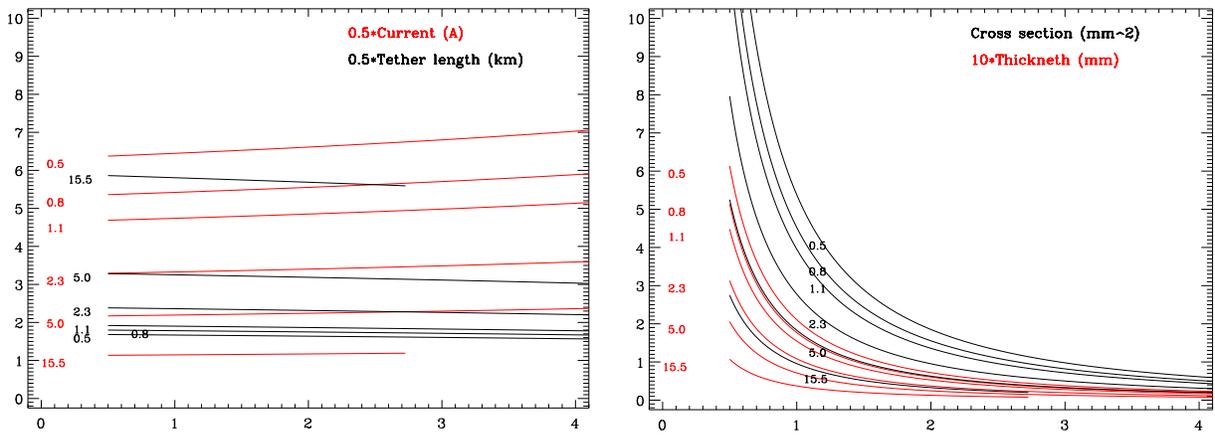


Figure 2(c). Grid-sphere bias 100V, transparency 0.8.



**Figure 3. Tether system efficiency for partly insulated tethers for ISS as functions on the dimensionless bare segment length for different ratio of bare and insulated segment lengths.**



**Figure 4 (a, b). Tether parameters for partly insulated tethers for triangle configuration for ISS.**

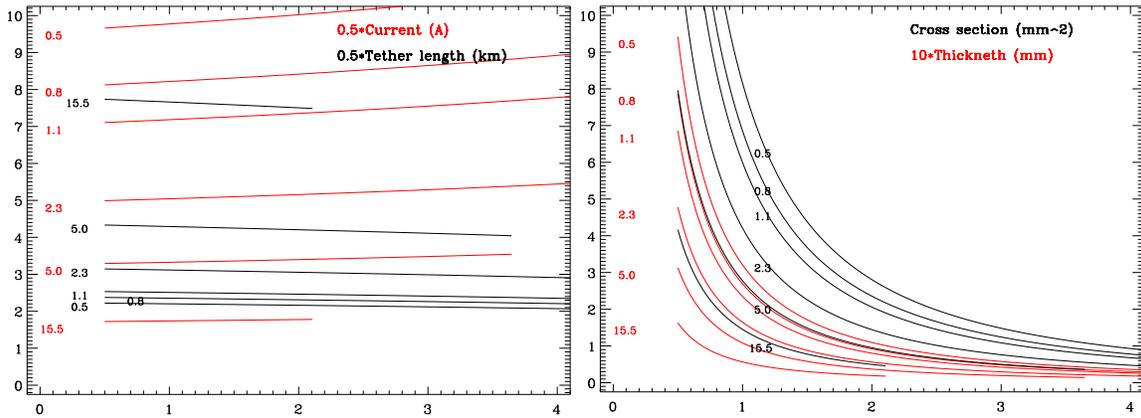


Figure 5 (a, b). Tether parameters for partly insulated tethers for one tether design for ISS.

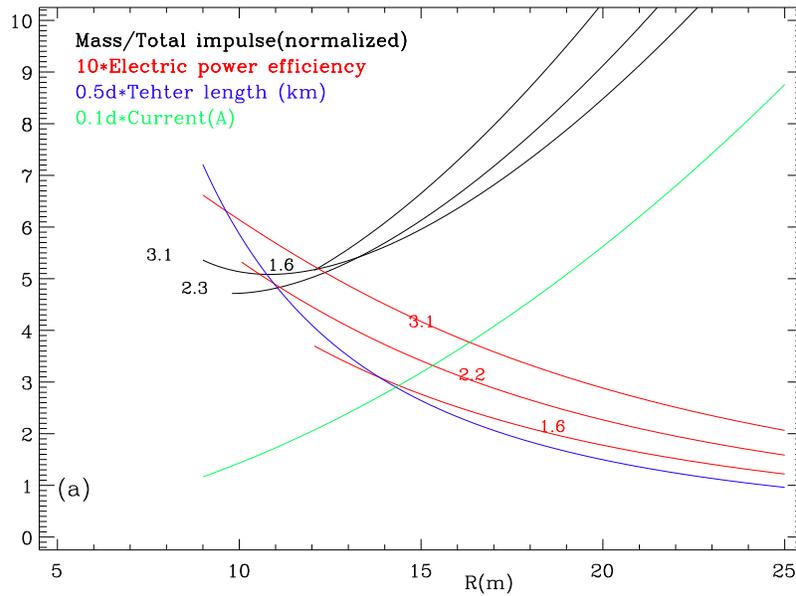


Figure 6 (a, b). Tether system parameters for MXER project as functions on the grid-sphere radii  $R$  for different tether cross-sections ( $\text{mm}^2$ ). (a) Grid-sphere bias 100V, transparency 0.9, 5 modules.

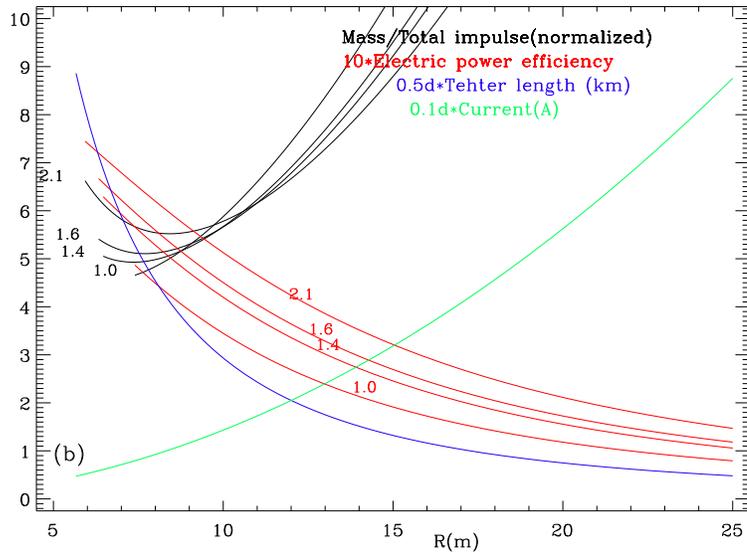


Figure 6 (b). 10 modules

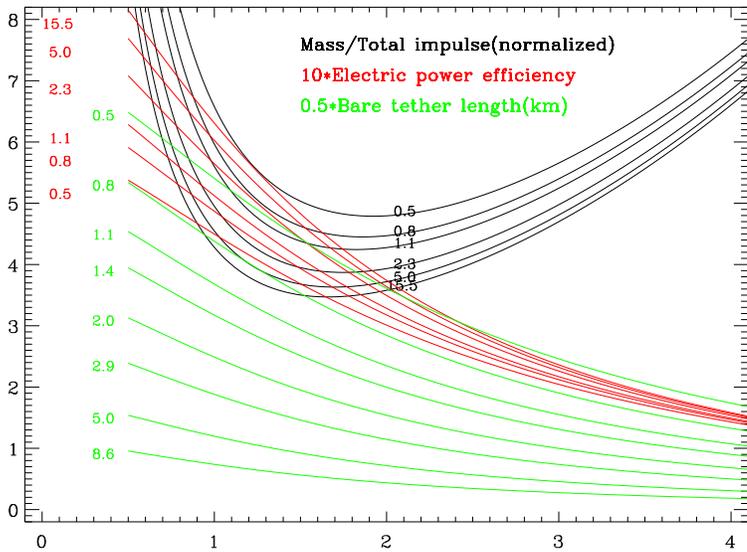


Figure 7. Tether system efficiency and length for partly insulated tethers for MXER project as functions on the dimensionless bare segment length for different ratio of bare and insulated segment lengths.