Mission Enabling and Enhancing Spacecraft Capabilities with MicroNewton Electric Propulsion

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Abstract— The capability to significantly improve current spacecraft pointing, precision orbit maintenance and disturbance mitigation were considered using precision, quiescent microNewton electric propulsion systems. Analysis results showed that electric propulsion systems operating in the microNewton to hundreds of microNewtons thrust range can offer significant improvements over state-of-the-art mission capabilities to enable 30 m Earth-fixed orbital tubes, constellation spacecraft position control to within nanometers and exoplanet observatory pointing with 0.1 milliarcsecond precision. Specific thrust levels and profiles required to support these capabilities are discussed.

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1. INTRODUCTION

Electric propulsion systems are under development for a broad range of mission applications that require thrust controllable in the microNewton to milliNewton range. These mission scenarios include single Earth observing spacecraft, deployable x-ray telescopes, exoplanet observatories and constellations of spacecraft for Earth and deep space observations. Many missions that are currently under consideration by NASA and the DoD could be improved or enabled by these microNewton electric propulsion systems with the capability to operate continuously and efficiently over a large throttle range at variable throttle frequency and with very low thrust noise. They could provide continuous drag compensation and attitude control with improved precision, structural dynamics, efficiency and lifetime in comparison to standard orbit maintenance and attitude control practices. These thruster technologies have the potential for replacing multiple systems on standard spacecraft architectures to reduce complexity and mass. The ESA GOCE mission is currently flying ion engines for continuous drag-free operation in a 2-3 m Earth-fixed orbital tube at ~250 km while mapping the Earth's gravitational field. The ion thrusters are operating at 1-20 mN with 12 microNewton thrust resolution. Colloid thrusters have been qualified to operate through 10s of microNewtons at better than 0.1 microNewton thrust resolution. Other electric thrusters are under development to operate between these two ranges. This paper presents the mission enabling and enhancing capabilities that microNewton electric propulsion offers and the thrust characteristics that they require.

2. DRAG-FREE OPERATIONAL CAPABILITY

Operating spacecraft in a drag-free mode can enable or improve a variety of high precision measurements for a broad class of scientific missions. The Laser Interferometer Space Antenna (LISA) mission requires a drag free constellation of three spacecraft in an Earth-trailing orbit to support the required picometer displacement measurements to detect and characterize gravity waves from super massive black hole mergers. Earth observation spacecraft benefit from flying drag-free for precision orbits in target displacement detection sensitivity. Two of these types of missions are discussed with the thrust profiles required to enable unique capabilities.

Constellation of Spacecraft

LISA is a joint ESA-NASA project to design, build and operate the first space-based, gravitational wave observatory. The LISA instrument consists of a constellation of 3 identical spacecraft, each with 2 proof masses, separated by 5 million km and moving together in an equilateral triangle configuration in orbit around the sun at the same distance as Earth. The Interferometer Measurement System (IMS) is the part of the LISA instrument that measures the distance between pairs of free-falling proof masses (PM) provided by the Gravitational Reference Sensor (GRS) in the Disturbance Reduction

System (DRS). A single spacecraft contains a scientific payload complement of optics and electronics for making the PM to spacecraft distance measurement and implementing the drag free control with the microthruster subsystem as the actuator.

The microthruster subsystem in the DRS provides the actuation for controlling the position and orientation of the spacecraft during all modes of operation. These modes include tip-off, acquisition (defocus and scan schemes), safe, and science. The DRS consists of the GRS, microthruster subsystem, and drag-free control laws. The GRS houses the PM and a set of sensors, actuators, and thermal and magnetic shields designed to keep the PMs undisturbed from spacecraft interactions and the external space environment so that picometer level changes to the $5x10^9$ m spacecraft separation distance can be detected. The DRS is responsible for ensuring that the residual acceleration of the PMs falls below the LISA sensitivity requirements by providing tight pointing and translational control of the LISA spacecraft and its PMs through use of multiple microthrusters located on the exterior of the spacecraft. The microthruster subsystem will include either FEEP or colloid thrusters. A configuration of the LISA spacecraft with colloid thrusters is shown in Fig. 1. The mass of each of the spacecraft is currently 400 kg. The colloid microthruster subsystem architecture currently includes only sun-opposing thrusters and relies on solar pressure to provide full control of the spacecraft. In the current spacecraft architecture, each spacecraft will have 3 operating microthruster clusters. At least six thrusters, with two thrusters in each cluster, will operate continuously during science operations for the entire LISA mission.

The mission thrust profiles were derived for the defocus acquisition scheme in acquisition mode and the science mode. The thrust range requirement for a single thruster depends on the needs of all operating modes. The maximum thrust is set by maximum slew rate requirements during acquisition. High thrust may also be required for tip-off and safe modes. At the current time, the maximum thrust required during acquisition is sufficient to meet the requirements for these modes also. The thrusters are operating continuously in these modes being commanded at a 10 Hz frequency. The thrust profiles for each of the thrusters on spacecraft A are given in Fig. 2 for the first 4,300 seconds in acquisition mode in the defocus acquisition scheme. The thrust requirements for each of the spacecraft are similar. The thrust profiles for the six thrusters on spacecraft A are given in Fig. 2 for the first 3,000 seconds in the science mode. The profiles during this period are expected to be representative of the remainder of the duration of operation in that mode, except for the initial higher thrust levels during the first 40 s. The thruster control scheme commands the thruster temporarily to the full thrust range during start-up in this mode for these initial higher thrust levels. The graphs show that the thruster is throttled at higher frequency in this mode. The thrust level statistics for the thrusters on each of the spacecraft are given in Table 1. The current thrust requirements are summarized in Table 2 with other thruster requirmements. The analysis results show that a drag-free constellation with nanometer level positioning precision in an Earth trailing orbit is enabled by a thruster with the capability to run continuously through a throttle range of 4-30 μN with 0.1 μN resolution and 0.1 μN/√Hz thrust noise.

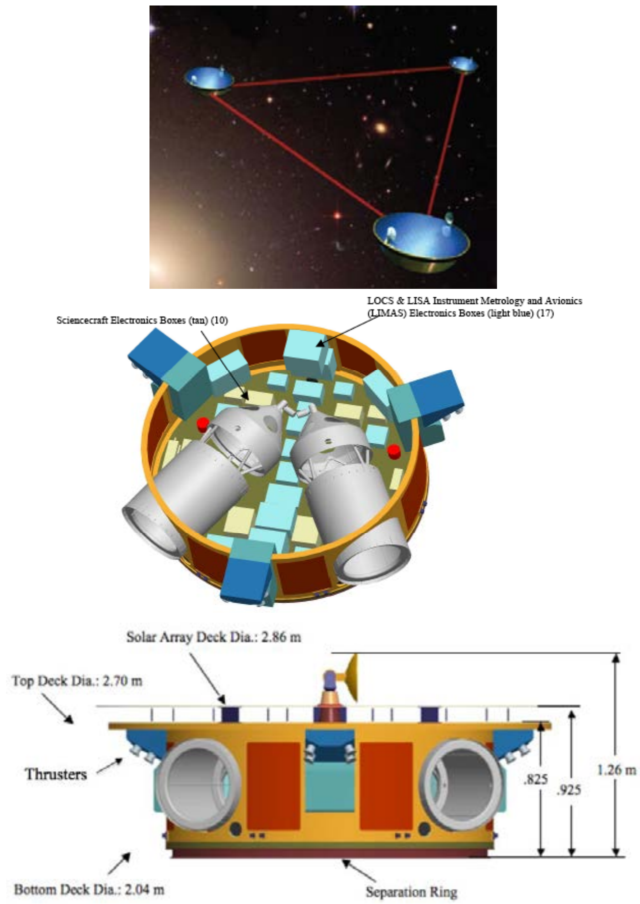

Figure 1. LISA spacecraft and mission formation flying configurations.

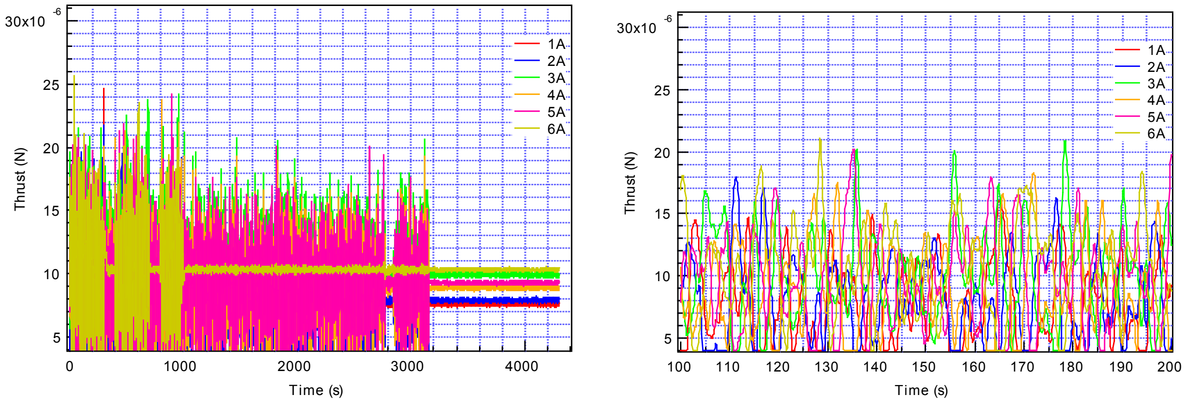

Figure 2. Acquisition mode thrust profiles for the thrusters on spacecraft A.

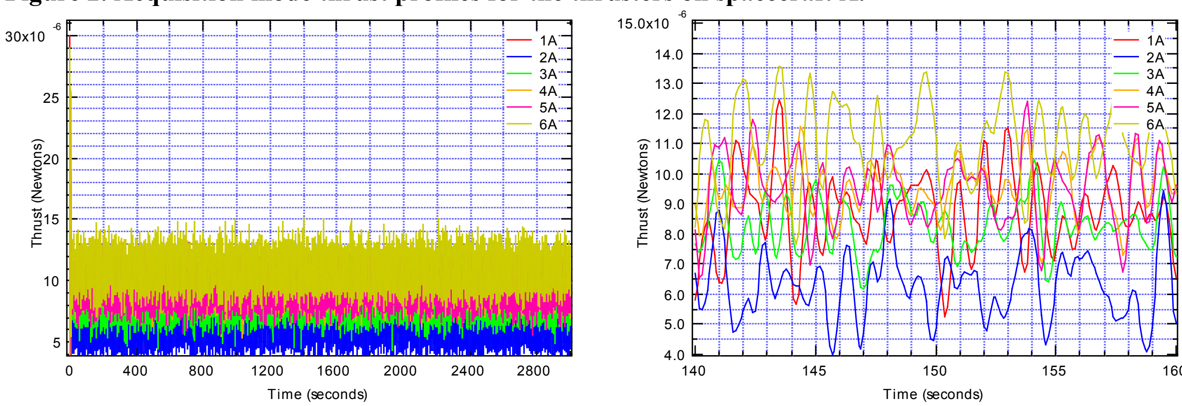

Figure 3. Science mode thrust profiles for the thrusters on spacecraft A.

Table 1. Thrust requirements for each of the 6 thrusters spacecraft A, B, and C.

Thrust (uN)	Range	Mean	σ	Range	Mean	σ
Acquisition Mode	**0 - 3200 s**			**> 3201 s**		
A combined	4.0 - 25.7	9.1	2.9	7.3 – 10.6	9.0	0.98
B combined	4.0 - 30.0	9.1	2.6	7.9 – 10.2	9.0	0.66
C combined	4.0 – 30.0	9.2	3.3	7.3 – 10.7	9.0	1.00
A,B,C combined	4.0 – 30.0	9.1	2.9	7.3 – 10.7	9.0	0.90
Science Mode	**0-40 s**			**> 40 s**		
A combined	4 – 30.0			4 - 15.2	8.9	1.8
B combined	4 – 30.0			4.0 – 14.3	8.7	1.7
C combined	4 – 30.0			4.0 – 14.7	8.9	1.8

Table 3. LISA thrust requirements in each of the operating modes.

Microthruster Requirements	Tip-Off	Safe	Commissioning/ Acquisition	Science
Performance				
Thrust Minimum	0 μN	0μN	4 μN	4 μN (observed)
Thrust Maximum	[30 μN] [TBC]	[30 μN][TBC]	30 μN	15.2 μN (observed)
Average Thrust	TBD	TBD	9.0 ± 0.9 μN (0.9 μN = 1σ thrust variation)	8.8 ± 1.8 μN (1.8 μN = 1σ thrust variation)
Thrust Precision	N/A	N/A	≤0.1 μN	≤0.1 μN
Thrust Noise	N/A	N/A	≤0.1 μN/√Hz	≤0.1 μN/√Hz
Thrust Vector Stability	TBD	TBD	≤2.5 mrad/√Hz	≤2.5 mrad/√Hz
Measurement Bandwidth	N/A	N/A	0.3 mHz to 0.1 Hz	0.03 mHz to 0.1 Hz
Thrust Command Rate	10 Hz	10 Hz	10 Hz	10 Hz
Lifetime				
Operational	72	3,650 hours (5 months)	730 hours (1 month)	40,000 hours (4.5 years)
Duration for consumables	72 hours	6,000 hours (8 months)	1,000 hours (1.7 months)	68,000 hours (7.75 years)

Total Expected Impulse per MTA	20 Ns	130 Ns	25 Ns	1300 Ns

Earth Orbiting Spacecraft

The electric propulsion system thrust requirements analysis for precision Earth-fixed orbit tube maintenance was conducted with an Earth observing spacecraft required to fly periodic repeat tracks. The advantage to flying in a precision orbital tube for this type of mission is improving the coherent change detection accuracy of moving targets on the ground. These targets could include water or ice boundaries. An Interferometric Synthetic Aperture Radar (InSAR) mission concept for tracking ground targets was considered in the analysis. The representative spacecraft configuration used in the analysis is shown in Fig. 4. The spacecraft had a frontal area of 4 m^2 and lateral area of 20 m^2. Both 1 day and 9 day ground repeat tracks were considered in polar sun synchronous 6 am/6 pm frozen orbits for the analysis. Attitude control was performed with reaction control wheels. The SAR antenna and solar panel were fixed with no moving appendages.

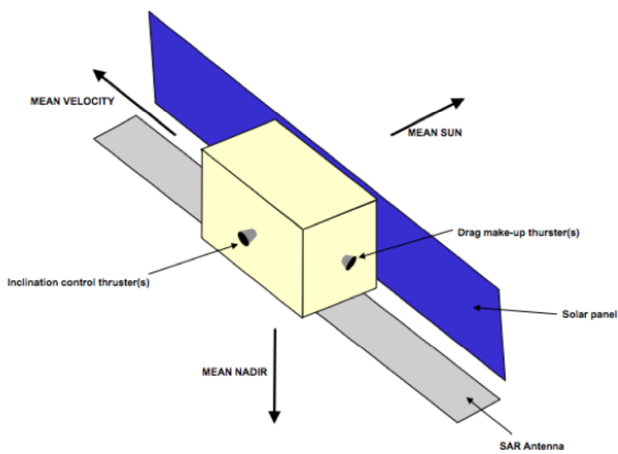

Figure 4. The spacecraft configuration considered in the analysis.

The thrust requirements analysis was conducted for altitude and inclination control for specific repeat track orbits with very low thrust electric propulsion systems. The major perturbation effects on the orbital altitude and inclination were considered. Altitude control was achieved through continuous tangential thrusting. Inclination control was achieved with normal thrusting at intervals around one or both of the nodes and in one or two directions about the nodes. It was achieved with annual and bi-weekly thrusting normal to the orbit, in the sun and anti-sun directions. The required thrust levels for the 9/132 orbit are given in Table 4. The same approach to the analysis was implemented for the other orbits considered. The thrust requirements for all of the orbits are summarized in Table 4. The orbital tube diameter is less than 30 m for all of the orbits considered with continuous drag compensation. This Earth-fixed orbital tube diameter is dictated by the third-body forces perturbing the orbit. Continuously compensating for the forces would reduce this diameter further and could be also be controlled with the electric propulsion system.

Low thrust electric propulsion was also considered for orbit transfer from the 9/134 track to the 1/15 track to identify the thrust requirements. The orbit transfer requirements are given in Table 5 with the transfer times at different thrust levels. Continuous tangential acceleration can be delivered for altitude change with low thrust systems. However, normal thrusting is limited to near the nodes for inclination changes. A 50% duty cycle was assumed in the analysis for inclination corrections and simultaneous use of normal and tangential thrusters. The results show that orbit transfer thrust levels are required to be two orders of magnitude larger than the orbital tube maintenance thrust levels to achieve transfer times ~ 40 days. Several very low thrust systems could be used to achieve these thrust levels or a higher thrust propulsion system.

The analysis results show that a thruster or cluster of them with a thrust range from tens of microNewtons to hundreds of microNewtons or a milliNewton could enable 30 m precision Earth-fixed orbital tube maintenance scenarios to improve target displacement detection. Thrust level precision of 1 microNewton would be attractive, however 10 microNewton precision should be acceptable. This capability could be achieved with two opposing thrusters oriented normal to a drag makeup thruster. Higher thrust requirements for the low altitude considered could be achieved with multiple thrusters. Multiple thrusters may also be required for orbit transfer maneuvers.

Table 4. Thrust level requirements.

Orbit cycle		**9**	**9**	**1**	**1**
Orbits per cycle		**134**	**134**	**15**	**16**
Inclination		**97.79**	**97.79**	**97.655**	**96.58**
Altitude range (Km)		**600-628**	**600-628**	**565-594**	**273-302**
10.7 cm solar flux level (sfu)		**175**	**250**	**175**	**175**
Tangential acceleration required for us drag control (km/s^2)		5.6x10^{-11}	2.8x10^{-10}	8.5x10^{-11}	7x10^{-9}
Tangential thrust required for instantaneous drag control (mN)					
Spacecraft Mass	400 kg	0.022	0.112	0.034	2.8
	1000 kg	0.056	0.280	0.085	7.0
	4000 kg	0.220	1.120	0.340	28.0
Normal acceleration for annual + bi-weekly ontrol with thrusters in both (sun and anti-ns (mN)		2.4x10^{-10} Km/s^2			
Normal thrust for annual + bi-weekly inclination control with thrusters in both (sun and anti-sun) directions (mN)					
Spacecraft Mass	400 kg	0.096			
	1000 kg	0.240			
	4000 kg	0.960			

Table 5. Orbit transfer ΔV, thrust requirements and orbit transfer times.

From	To	Semi-Major Axis Change (km)	Tangential ΔV Required (m/s)	Inclination Change	Normal ΔV Required (m/s)	Thrust Level (km/s^2)	Transfer time (days)
9/134	1/15	-34	~18	0.135^o	~18	1x10^{-9} [10 mN for 1000 kg]	417
						1x10^{-8} [100 mN for 1000 kg]	41.7
						1x10^{-7} [1000 mN for 1000 kg]	4.17

3. ULTRA-PRECISION ATTITUDE CONTROL OPERATIONAL CAPABILITY

The precision pointing capability using electric propulsion for was characterized for exoplanet observatory missions. Recently, several direct-detection space observatories were studied as part of determining a roadmap for near-term exoplanet missions. Many of the Astrophysics Strategic Mission Concept Studies (ASMCS) consisted of approximately 1.5 m-diameter, monolithic coronagraphs for cost competitiveness. A key challenge for these coronagraphs is an order of magnitude improvement in pointing step precision from several milliarcsceconds (mas), which is the state of the art, to several tenths of a milliarcsecond. Additionally, multiple vibration isolation sub-systems are necessary with the traditional attitude control system (ACS) that rely on reaction wheels to meet the vibration requirements. Electric propulsion system options become very attractive with this combination of sub-milliarcsecond pointing, which requires on the order of 10 uNs impulses ANGULAR IMPULSE, and stringent vibration requirements, which micro-impulses have been shown to satisfy.

The precision pointing capability that low, continuous and quiescent thrust electric propulsion devices offer was assessed for the ACCESS monolithic-coronagraph exoplanet mission concept, which has the most stringent pointing requirements [1]. The ultimate payload pointing requirement for ACCESS is 0.1 mas. For comparison, the pointing achieved on-orbit for SIRTF was ~27 mas (1σ) and for Hubble is 5 mas (1σ). The ACCESS mission pointing requirement is 50 times more precise than the state-of-the-art. Several stages of control were proposed for ACCESS and similar ASMCS missions to achieve the required payload pointing precision and vibration environment: (1) coarse-level via spacecraft pointing with reaction wheels; (2) a medium-level via telescope actuation, for example, a hexapod or active secondary; and, finally, (3) fine-level via active optics, such as a deformable mirror or a fast-steering mirror. The coarse-level spacecraft requirements are much less demanding than the state-of-the-art in an effort to keep cost and mass manageable. While the multi-layer approach relieves the precision-pointing burden of the spacecraft bus, much more complex payload actuation subsystems are required. Most importantly, the ultra-precise requirements necessitate careful analysis of reaction wheel-induced vibrations and, in all cases, passive or active isolation of the payload from the spacecraft bus and its reaction wheels.

A preliminary ACS simulation was developed to characterize capability of a low-thrust electric-propulsion system to provide the required pointing precision. The solid model of the spacecraft developed for the analysis is shown in Fig. 5. There are four thruster clusters on the spacecraft with five thrusters in each cluster. This configuration has design heritage from the TPF-I mission studies and provides single-failure redundancy and some robustness to the failure of two thrusters [2]. The thruster locations and thrust vectors are shown in green in Fig. 13. The center-of-mass is indicated by the red dot, which is 1 m above the thruster locations. Note that the thrusters are *not* centered on the CM to show that CM-offset is not a limitation to performance. Thruster misalignments were not considered. The non-diagonal moment of inertia is from ACCESS proposal data (not shown here since competition-sensitive). A conservative bound on the solar pressure torque is 3e-5 Nm for the geometry shown in Fig. 13. To simplify thrust allocation, the electric thruster performance was simulated with 1 mN of thrust and pulse-width-modulation down to 1 ms. A thrust level throttling approach is expected to further improve performance with the actuators more closely matching the control design assumptions (i.e., amplitude modulation versus pulse-width modulation). A fine guidance sensor with a precision of 0.05 mas (1σ) was assumed. This precision level is half of the control requirement and would be needed for active optics with any attitude control approach. For example, Spitzer uses a fine guidance sensor on its focal plane that is fed back to ACS [3].

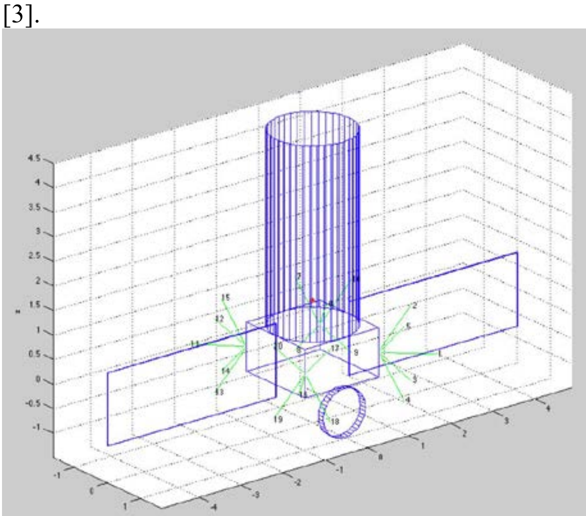

Figure 5. The assumed ACCESS spacecraft and thruster configuration for the precision pointing analysis.

The attitude errors on each of the axes was characterized in the analysis. The results are shown in Fig. 6. The z-axis, which is the telescope boresight, exceeds the 0.1 mas requirement. However, the 0.1 mas requirement does not apply to this axis. The 0.1 mas requirement only applies to the tip/tilt, x/y axes. The attitude error requirement about the roll axis is only 5000 mas. Additionally, the integral action in the x-axis can be seen as the control "learns" the solar pressure torque after a large departure (the blue line that goes to -12 mas in the upper-left part of Fig. 14). Since the ACCESS jitter requirements are over 1000 s intervals, 1200 s was simulated: ~200 s for the integral action to cancel the solar pressure torque plus 1000 s.

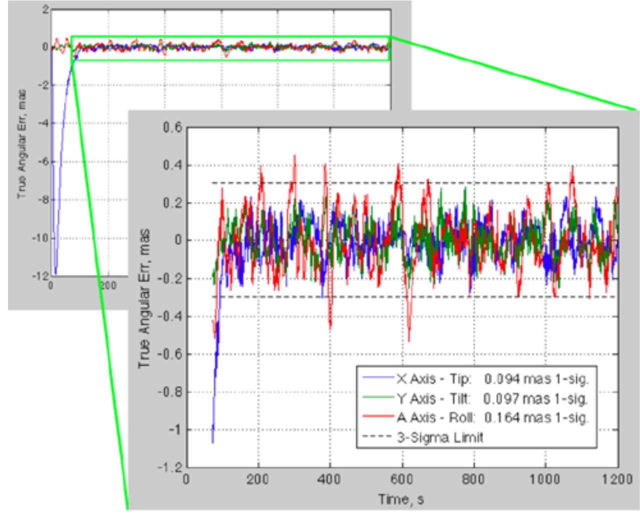

Figure 6. True attitude error by axis for preliminary ACCESS simulation using an electric thruster attitude control. In the upper left, an overview is shown of the entire time history. The zoomed portion shows steady-state performance meets 0.1 mas (1σ).

The preliminary simulation results suggest that the most stringent fine-pointing requirement of the monolithic ASMCS missions can be met with electric-thruster attitude control. A higher-fidelity attitude control simulation is needed to fully explore the optimal requirements for an electric thruster-based attitude control system and characterize on-times and fuel consumption. However, the preliminary results suggest that a thruster with the simulated characteristics will allow: (1) the medium-level of actuation to be eliminated, (2) both reaction wheels and a hydrazine thruster system for momentum management to be eliminated, and (3) the active optics to be greatly simplified since the telescope can be pointed close to the fine-level requirement.

While a representative 1mN thruster was used with a minimum on-time of 1 ms, the optimal thrust level for precision pointing is also of interest. To investigate how the achievable precision varies with thrust magnitude, the simulation was repeated with a minimum on-time of 0.1 ms. Figure 6 shows the maximum and minimum impulses from the twenty thrusters as a function of time for both 1 ms and 0.1 ms minimum on-times. Also shown as a dashed red line is the impulse needed to counteract solar pressure. For both minimum on-times, the maximum impulse remains in the vicinity of that needed for solar pressure, as expected. The minimum impulse, however, shows a marked difference. For 1 ms, the minimum impulse is essentially always 1 μNs, which is the impulse at minimum on-time. At least one thruster is always on for the minimum time because of rounding. If a thruster was commanded to be on between half the minimum on-time and the minimum on-time, it was turned on for the full minimum on-time. With a 0.1 ms minimum on-time, however, the minimum impulse can be seen to be responding to sensor noise. This response indicates that the performance is *not* limited by the minimum impulse. For this case, the performance in every axis was approximately 0.055 mas (1σ), which corresponds to the sensor noise limit. Recall the sensor has noise of 0.05 mas (1σ). Hence, if 1 ms is the actual minimum on-time as limited by the electronics, the thrust level could be reduced to 0.1 mN to achieve sensor noise-limited pointing.

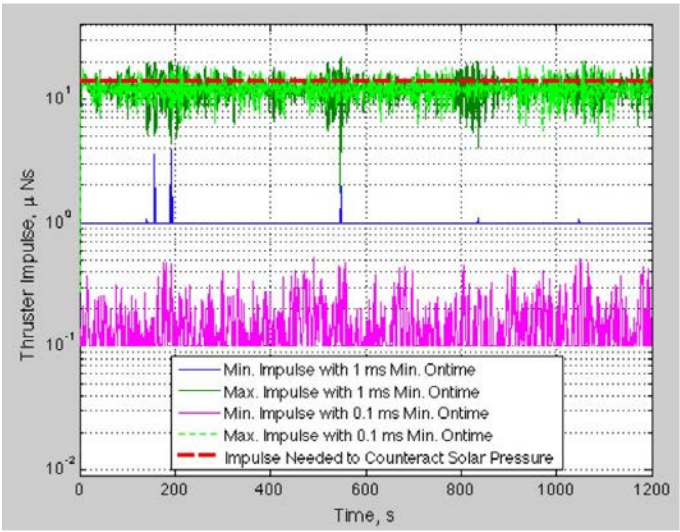

Figure 7. Maximum and minimum impulses over all 20 thrusters during ACCESS simulation for both 1 ms and 0.1 ms minimum on-times.

Slew time is also a key driver for observational efficiency that drives thrust requirements. Slew time is the fraction of time spent collecting science data and not performing retargeting, up/downlinking, and other engineering functions. The time for ACCESS to slew 15° would be 9 minutes at 1 mN. Decreasing the thrust level to 0.1 mN would result in a slew time of 27 min. This slew time for retargeting could be unacceptable for the number of science targets. The capability of electric propulsion to throttle from 0.1 mN up to milliNewtons with a 1 ms pulse-width modulation is the attribute that qualifies it as an ideal actuator for ACCESS. Throttling and pulse-width modulation allows electric propulsion to achieve both acceptable slew times and ultra-precise pointing.

In addition to improving the pointing precision capability over the state of the art, significant reductions in actuator-induced vibrations and spacecraft mass are expected. A FEM-based analysis of the 3 mN pulse-width modulated thruster vibrations was not conducted for the ACCESS spacecraft. However, such an analysis was carried out for the DS-3/StarLight formation interferometer mission design [4]. StarLight consisted of two spacecraft that included a collector and a collector/combiner. For the latter, a 246-degree-of-freedom flexible model was developed of the spacecraft and interferometric payload, including a bus, solar panels, optics bench, optics bench support structure, mirror mounts, and optical delay line. The delay line has a first mode at 4 Hz and the support structure at 90 Hz. This FEM was excited with 100 μNs translational impulses at the thruster nodes. For comparison, the maximum impulse delivered in the previous ACCESS simulation was 15 μNs. The maximum vibration level in the interferometric payload, as characterized by optical path difference, was 5 nm RMS with a maximum displacement of 35 nm due to the lightly damped fundamental mode of the optical delay line. Since the ACCESS impulses are seven-times smaller, the induced vibrations will be correspondingly reduced.

Significant spacecraft mass reductions can also be realized with electric thruster-based attitude control in comparison to traditional approaches. The preliminary FEM analyses shows that payload vibration isolation systems can be removed because the tested electric thruster impulse levels do not excite spacecraft structural modes above the nanometer level. Eliminating this element translates into a significant mass savings for the spacecraft. In addition to removing the need for vibration isolation, an electric propulsion system can reduce the spacecraft launch mass with much higher propellant utilization efficiency. Table 6 shows that the launch mass can be reduced by 14% using an electric-thruster approach to attitude control. In this mass comparison analysis, the traditional thruster mass was based on 12MR-103D thrusters. Small ion thrusters using xenon propellant were considered for the electric propulsion system with 20 thrusters for 2 failure redundancy. Propellant requirements were based on the maximum possible solar torque of 3e-5 Nm and SNAP JDEM L2 orbit design because an L2 orbit is base-lined for ACCESS. SNAP required 99 m/s for orbit transfer and 5 m/s/yr for maintenance. Momentum unloading required 3.4 kg of hydrazine for a five-year mission with MR-103D thrusters at the corners of ACCESS base-lined TRW T310 bus with 1.75 m moment arm, a specific impulse of 180 s and a flow rate of 0.5 g/s. Orbit maintenance fuel mass was based on a T310 maximum launch mass of 2160 kg and a propellant specific impulse of 209 s. The electric propulsion system xenon propellant mass was estimated to be 0.025 kg for momentum unloading and 7.26 kg for orbit insertion and maintenance. The traditional system tank was assumed to be the ATK 80428-1 tank with a 113 kg rating for the mass estimate. The supercritical xenon tank mass was assumed to be 10% of the xenon mass. The additional battery in the electric propulsion system adds redundant 1000 W-hr for two hours of battery-only operation. De-tumbling from 1 deg/s is estimated at 1 hour with the electric propulsion system. An additional 0.4 m^2 of solar panels is assumed for 500 W at MRO areal density. The electric propulsion system required 5 power processing units for 4 primary units and 1 redundant unit. The active hexapod mass estimate was based on scaling the space-qualified ESA hexapod with a mass of 116 kg to support 35 kg. The mass estimate for a mirror with a 1.5 m diameter is 53 kg at 30 kg/m^2. The mass estimate for other elements of the system including the secondary optics, coronograph and active optics was also 53 kg. Half of the scaled mass of 351 kg was assumed for the hexapod to give the traditional ACCESS architecture a mass advantage. The traditional system wet mass was assumed to be the maximum T310 bus wet mass. The mass estimate for the total propulsive fuel fraction assumed similar feed system components for both approaches.

This preliminary analysis shows that electric propulsion (EP)-based attitude control with 0.1-15 μN-s impulse capability brings naturally-quiescent, ultra-precise pointing that reduces launch mass >10% and reduces overall spacecraft complexity by eliminating reaction wheels, hydrazine thrusters, vibration isolation subsystems, and medium-level payload actuation subsystems and by relaxing requirements on active payload optics.

Table 6. Mass of traditional and EP-based ACS for ACCESS-class mission.

Subsystem	Mass (kg)	
	Traditional	EP
4 HR-16 Reaction wheels	48	0
Thrusters	4.0	10
Propellant	105.4	7.3
Tank	29	0.8
Additional battery	0	19.5
Additional Solar Panel	0	2
EP Thruster Power Processing Unit	0	25
Active Hexapod	175.5	0
Propulsion System Sub-total	**361.9**	**64.6**
Dry subsystem mass without ACS and Hexapod	1798.1	1798.1
Wet mass	2160	1862.7
Total Propulsive "fuel Fraction" (%)	17	3
Mass Savings over Traditional (%)		**14**

4. SUMMARY

MicroNewton propulsion systems can enable or improve a broad range of mission scenarios and spacecraft architectures. Thrust requirements were derived for candidate mission scenarios with microNewton electric thruster characteristics. The results of the analysis showed that precision 30 m Earth-fixed orbital tubes at ~600 km for 400-4000 kg spacecraft require continuous thrust at tens to hundreds of microNewtons. An order of magnitude increase in thrust is required at an altitude of ~300 km. A drag-free constellation in an Earth-trailing orbit would require continuous and continuously throttled thrust at microNewtons to tens of microNewtons with 0.1 microNewton precision and 0.1 microNewton/√Hz for position and attitude control to enable displacement measurements over 5 million kilometers with picometer resolution. Ultra precise pointing of exoplanet observatories to 0.1 milliarcsecond could be achieved with thrusters operating continuously with pulse-width modulated impulses of 0.1 to 15 uN-s. A thrust level throttling approach is expected to further improve pointing precision. It was shown that replacing reaction wheels with electric thrusters for attitude control would significantly improve spacecraft pointing precision, vibrations and mass. Electric thrusters with a thrust range of microNewtons to hundreds of microNewtons, continuous thrust and continuously variable thrust can improve spacecraft orbit, pointing and positioning precision by more than an order of magnitude over capabilities offered by standard approaches to improve mission performance and enable new capabilities for a very broad range of mission applications.

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[1]

BIOGRAPHY

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