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Sample Mission Application of Capacitor Powered Hall Thrusters

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ABSTRACT

This study assesses the use of capacitor powered Hall thrusters for drag makeup of a sample LEO spacecraft. Charged by solar array power, the capacitors provide high voltage power directly to the Hall thrusters, alleviating the need for a costly power processing unit. Capacitor driven Hall thruster performance is compared to a baseline state-of-art hydrazine monopropellant system as well as Hall thrusters driven through a power processing unit directly connected to solar array power or a battery. Propulsion system wet mass is the primary figure of merit and is traded in terms of increased net mass (spacecraft mass less wet propulsion system mass). Potential implications in terms of system cost or complexity are also discussed. Results show that the simple, lower cost capacitor/Hall combination provides comparable net mass to the solar array and battery powered Hall thruster systems. Increases in net mass range from 15-40% when compared to state-of-art monopropellant systems.

INTRODUCTION

Electric propulsion has provided orbit maintenance of low Earth orbit (LEO) spacecraft in the past; the Russian Meteor spacecraft used Hall thrusters for orbit adjustment and the U.S. Navy Transit spacecraft used pulsed plasma thrusters to compensate for orbital disturbances.[1,2] Both these missions used relatively high orbits, approximately 1000 km, and propulsion was not required to compensate for atmospheric drag. Atmospheric drag does have a notable impact on orbit maintenance at low Earth orbits below 600 km.[3] For very low orbit altitudes the use of electric propulsion is often not possible due to the relatively low thrust associated with these systems when compared to the drag forces. Electric propulsion thrust levels can be increased with added (dedicated) solar arrays but this increases the drag force due to the added solar array area as shown by Tilley, *et al*.[4] Added solar arrays can also increase the system cost and complication. Adding large solar arrays to provide for drag makeup can be avoided by using a much smaller solar array and storing the electric energy for periodic makeup burns. Capacitors and batteries can be considered for such energy storage, each with advantages and disadvantages. State-of-art (SOA), space rated nickel cadmium and nickel hydrogen batteries have a greater energy density than capacitors but require a power processing unit to provide the high voltages required by Hall thrusters. SOA batteries also have a limited depth of discharge due to cycling impacts on lifetime and are still relatively expensive.[3]

Capacitors, on the other hand, are relatively inexpensive and have advantages for use with electric propulsion. As opposed to batteries, capacitors can provide the high voltages required by electrostatic thrusters. By eliminating the discharge power system, they reduce power processing unit (PPU) mass and cost. However they do not produce a constant voltage. Fortunately, Hall effect electrostatic thrusters can utilize these varied voltages with tolerable impact on thruster performance. Unlike current space-rated batteries, capacitors can be cycled over 600,000 times with minimal degradation.[5] The use of capacitors for powering a Hall thruster was recently validated by Hrbud, *et al.*[5] This analysis is based on those results.

This study assesses the use of capacitor powered Hall thrusters for drag makeup of a sample LEO spacecraft. Charged by a solar array, the capacitors provide high voltage power directly to the Hall thrusters, greatly reducing the power processing unit mass and complexity. The capacitor driven Hall thruster performance is compared to a baseline state-of-art hydrazine monopropellant system. Hall thruster systems driven through a power processing unit directly from a solar array or through a battery are also compared. Propulsion system wet mass is the primary figure of merit and is traded in terms of increased net mass (spacecraft mass less wet propulsion system mass). Potential implications in terms of system cost or complexity are also discussed.

MISSION ANALYSIS OPTIONS AND ASSUMPTIONS

Sample LEO Application Mission: ORACLE

The proposed NASA LEO atmospheric spacecraft ORACLE was used as a sample application for this study. The ORACLE spacecraft supports a Differential Absorption Lidar (DIAL) based on Langley Research Center's Lidar Atmospheric Sensing Experiment (LASE).[6] The mission is currently in the conceptual stage and preliminary estimates of the spacecraft initial mass and projected area are 1000 kg and 5 m^2 (not including solar array), respectively. A 6am/6pm, 300 km, 96.67° sun synchronous orbit is desired with a 2 year lifetime. The required 0.6 kW solar array is assumed to fly edge-on with respect to the velocity vector and in this configuration not causing any appreciable drag. The ORACLE bus carries a solar array to provide 0.6 kW for bus and payload operations.

Orbital Analyses

In the assumed missions the ORACLE spacecraft is kept at a 300 km sun synchronous orbit for 2 years. Two orbit cases were considered, a 6am/6pm and a 12am/12pm sunsynchronous 300 km orbits (figure 1), in order to bound the operational orbits between the minimum and maximum shadowing.

Some operational orbit band with lower and upper allowed altitudes must be assumed; for this mission a 299 km to 301 km band was chosen as typical to produce a representative delta V for drag makeup. This orbit band depends on many factors including how accurately the spacecraft's altitude is known and the level of spacecraft autonomy. In actuality, each of the systems in this study would have a different operational band depending on the capacitor or battery charge time or the availability of sunlight for the solar arrays. This operational band defines the duty cycle of the propulsion system. The duty cycle is merely the time to raise to the top of orbit band divided the time to raise to the top of orbit band plus the time to drag down to bottom of orbit band.

The spacecraft is assumed to be continuously in sunlight for the 6am/6pm baseline ORACLE orbit. In actuality, some shade periods are encountered a few months each year. This has minor impacts on this analysis. In this configuration any solar array added to provide power for the electric propulsion system is also assumed to be edge on to the velocity and thus not cause any appreciable drag.

In order to gauge the impact of maximum shading and added solar array drag a modified ORACLE mission is assumed in this study which places the operational orbit at a 12am/12pm, 300 km sun synchronous orbit with a 2 year lifetime. In this case the drag on the solar arrays is significant and it is assumed that a drag area of half the solar array area is present all the time. This orbit also experiences the maximum shading (36.6 minutes every 90.5 minute orbit.) Any impact of Hall thruster operation on instrument contamination is beyond the scope of this analysis.

The atmospheric density model used in the analyses is based on the F10.7 index atmosphere calculated with the DENS code. Two cases were chosen, the F10.7 = 150 or 250×10^{-22} W/(m^2 Hz) index to represent an all-time average and a solar maximum atmospheric density, respectively. Of the last five solar maximum years, only one had a monthly mean radio flux at F10.7 cm over 250×10^{-22} W/(m^2 Hz) and that peaked briefly at 290×10^{-22} W/(m^2 Hz). The other four solar maximum years had peaks below 250×10^{-22} W/(m^2 Hz).[3] The F10.7 = 150×10^{-22} W/(m^2 Hz) atmospheric density is roughly average. For example, the F10.7 = 250×10^{-22} W/(m^2 Hz) and 150×10^{-22} W/(m^2 Hz) atmospheres predict densities of 5.2e-11 kg/m^3 and 2.6e-11 kg/ m^3, respectively, for a 300 km circular orbit.

All mission analyses were performed using a simple iterative routine to calculate circular orbit altitude change assuming constant drag force versus the thrusting force over a circular orbit.[7] The model did not account for daily atmospheric variations. Impulsive devices, such as the SOA monopropellant thrusters, may employ several perigee and apogee burns to achieve the higher orbit with the thrusters pointed in the circumferential direction at the apogee and perigee. The lower thrust devices need to always be pointed in the circumferential direction during their burn. This should be possible for nadir pointing ORACLE class spacecraft.

The thruster/capacitor modeling equations are shown in the following sections. While adjustments for shading during the orbit were included in the model's equations, they are excluded in the equations shown in the paper for simplicity. When shade is encountered the thruster is allowed to burn but no capacitor or battery charging takes place.

SYSTEM ASSUMPTIONS AND MODELING

Propulsion Systems

Hall thrusters driven directly from a capacitor or through a PPU using battery or solar array power were compared to a baseline SOA chemical system. These case configurations are shown in Figure 2. Configurations 1-5 provide drag makeup propulsion with various combinations of thruster power levels and power systems. Configurations 1 and 2 perform the drag makeup mission with two different power level Hall thrusters using dedicated solar array and a power processing unit. Configurations 3 and 4 utilize the higher power Hall thruster with capacitor energy storage and a minimized PPU with a smaller solar array scaled (depending on shadow and drag assumptions) to provide enough power for pulsed Hall thruster operation. Configuration 5 also scales the solar array depending on shadow and drag assumptions but still requires a PPU for the Hall thruster. The baseline chemical propulsion system is designated as Configuration 6.

The baseline propulsion system is assumed to be a SOA 225 s specific impulse (I_{sp}) hydrazine monopropellant system This analysis assumes two Hall effect thrusters at different power levels; a 0.75 kW or a 1.3 kW thruster with anode layer (TAL). Table I provides the assumed characteristics of the 0.75 kW TAL[7], the 1.3 kW TAL[8], and the SOA monopropellant systems.[9] (The SPT and T series Hall thrusters would provide similar results.) Only the 1.3 kW TAL thruster is considered for the various power system configurations (2,3,4,5). Since the battery powered 1.3 kW TAL requires solar array power levels approaching 0.8 kW the solar array driven 0.75 kW TAL configuration (1) with similarly sized solar arrays to configuration 5 is used to highlight the impacts of using the higher power, better performing 1.3 kW TAL.

During operation of the Hall thruster with the capacitor the voltage drops from 400 V to 150 V. The impact of this voltage variation on thruster lifetime is unknown. This variation in voltage also causes a variation in thruster performance including thrust, I_{sp} and efficiency as show by Hrbud, *et al*.[5] An average performance point was chosen as representative for this study. This same performance point was also chosen for the battery and solar array powered Hall thrusters to create similar fuel and thrust performance and more clearly demonstrate the impacts of the power systems. The 0.75 kW thruster while set to the same Isp point has a lower power and efficiency. For the capacitor and battery driven Hall thrusters the burn time for each capacitor or battery charge is defined by the following relation:

$$T_b = n\ E\ /\ P_t$$

where T_b = Thruster Burn Time per charge, n = number of capacitors (or batteries), E = Capacitor (or battery) Energy Level, and P_t = Thruster Power Level.

A cathode suitable for use with Hall thrusters has been tested in excess of 30,000 cycles.[10] This cathode cycling limitation will impact the number of capacitor banks required as described in the next section. The TAL thrusters themselves have lifetime limits in terms of hours of operation: 3000 hours[7] for the 0.75 kW Hall thruster and >5000 hours[11] for the 1.3 kW Hall thruster.

The 1.3 kW Hall thruster utilizes a 92% efficient, 10 kg/kW PPU for the array and battery driven options but is changed to a 99% efficient, 3 kg/kW PPU for the capacitor driven option.[12] This smaller PPU replaces the normal low to high voltage conditioner (approximately 40V up to 300V) with an EMI filter/matching network. The smaller PPU retains the thermal throttle and cathode heater/ignitor of the larger PPU.[12] Thus the 1.3 kW Hall thruster system is most efficient using capacitors since the total output losses of the capacitor and EMI filter/matching unit are assumed to be 99% as compared to the 92% efficient PPU. Each of the 1.3 kW thrusters operates at an averaged efficiency of 50%. Note the solar array driven 1.3 kW thruster (configuration 2) has been given a greater solar array power due to its less efficient PPU in order to duplicate the capacitor and battery configurations (3,4,5) thrust levels. This PPU mass and complexity reduction may also reduce costs.

Power Systems

For the purpose of this analysis no spacecraft power was considered available for the Hall thruster system operation; therefore, the existing payload GaAs solar array area will be increased to either power the Hall thruster directly through a PPU or to charge a Ni/H_2 battery or a capacitor, which in turn will power the Hall thruster. This creates the most conservative case. If an independent solar array system were added for the propulsion system these solar arrays could feasibly be feathered when the thrusters are not in use and the drag could be reduced in some of the cases analyzed. In this analysis an independent array system is not considered due to its perceived added cost and complexity. The assumed GaAs array area and mass densities are 224 W/m^2 and 53 kg/kW, respectively.[6] Although some degradation of the arrays will occur it is ignored in this analysis. The size of the solar array to charge the battery or capacitor bank is defined by the following relationship:

$$P_c = (n \ E / T_c) \ CE$$

where P_c= Power Needed for Capacitor (or Battery) Charging, n = number of capacitors (or batteries), E = Capacitor (or battery) Energy Level, T_c = charge time, and CE = charging efficiency. A 95% capacitor charging efficiency is assumed.[5] A 90% charging efficiency is used for the battery system.[3]

The charge time for each capacitor or battery is merely the thruster burn time per charge divided by the duty cycle. The capacitors or battery can not be charged in shadow.

A state of the art Ni/H_2 battery technology is chosen to store the battery power for this Hall thruster application. Based on an Eagle-Picher nickel-hydrogen common pressure vessel 12 Ampere-Hour, 2.5 Volt cell, a 37.5 Wh/kg specific energy density is assumed.[13] The battery cycling over the two year mission is limited to 10,000 cycles. The corresponding depth of discharge (DOD) is therefore roughly 55%.[3] The battery charging efficiency is assumed to be 90%.[3] The structure and connecting hardware is assumed be 20% of the battery cell mass based on the Intelsat V design.[14] A modified effective energy density of 17 Wh/kg or 62 kJ/kg is determined considering the 55% DOD limit and the 20% support mass factor. The battery charger control and regulator specific mass is set at 1.7 kg/kW.[15] While the battery may have to be reconditioned due to cycling effects the impact is not considered in this analysis.

Two capacitor options were assumed (see Table II) Panasonic Aluminum-Organic Electrolyte2 (Pan/OE-2) and a joint Maxwell Laboratories / Auburn University aluminum-organic electrolyte (Max/Al-OE). The Pan/Al-OE2 type capacitors were tested running a TAL thruster.[5] The Max/Al-OE capacitor has the highest energy density of the two capacitors: 30 kJ/kg. Similar to the battery assumption, the structure and connecting hardware is assumed to be 20% of the capacitor mass and a charger/discharger controller specific mass is set at 1.7 kg/kW.

The capacitors are assumed to run the thrusters from a 400V down to a 150 V level. Thus some percentage of power is left over in the capacitor and is unusable. Using the $\frac{1}{2}CV^2$ energy equation this unusable portion was calculated to be 14% of the maximum energy. Therefore, the capacitor energy level is 86% of the specified energy level. Using this relationship the Pan/Al-OE2 and a Max/Al-OE had 275 kJ and 1579 kJ per charge, respectively, available to the thruster. It is assumed that the capacitor can be charged even during discharge periods.[5]

Although the capacitor banks may be cycled over 600,000 times[5], the Hall thruster cathode is assumed be limited to less than 30,000 cycles.[10] Therefore, additional capacitor banks will be added in this analysis to keep the number of cycles below 30,000.

RESULTS

The ability of Hall thrusters to increase the useable ORACLE spacecraft mass (net mass) was analyzed for both average and solar maximum atmospheres with both no shade and worst case shade orbits (see orbit analyses section). In general, each case assumes that extra solar array area is added to directly power the Hall thruster PPU or charge the capacitor or battery.

Results show that the Hall thrusters in most configurations can keep the ORACLE spacecraft at the desired 300 km orbit, even during solar maximum periods. All the thruster systems could maintain the orbit for an average atmosphere. The 0.75 kW Hall system's (configuration 1) thrusting force is only slightly more than twice the worst case drag; it did not have sufficient margin to maintain the 300 km orbit under worst-case shaded, solar maximum drag conditions. Under these same worst case conditions, the 1.3 kW Hall configurations (2-5) had a thrust to drag fraction of over three which was sufficient to overcome the drag in all cases analyzed.

Each of the propulsion systems compared must be operated a certain length of time to offset the drag. These duty cycle requirements for each system combination are shown in Tables IV-VII. The lifetimes required for each of the mission shadow/density combinations were within the allowable limits for the 1.3 kW thruster but too great for the 0.75 kW thruster. The relative advantages and disadvantages of each propulsion technology for this ORACLE mission are given in Table III .

Minimum Shade Orbit

At a 6am/6pm, 300 km sun synchronous orbit shade periods are only encountered for a four month period; the rest of the year no shading is encountered. For this analysis no shading is assumed for the 6am/6pm case to bound the maximum shading case presented in the next section. Assuming the ORACLE launch mass of 1000 kg is constant for all propulsion options and either a solar average or solar maximum atmosphere, the useable spacecraft mass is directly determined (see Tables IV and V).

The data for the solar average assumption are shown in Table IV. Figure 3 illustrates that net mass increases of over 18% are possible with the use of Hall thrusters compared to a SOA monopropellant system. It can be seen in Table IV that the duty cycles (fraction of time the Hall thruster system must operate) of the 1.3 kW Hall systems are lower (10% verses the 20%) compared to the 0.75 kW system. The capacitor and battery systems only require 140W and 160W, respectively, of dedicated solar array to be added to the spacecraft as opposed to 815 and 1413 W arrays for the solar array powered Hall systems. The battery systems, while lighter than the capacitor systems for this case, do need slightly more solar array due to greater charging inefficiencies. In addition, the reduced size of the array and the reported low cost of capacitor banks (in comparison to solar arrays or batteries) may significantly reduce system cost.

Figure 4 and Table V show the results for the solar maximum assumption. Net mass increases of up to 40% compared to a SOA monopropellant system are achieved with the use of Hall thrusters in any configuration. Table V shows that the duty cycle of the 1.3 kW systems are again lower than the 0.75 kW thruster but twice that required for the solar average case. The 0.75 kW thruster must be used past its useful lifetime. The capacitor systems, while needing more dedicated solar arrays than the solar average case, only require 276 W of dedicated solar array to be added to the spacecraft. The greater duty cycle and required array are driven by the increase in atmospheric density at solar maximum. For the solar maximum case the 0.75 kW Hall system is the lightest, but violates its 3000 hour lifetime.

The solar array driven 0.75 kW and 1.3 kW Hall thrusters perform just enough thrusting cycles to allow the spacecraft to drag down to the assumed lower altitude (299 km) and then operate on the order of hours to days to raise the satellite to the upper orbit (301 km). Due to capacitor and battery energy limitations, the capacitor and battery driven Hall thrusters are operated many more times for shorter periods of 7 to 20 minutes as shown in Tables IV and V. This would result in a tighter operational orbit band than assumed. In reality, the solar array driven Hall thruster systems could perform the same cycling as the capacitor and battery systems and, therefore, keep the satellite in the same orbit band.

The additional cycling of the capacitor systems requires that an additional capacitor bank is used for the Pan/Al-OE2 case to limit the Hall thruster cathode to 30,000 cycles. The cycling of the higher energy Max/Al-OE is below 30,000 cycles and an additional capacitor bank is not required.

Maximum Shade Orbit

At a 12am/12pm, 300 km sun synchronous orbit, maximum shade periods of 36.6 minutes are encountered during every 90.5 minute orbit. The net masses for the maximum shaded cases are shown in Tables VI and VII. Overall, the required duty cycles and additional array areas for the capacitor driven Hall thrusters are higher compared to the no shade cases due to the increased drag caused by the additional solar arrays.

For the solar average atmosphere, net mass increases of around 20% are possible with any Hall propulsion system configuration (See Table VI and Figure 5.) The dedicated solar array areas have a large impact on each system case as shown by the increased duty cycles. The impact of shading also requires larger dedicated arrays for the capacitor and battery driven systems due to the decreased available charge time per orbit. The capacitor driven Hall thruster system configurations (3,4) have the smallest duty cycle and dedicated array masses. Only the 1.3 kW Hall thruster system configurations have sufficient lifetimes to perform the mission.

For the solar maximum atmosphere, net mass gains of over 45% are achievable using 1.3 kW Hall technology configurations (See Table VII and Figure 6.) The 0.75 kW Hall system, however, is unable to maintain the orbit in this solar maximum, shaded case. Duty cycles and required additional arrays are the greatest for these cases as shown in Table VII. The burn times for the capacitor driven Hall system configurations are again on the order of minutes (e.g., 20 minute burns every 40 minutes).

CONCLUSIONS

Regardless of atmospheric density assumption the Hall thruster configurations (1-5) reduce the required propulsion system mass compared to the monopropellant wet system mass. Thruster duty cycles from 10% to 31% were required for the capacitor powered configurations (3,4) depending on orbit shade and atmospheric density assumption. The best performing capacitor system depended on the allowable cycles of the Hall thruster. Further work should analyze these results to match the best combination of capacitor bank voltages and sizes for each application.

Overall, the Hall thruster systems added 15-40% net mass compared to the SOA monopropellant system. While the solar array powered 0.75 kW Hall propulsion system (configuration 1) outperforms the other systems for most of the cases, it has several limitations; the 0.75 kW system is unable to maintain orbit under worst case shade and drag conditions, it requires twice the duty cycle of the other Hall configurations, and in all instances the thruster lifetime limits are violated. The solar array powered 1.3 kW propulsion system (configuration 2) provides performance similar to the capacitor system configurations. In this instance the simpler and cheaper capacitor systems, configurations 3 and 4, would probably be preferred over configuration 2. Due to its higher energy density, the battery powered Hall propulsion system (configuration 5) almost always provides more net mass than the capacitor configurations 3 and 4. As with the array powered propulsion system, the capacitor configuration's greater simplicity and lower cost would probably offset the battery system's net mass advantages.

The capacitor driven Hall thrusters required less amounts of dedicated solar array than either the solar array or battery powered Hall thrusters. This reduced solar array area would substantially reduce the drag force the satellite encounters and consequently the drag makeup fuel required. Assuming solar arrays are more expensive than capacitor banks the system cost would also be reduced. The capacitor driven Hall thruster also allows for the use of a more efficient, higher $I_{sp,}$ longer life Hall system that requires less fuel and less dedicated power.

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Table I. Thruster Characteristics

Thruster System Characteristics	750 W Hall	1.3 kW Hall Solar Array /Capacitor /Battery	SOA MonoProp
Isp	1600 sec	1600 sec	225 sec
Overall Efficiency	0.41	0.46/0.50/0.46	1.00
Thruster Power Level (into PPU)	750 W	1413 / 1313 / 1413 W	n/a
Per Thruster Mass	3.6 kg	8.0 kg	0.33 kg
Per PPU Mass	10 kg/kW	10 / 3 / 10 kg/kW	n/a
Fixed Propellant Sys Mass	1.0 kg	1.0 kg	1.82 kg
Propellant Tankage Fraction	0.100	0.100	0.072
Propellant density	1.71 g/cc	1.71 g/cc	1.00 g/cc
# of thrusters	1	1	2
Engine(s) Thrust	40 mN	83 mN	4500 mN

Table II. Capacitor Battery Specifications

Capacitor and Battery Specifications	Panasonic Capacitor	Maxwell / Auburn Capacitor	Eagle-Picher $Ni\text{-}H_2$ Batteries
Configuration Designation	Pan/Al-OE2	Max/A1-OE	RNHC-12-13 (cell)
Number of Units	135	108	varied
Charge Voltage	405	378	2.5(ea)
Capacitance (F)	4	25.7	-
Energy (J)	320	1836	-
Mass (kg)	40.5	61	scaled
Energy / Mass (J/g)	7.9	30 .1	62

Table III. Relative Advantages and Disadvantages of Propulsion Technologies for the ORACLE Mission

Technology	Advantages	Disadvantages
SOA Monopropellant	Off-the-Shelf, Quick maneuvers, no added solar array	Low Isp - large fuel requirements
Hall Thrusters with Solar Arrays	High Isp - low fuel requirements, few thruster cycles	Requires a power processing unit and a large dedicated solar array
Hall Thrusters with Batteries	High Isp - low fuel requirements, small dedicated solar array	Requires power processing unit and more thruster cycles
Hall Thrusters with Capacitors	High Isp - lowest fuel requirements, small dedicated solar array, relatively no power processing unit	Requires more thruster cycles

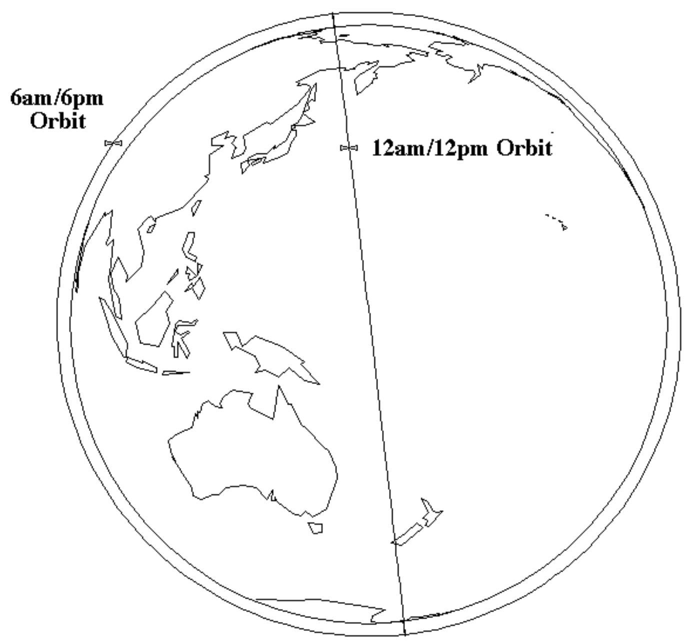

Figure 1 Sunsynchronous Orbits

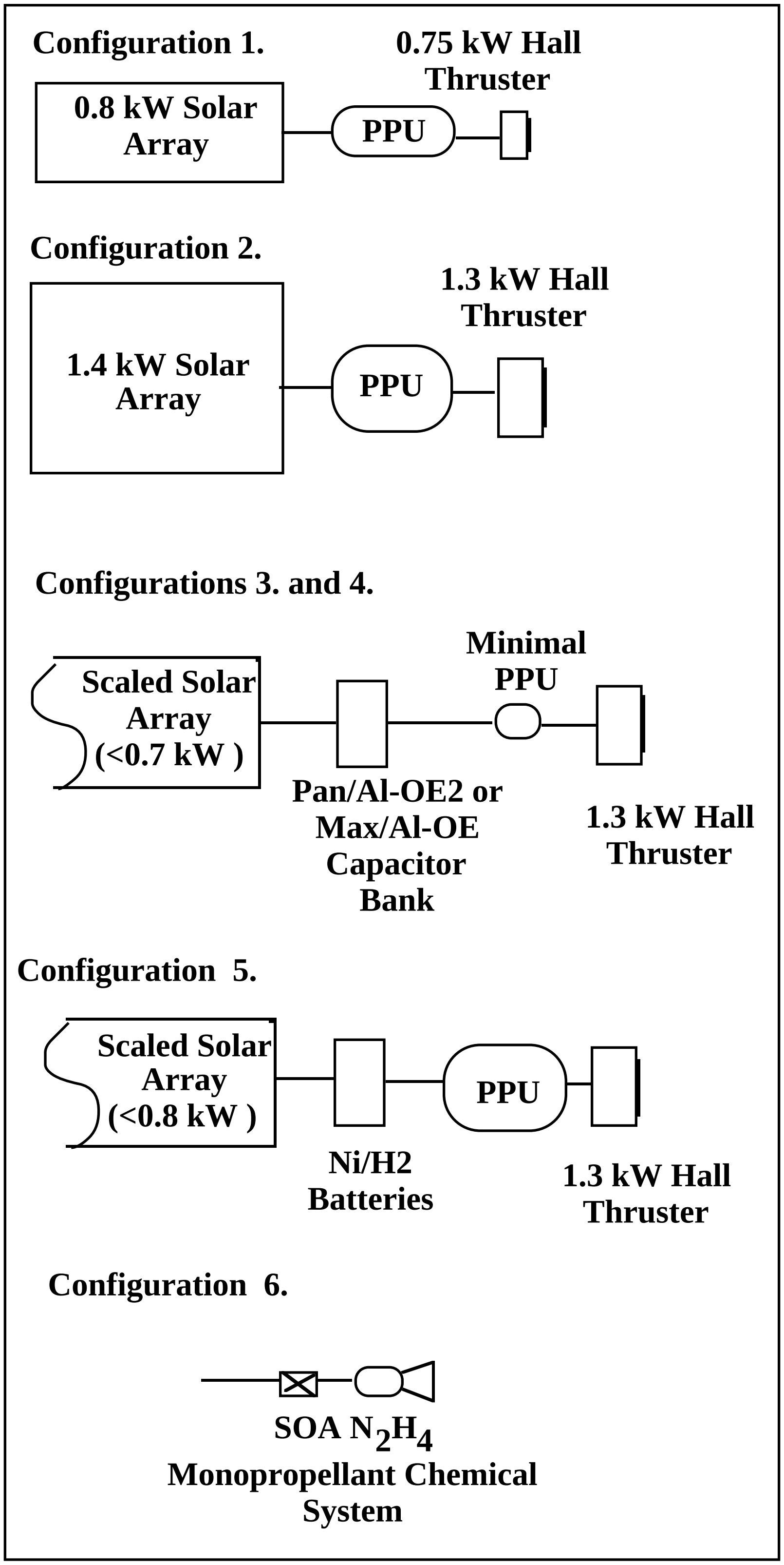

Figure 2. Propulsion System Cases

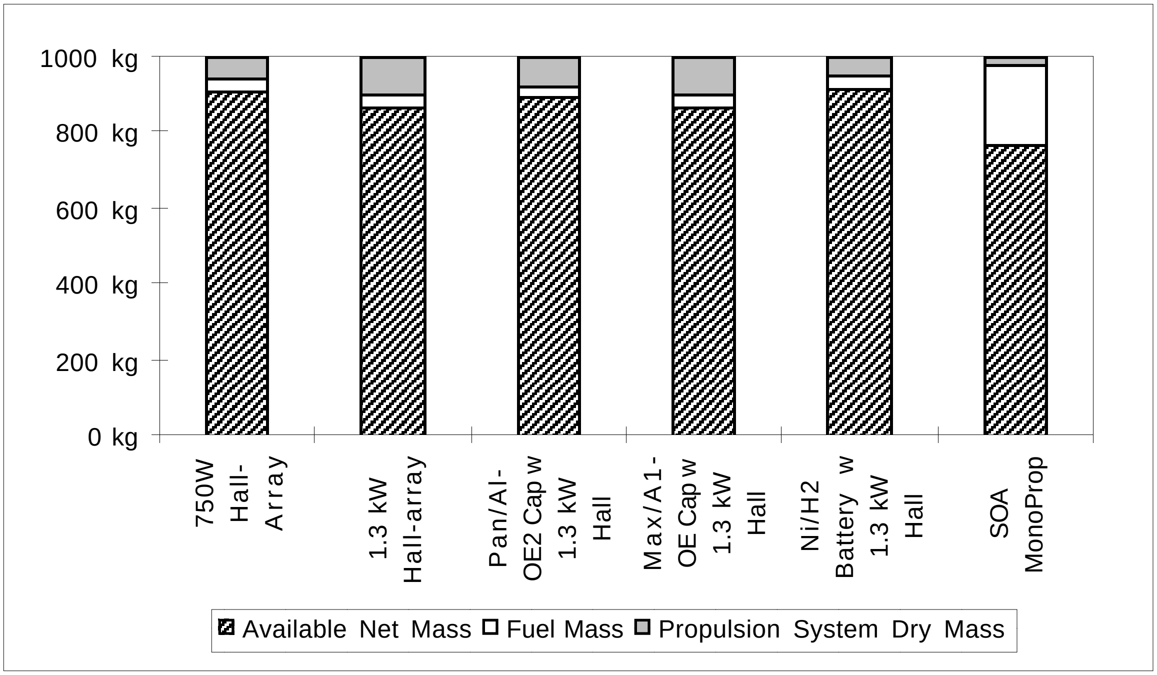

Figure 3. Masses vs. Technology Type (Solar Average Atmospheric Density, 6am/6pm orbit)

Propulsion System Configuration	1. 750W Hall-Array	2. 1.3 kW Hall-array	3. Pan/Al-OE2 Cap w 1.3 kW Hall	4. Max/A1-OE Cap w 1.3 kW Hall	5. Ni/H2 Battery w 1.3 kW Hall	6. SOA MonoProp
Available Net Mass	907 kg	865 kg	891 kg	867 kg	915 kg	770 kg
Fuel Mass	34 kg	34 kg	34 kg	34 kg	34 kg	213 kg
Propulsion System Dry Mass	59 kg	101 kg	75 kg	99 kg	51 kg	18 kg
Dedicated EP Solar Array Power Level	815 W	1413 W	143 W	143 W	161 W	0 W
Dedicated EP Solar Array Mass (53 kg/kW)	43 kg	75 kg	8 kg	8 kg	9 kg	0 kg
Duty Cycle (thrust time / total time)	0.20	0.10	0.10	0.10	0.10	
Number Of Capacitor Banks	n/a	n/a	1	1	1	
Thruster burn Time per cycle	0.4 d	0.2 d	3.5 min	20.0 min	9.9 min	
Capacitor/Battery charge Time	1.8 d	1.6 d	33.8 min	193.7 min	95.3 min	
Thruster cycles (ea)	332 cycles	400 cycles	28212 cycles	4917 cycles	10000 cycles	
Thruster Total burn time (ea)	3444 hrs	1781 hrs	1642 hrs	1642 hrs	1642 hrs	

Table IV. Summary for Solar Average, 6am/6pm orbit

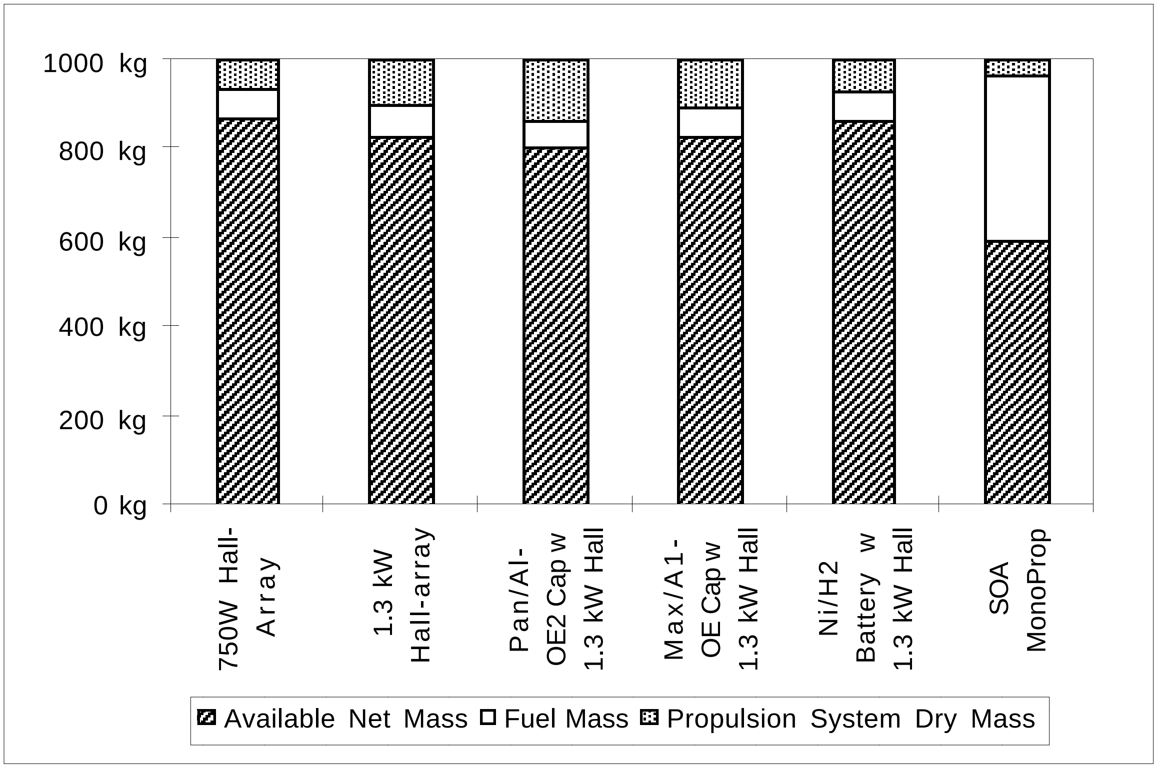

Figure 4. Masses vs. Technology Type (Solar Maximum Atmospheric Density, 6am/6pm orbit)

Propulsion System Configuration	1. 750W Hall-Array	2. 1.3 kW Hall-array	3. Pan/Al-OE2 Cap w 1.3 kW Hall	4. Max/A1-OE Cap w 1.3 kW Hall	5. Ni/H2 Battery w 1.3 kW Hall	6. SOA MonoProp
Available Net Mass	872 kg	831 kg	802 kg	826 kg	863 kg	590 kg
Fuel Mass	65 kg	64 kg	64 kg	64 kg	64 kg	380 kg
Propulsion System Dry Mass	63 kg	104 kg	133 kg	109 kg	72 kg	30 kg
Dedicated EP Solar Array Power Level	815 W	1413 W	276 W	276 W	311 W	0 W
Dedicated EP Solar Array Mass (53 kg/kW)	43 kg	75 kg	15 kg	15 kg	16 kg	0 kg
Duty Cycle (thrust time / total time)	0.39	0.20	0.20	0.20	0.20	
Number Of Capacitor Banks	n/a	n/a	2	1	1	
Thruster burn Time per cycle	0.6 d	0.3 d	7.0 min	20.0 min	17.5 min	
Capacitor charge Time	0.9 d	1.0 d	34.9 min	100.2 min	87.6 min	
Thruster cycles (ea)	505 cycles	581 cycles	25078 cycles	8742 cycles	10000 cycles	
Thruster Total burn time (ea)	6629 hrs	3390 hrs	2920 hrs	2920 hrs	2920 hrs	

Table V. Summary of Solar Maximum, 6am/6pm orbit Technology Option

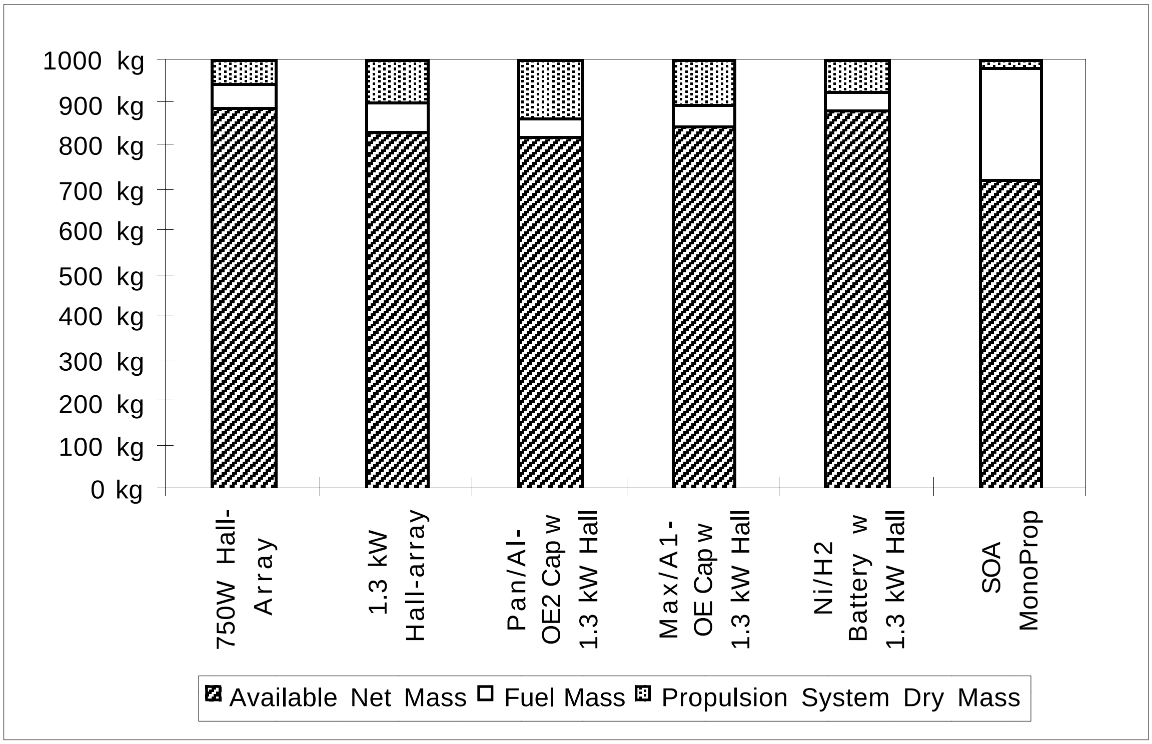

Figure 5. Masses vs. Technology Type (Solar Average Atmospheric Density, 12am/12pm orbit)

Propulsion System Configuration	1. 750W Hall-Array	2. 1.3 kW Hall-array	3. Pan/Al-OE2 Cap w 1.3 kW Hall	4. Max/A1-OE Cap w 1.3 kW Hall	5. Ni/H2 Battery w 1.3 kW Hall	6. SOA MonoProp
Available Net Mass	886 kg	835 kg	819 kg	843 kg	876 kg	716 kg
Fuel Mass	53 kg	61 kg	46 kg	46 kg	46 kg	262 kg
Propulsion System Dry Mass	61 kg	104 kg	135 kg	111 kg	78 kg	21 kg
Dedicated EP Solar Array Power Level	815 W	1413 W	331 W	331 W	373 W	0 W
Dedicated EP Solar Array Mass (53 kg/kW)	43 kg	75 kg	18 kg	18 kg	20 kg	0 kg
Duty Cycle (thrust time / total time)	0.31	0.19	0.14	0.14	0.14	
Number Of Capacitor Banks	n/a	n/a	2	1	1	
Thruster burn Time per cycle	1.1 d	0.4 d	7.0 min	20.0 min	20.3 min	
Capacitor charge Time	1.0 d	0.9 d	29.1 min	83.5 min	84.8 min	
Thruster cycles (ea)	342 cycles	528 cycles	29123 cycles	10152 cycles	10000 cycles	
Thruster Total burn time (ea)	5368 hrs	3213 hrs	3391 hrs	3391 hrs	3391 hrs	

Table VI. Summary of Solar Average, 12am/12pm orbit Technology Option

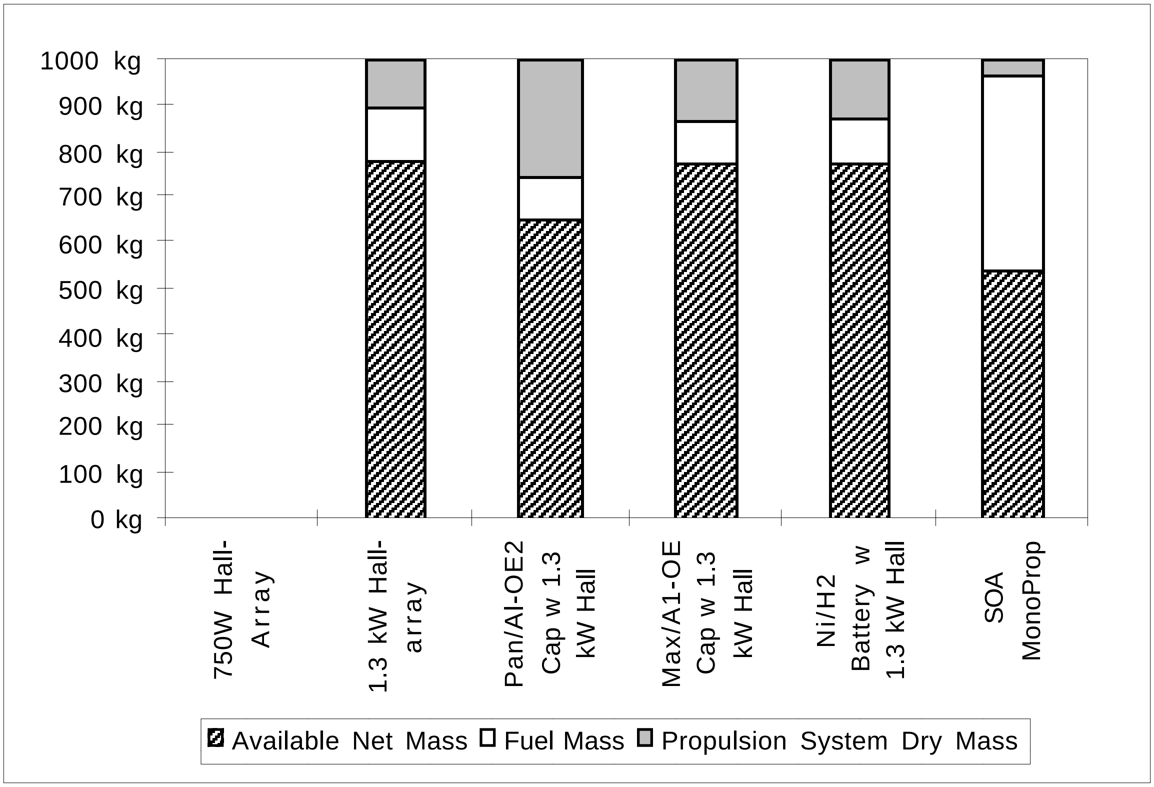

Figure 6. Masses vs. Technology Type (Solar Maximum Atmospheric Density, 12am/12pm orbit)

Propulsion System Configuration	1. 750W Hall-Array	2. 1.3 kW Hall-array	3. Pan/Al-OE2 Cap w 1.3 kW Hall	4. Max/A1-OE Cap w 1.3 kW Hall	5. Ni/H2 Battery w 1.3 kW Hall	6. SOA MonoProp
Available Net Mass	fails to maintain orbit	779 kg	650 kg	771 kg	773 kg	539 kg
Fuel Mass	n/a	112 kg	94 kg	94 kg	99 kg	428 kg
Propulsion System Dry Mass	n/a	109 kg	256 kg	134 kg	128 kg	33 kg
Dedicated EP Solar Array Power Level	815 W	1413 W	689 W	689 W	818 W	0 W
Dedicated EP Solar Array Mass (53 kg/kW)	43 kg	75 kg	37 kg	37 kg	43 kg	0 kg
Duty Cycle (thrust time / total time)	n/a	0.36	0.30	0.30	0.31	
Number Of Capacitor Banks	n/a	n/a	4	1	1	
Thruster burn Time per cycle	n/a	0.8 d	14.0 min	20.0 min	36.2 min	
Capacitor charge Time	n/a	0.5 d	27.9 min	40.1 min	68.9 min	
Thruster cycles (ea)	n/a	581 cycles	25079 cycles	17484 cycles	10000 cycles	
Thruster Total burn time (ea)	n/a	5894 hrs	5840 hrs	5840 hrs	6041 hrs	

Table VII. Summary of Solar Maximum, 12am/12pm orbit

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13. ABSTRACT ***(Maximum 200 words)***

This study assesses the use of capacitor powered Hall thrusters for drag makeup of a sample LEO spacecraft. Charged by solar array power, the capacitors provide high voltage power directly to the Hall thrusters, alleviating the need for a costly power processing unit. Capacitor driven Hall thruster performance is compared to a baseline state-of-art hydrazine monopropellant system as well as Hall thrusters driven through a power processing unit directly connected to solar array power or a battery. Propulsion system wet mass is the primary figure of merit and is traded in terms of increased net mass (spacecraft mass less wet propulsion system mass). Potential implications in terms of system cost or complexity are also discussed. Results show that the simple, lower cost capacitor/Hall combination provides comparable net mass to the solar array and battery powered Hall thruster systems. Increases in net mass range from 15-40% when compared to state-of-art monopropellant systems.

14. SUBJECT TERMS

Electric propulsion; Capacitor; Drag makeup; Hall thruster; Station keeping

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