Scaling of a Colloid Thruster system for microNewton to milliNewton Thrust levels

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The concept of a voltage modulated electrospray thruster using individually addressable clusters of emitters is described. These clusters enable specific thrust ranges to be obtained with thrust variation over three orders of magnitude. Voltage control of electrospray parameters is used to achieve thrust throttling within these ranges. A parametric study is presented to demonstrate the feasibility and competitiveness of using this colloid thruster concept for several formation flying (FF) missions. Electrospray data from a single emitter using the ionic liquid EMI-BF_4 as a propellant is reported and shows that thrust levels across the entire thrust range, for these missions, from 0.5μN to ~10mN are feasible with such a system.

Nomenclature

C	=	capacitance
I_T	=	total spray current
I_{sp}	=	specific impulse
P	=	power
Q	=	flow rate
R	=	resistance
T	=	thrust
V_{acc}	=	acceleration stage potential
V_{ext}	=	extraction potential
V_{AT}	=	total acceleration voltage
FF	=	formation flying
S/C	=	spacecraft
q/m	=	specific charge
ρ	=	fluid mass density

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I. Introduction

IN recent years the spacecraft industry has seen an increasing demand for small satellites and spacecraft. This is in part due to the advances in computation and fabrication technologies that allow greater functionality at reduced cost and mass than was previously possible. The increasing demands for large aperture science missions to achieve specific scientific goals may be satisfied by controlled arrays of potentially much smaller spacecraft. Some scientific objectives can of course only be realized by formation flying (FF) configurations such as those typified by the Darwin and Lisa missions. These features have been coupled with increasing capability of small spacecraft systems and the associated growth in production. Historically such small spacecraft have had limited manoeuvring capability due to the almost exclusive use of cold gas propulsion. However the trend observed in scientific mission evolution, combined with increasing launches of dedicated small missions ranging from communications to earth observation applications, dictates the need for enhanced propulsion capabilities, complementing the associated reduction of spacecraft system mass. The colloid thruster has been identified as a candidate technology for on-board micro-propulsion for such missions[1].

The concept of the colloid thruster was first developed in the early 1960's however the original systems were conventionally fabricated resulting in a low thrust to mass ratio and relatively large power requirements. Such systems, in the main adopted doped glycol solutions as propellants, which resulted in low I_{sp}s. However a resurgence of interest in these colloid concepts has arisen from the advent of appropriate micro-fabrication technologies along with a range of more suitable propellants. These new systems exhibit potential performance parameters that appear highly competitive for many low thrust, high I_{sp} missions, wherein power is severely limited.

The colloid thruster uses electrospray atomization, whereby an electrolytic fluid (with conductivity ~1S/m) is injected, from an emitter, into an electric field (~10^6V/m) generated by an electrical potential difference between the emitter and an extraction grid. The fluid, under the influence of the electric field, forms a structure known as a Taylor cone. At the apex of this cone a jet is formed which subsequently breaks up to form a charged spray with species having a charge to mass ratio, q/m, typically 1-100kC/kg. This charged spray is then accelerated in a static electric field to produce a thrust. Figure 1 shows images of these cone-jet structures formed on micro-fabricated arrays[2]. A schematic of a typical configuration is given in Figure 2

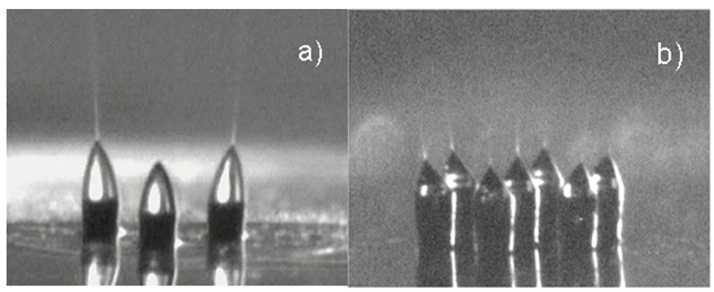

Figure 1. CCD images of cone-jet structures formed on a micro-fabricated a) 3 emitter array and b) 7 emitter array from Ref 2

The low thrust level delivered by a single electrospray emitter is typically in the order of only 0.5μN. This necessitates the use of large numbers of emitters to develop sufficient thrust for many anticipated orbital manoeuvres. Present thruster design concepts commonly involve a number of discrete emitter arrays that can be operated individually to give a scalable thrust output[3,4], where the total thrust available is simply a function of the number of emitters. These systems operate using the traditional form of electrospray where a liquid is fed to the emitter at a flow rate fixed by a pump or regulated by gas pressure. The use of fluid pumps or pressurization systems adds complexity, cost and mass to the thruster system. An alternative mode of electrospray is discussed here in which the applied

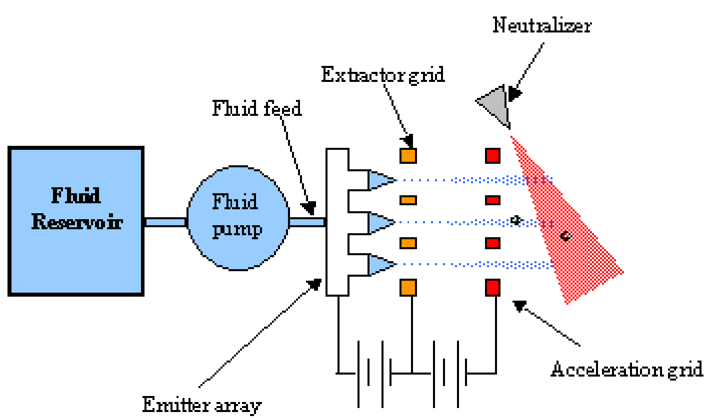

Figure 2. Schematic of a conventional colloid thruster system

field required to form the electrospray is also used to control the flow rate of fluid to the emitter. Here we use data for the ionic liquid EMI-BF_4 from a single nozzle to predict the thrust scaling characteristics for a MEMS based array design[5].

A. Candidate Mission Requirements Review

A review of the propulsive requirements for several missions, namely Proba 3[6], Darwin[7] and Lisa[8], reveals that a micro-propulsion concept for such FF needs to address several key features.

1. The ability to achieve several specific thrust levels, separated by a significant change in actual thrust e.g. 1μN, 50μN, etc. These differing thrust levels are associated with different FF manoeuvres such as formation maintenance (typically low thrust range) and formation slewing (typically higher thrust range)
2. At each specified thrust level there is a need for thrust variability for fine control of the thrust across part or all, of the thrust range.
3. A thrust range from 1μN to ~10 mN is required to satisfy all the onboard micro-propulsion requirements.
4. A thrust command accuracy of ~0.5μN is appropriate within the lower thrust ranges <100μN.
5. Whilst dependent upon the thrust level, the overall total impulse to carry out the technology demonstrator flight Proba 3 is probably of order 10kNs (I_{sp} ~ 500 –1500s), although the major science missions require a total impulse an order of magnitude greater than this figure.
6. All missions operate within significant power constraints and hence for each mission reviewed it is anticipated that the specific power should be less than ~50W/m

II. Thruster Concept

This review of the candidate mission requirements identifies that to meet the full performance requirements for a range of FF missions, thrust must be variable over 3 orders of magnitude. However as noted, the thrust level demanded is not continuous over this range. This suggests a concept ideally suited to the colloid system, in which the gross changes in thrust are achieved by selecting regions of the overall array, with each emitter operated at some nominal flow rate; fine thrust control is then obtained by varying the flow rate over all or only part of the array.

The issue of scalability in performance with array size, over a limited number of emitters has been previously demonstrated in early QMUL work[9]. If each emitter element of the array is "electrically isolated" from all other elements, then there is in principle no reason why the simple addition of more active elements cannot be extended indefinitely. Here the term "electrically isolated" refers to the absence of electric field interactions between individual emitter elements and the fluid meniscus on these elements together with the absence of any space charge effects associated with droplet sprays from individual elements in the array. On this assumption the ability for a colloid thruster concept to potentially generate thrust over the three order of magnitude range seems well within the capability of a suitably designed micro-fabricated system. Indeed using the approach proposed initially by Paine[10,11] in the QMUL group, albeit in somewhat modified form, would seem to have the potential to achieve an unlimited range in thrust from a 'single' propulsion unit.

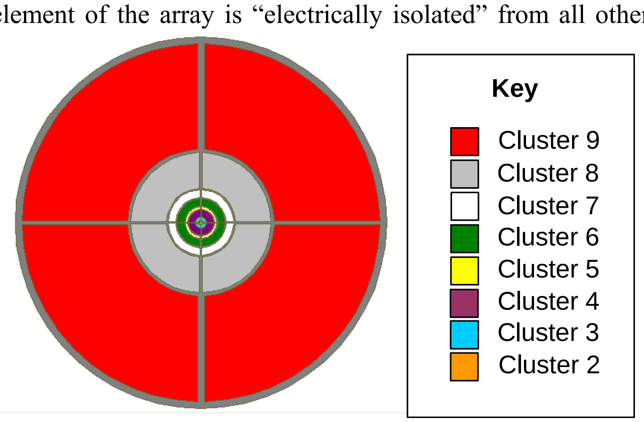

Figure 3. Schematic of array cluster configuration Colour code relates to sub-array clustering.

The basic thruster concept is that of micro-fabricated arrays of capillary structures with individual electrically isolated extraction electrodes for each emitter[5]. These arrays will be grouped into concentric switchable clusters to target specific thrust levels. A typical cluster configuration is given in figure 3, the outside diameter of this system is ~100mm and maximum thrust ~68mN, the thrust levels of the individual clusters are given in table 1.

A. Flow rate control - Voltage Driven Electrospray

Traditional colloid thruster systems have relied on the use of pumps or applied pressure to achieve and control the flow rates necessary for the formation of a stable electrospray. However earlier published work from QMUL electrospray group has shown that the flow rate in pressure driven systems is enhanced by the applied electric field required to produce the electrospray[12,13,14]. We have also recently demonstrated that the flow rate in an electrospray system may be entirely controlled by the applied electric field in a mode known as nano-electrospray[15,16,17]. For highly conducting liquids such as the ionic liquid EMI-BF_4 (with a conductivity ~1.4S/m) the minimum flow rate for stable cone jet operation, according to the scaling laws of Ganan-Calvo[18], is of the order of 0.002 nL/s. Thus it is feasible for highly conducting liquids that the stable cone jet mode of operation is achievable purely by voltage driven flow. Experimental data given in Figure 4 illustrates how the applied voltage may be used to control both current and flow rate in a voltage driven electrospray system for the ionic liquid EMI-BF_4. It is observed that flow rate control is achieved over a significant range, varying by an order of magnitude. Clearly using this method of flow control the need for a propellant pumping system is avoided, with a consequent reduction in design complexity, mass and hence overall system cost.

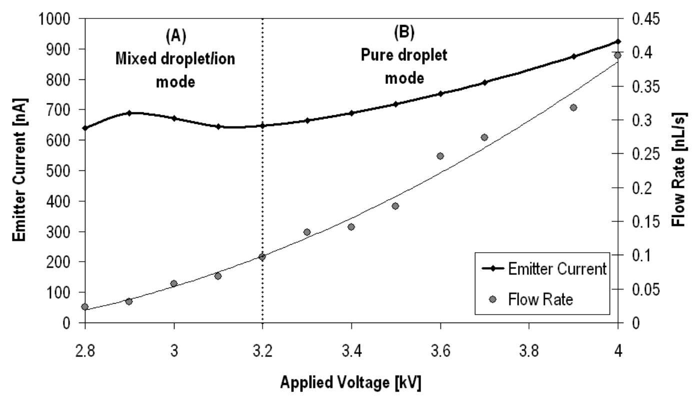

Figure 4. Emitter current and flow rate vs applied voltage for EMI BF_4.

B. Thrust Throttling

Thrust throttling in conventional colloid thrusters is achieved either by varying the flow rate or the acceleration voltage, or using these in combination, as shown in the Busek thruster[19].

The data shown in figure 4 demonstrates an alternative method of thrust throttling: by varying the extraction voltage to subtly vary the specific charge of the emitted particles, which also alters the flow rate through the emitter.

The thrust and I_{sp} for an electrostatic thruster are given by :

$$T = \sqrt{2\rho Q I_T V_{AT}} \tag{1}$$

$$I_{sp} = \frac{T}{Q\rho g} \tag{2}$$

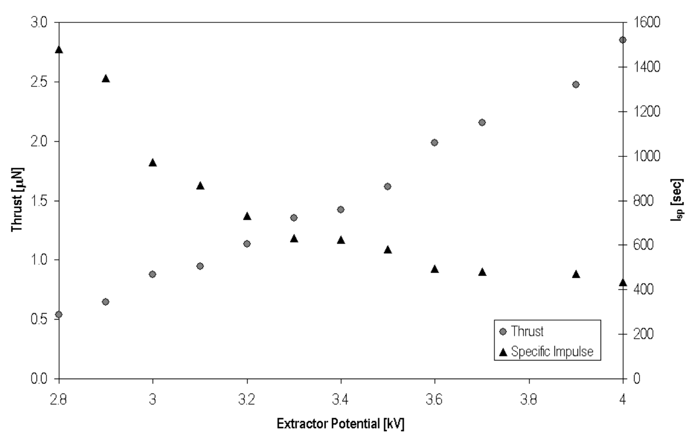

Figure 5. Effect of extractor voltage on Thrust and Specific Impulse

The total acceleration potential, V_{AT} , is the sum of the extraction potential, V_{ext} and the acceleration stage potential V_{acc}. However the loss in potential due to the cone formation process must also be taken into account (~10% (Ref 20)) hence the assumed total acceleration potential for this case is given by:

$$V_{AT} = V_{acc} + \eta_c V_{ext} \qquad (3)$$

where the efficiency factor η_c is ~ 0.9

Using eq (1) and eq (2) with the data from figure 4 the effect of varying the extraction potential on the thrust and I_{sp} for a single emitter with V_{acc} = 5kV has been determined, and is given in figure 5. From this figure it can be seen that for a 1.2kV change in extractor potential the thrust may be varied by almost an order of magnitude from 0.5μN to 3μN.

Extractor vs Accelerator throttling

A comparison of achieving thrust throttling by varying the extraction and acceleration potentials, using the EMI-BF_4 data from figures 4 and 5, is given to evaluate the merits of both methods of throttling. In this comparison two cases are considered. In scenario A the acceleration potential is fixed at 5kV and the extractor potential is varied between 2.8 and 4kV and in scenario B the extraction potential is fixed at 2.8kV (for the highest I_{sp}) and the acceleration potential is varied. Figure 6 gives the total required potential for both these modes of thrust throttling for a single emitter. It is clear from this that throttling via the acceleration potential alone is impracticable as potentials of the order of 200kV would be required to achieve the same values of thrust as those obtained from throttling the extraction potential between 2.8 and 4kV. Evidently accelerator grid thrust throttling is only feasible over a very limited range of thrust range. Figure 7 shows the effect of thrust throttling on the specific power** by both methods. This illustrates that the power demand in the variable extractor approach is much lower than in the variable accelerator mode and that for the highest thrust level the power in the variable acceleration method is near the limit for the total system power requirements.

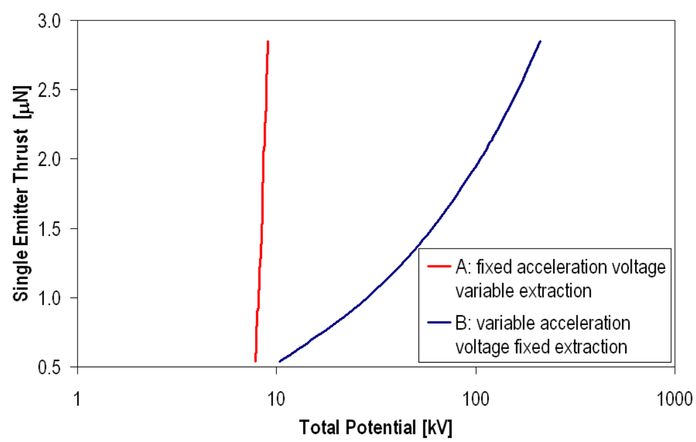

Figure 6. Required Potentials for Thrust Throttling

Thus on the basis of power demand and practical voltages achievable varying the extractor potential is the most practical solution for pure voltage control of thrust. However this control does provide an overhead in the performance of the system. This is demonstrated in the results presented in figure 5. This identifies that as the voltage is increased at the extractor, the droplets in the spray become less highly charged and hence the specific impulse is reduced. Even with this reduction there is still a significant thrust throttling capability achieved by this method, for which the delivered I_{sp} is within the requirements for the FF missions considered.

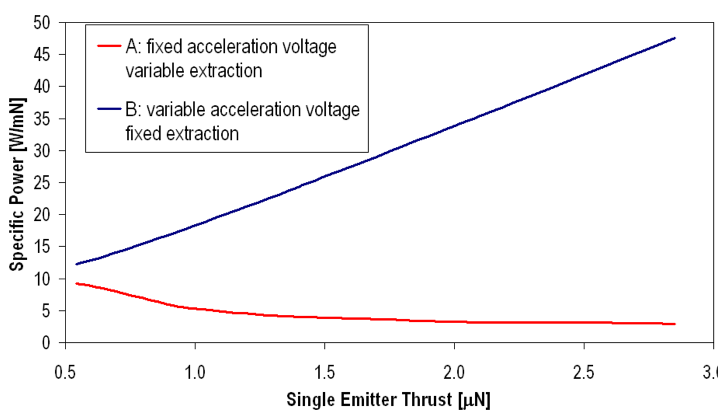

Figure 7. Effect of Thrust Throttling on Specific Power

** the model used for power estimation is given in the appendix

C. System Scaling

Assuming emitter areal densities for a MEMS array[5] and leaving adequate room for support structures the overall thruster diameter for a given thrust level has been determined and is given in figure 8. From this plot it can be seen that a 20mN system would have a diameter ~60mm. This compares well with the T5 ion thruster from QinetiQ that has a diameter of 180mm for a similar thrust range.

A typical cluster configuration based on data for a typical FF mission[6] is given in table 1. From this table it is seen that a thruster system capable of producing ~ 10mN thrust levels would require a total of ~20,000 emitters. The micro-fabrication of arrays of this size is feasible and is reported in Ref 2 although the operation of such large arrays has thus far not been tested. It can also be seen from table 1 that the impulse requirements for such a mission are satisfied by a total fuel mass ~ 100g. It is clear from this scaling projection that the mass and dimensions of the proposed system are in line with the requirements of a micro-propulsion system for typical FF missions.

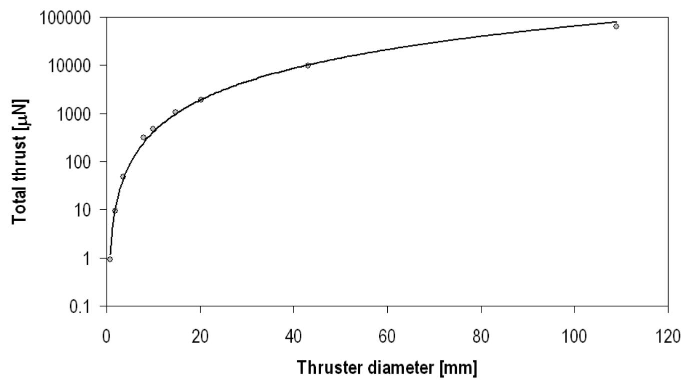

Figure 8. Thruster diameter scaling

Table 1. Array cluster design to meet typical FF mission requirements

Cluster number	Thrust [µN]	Number of emitters per cluster	Total Number of emitters	Fuel mass [g]	Impulse[††] [Ns]
1	1	2	2	$1.87*10^{-4}$	0.029
2	9	16	18	0.26	9.94
3	48	71	89	0.73	25.09
4	310	485	574	0.06	7.20
5	472	299	873	0.19	29.24
6	1050	1069	1942	1.28	98.30
7	1934	1634	3576	0.39	59.88
8	9682	14324	17900	25.26	2902
9	67857	100475	125449	82.34	5704

III. Conclusions

Using original data of the ionic liquid EMI-BF_4 from a single emitter obtained at QMUL electrospray laboratories a concept for a colloid thruster system based on individually addressable clusters of MEMS arrays has been evaluated in terms of the performance requirements for several upcoming FF missions. It has been shown that thrust levels and power requirements across the entire thrust range, for these missions, from 0.5µN to ~10s mN are achievable from such a system. The dimensions of these systems also compare well to those of current Ion engines.

[††] assuming a tank depth of 10mm and ~100g of fuel

Appendix

Power model

The main circuit elements for an electrospray from a single emitter with extraction and acceleration electrodes are given in figure 9a however various elements can be assumed negligible – if R_{EA} ,R_{SE} ,R_{LA} and R_{LE} are large (i.e. the leakage currents to the extractor and accelerator and through the insulating standoffs are low) then the circuit can be simplified to that of a resistor in series with the high voltage supply, figure 9b, where the value of the resistance R_{eL} is dependent on the spray current and some inherent efficiency factor due to DC/DC conversion efficiency. Thus the power in the circuit may be simply estimated by

$$P = V_{AT} I_T \quad (3)$$

Where V_{AT} is the total high voltage potential and I_T is the total spray current

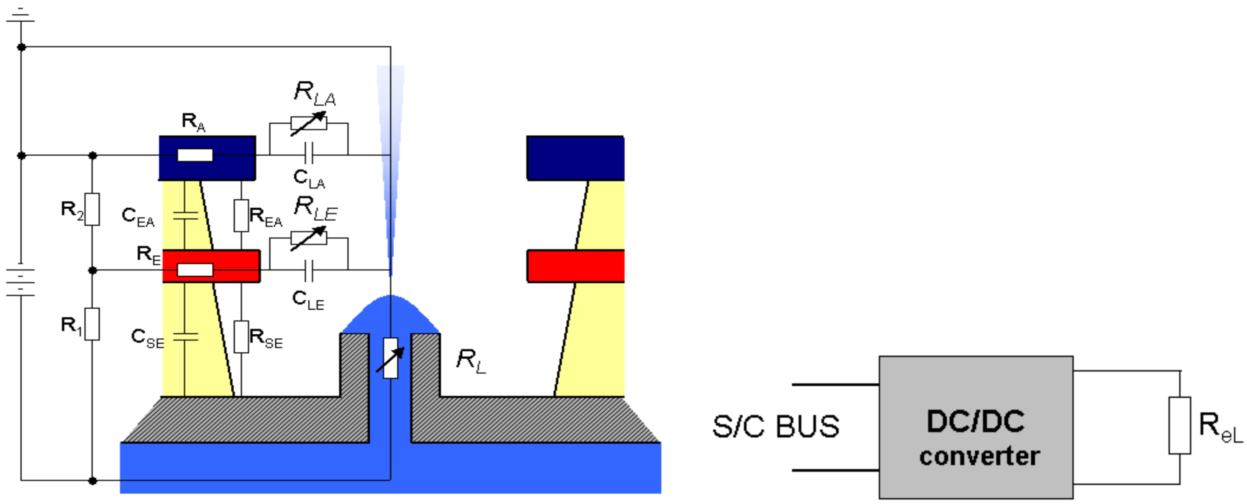

Figure 9. a. Circuit diagram of colloid thruster nozzle b. Simplified equivalent circuit

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References

[1] Ziemer, J.K., Merkowitz, S.M., "Microthrust propulsion for the LISA mission", *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, USA, (2004)
[2] Alexander, M.S et al, "Electrospray Performance of Microfabricated Colloid Thruster Arrays", *Journal of Propulsion and Power*, Vol 22 issue 3 May-June 2006
[3] Kent, B., Stark, J., Stevens, B., Alexander, M., Baker, A., Gibbon, D., Liddle, D., "A MEMS Based Experimental Colloid Thruster Package for Nano satellites," *18th annual AIAA/USU Conference on Small Satellites*, 2004, AIAA/USU SSC04-X1-3
[4] Gamero-Castano, M. "Characterization of a Six-Emitter Colloid Thruster using a Torsional Balance", *Journal of Propulsion and Power*, Vol. 20, No. 4, 2004
[5] Krpoun,R., et al. "Design and fabrication of an integrated MEMS- Based Colloid Micro-propulsion system" *30th International Electric Propulsion Conference.* Florence, 2007 IEPC -2007- 99
[6] ESA, CDF Study Report Proba 3 Formation Flight Technology Demonstrator and Coronagraph Mission. 2005, ESA. p. CDF-42(A).
[7] ESA, Darwin TTN+ Mission Design Assessment. 2004, ESA. p. SCI-A/2004/187/Darwin/DMS.
[8] ESA, LISA - System and Technology Study Report. 2000. p. ESA-SCI(2000)11v1.05
[9] Alexander, M.S., et al., "Electrospray Performance of Micro-fabricated Colloid Thruster Arrays" *Journal of Propulsion and Power*, 2006. 22(3).
[10] Paine, M.D. "Testing Of A Digital Colloid Thruster For Precise Thrust Throttling." *29th International Electric Propulsion Conference*. Princeton University, 2005 IEPC-2005-60.
[11] Paine, M. "A micro-fabricated colloid microthruster : high voltage electrostatic fields on a MEMS device", Ph.D. Dissertation, University of Southampton, School of Engineering Sciences, 2002
[12] Alexander, M.S., Smith, K.L. and Stark, J.P.W. "Voltage Effects on the Volumetric Flow Rate and Thrust produced in Electrospray Propulsion Systems", *29th International Electric Propulsion Conference*, Princeton, 2005, IEPC-2005-87
[13] Smith K.L., Alexander, M.S. and Stark, J.P.W. "The Sensitivity of Volumetric Flow Rate to Applied Voltage in Cone-Jet Mode Electrospray and the Influence of Solution Properties and Emitter Geometry", *Physics of Fluids* Vol.18, 092104, September 2006
[14] Alexander, M.S., Smith K.L., Paine M.D. and Stark, J.P.W. "Voltage Modulation of Flow Rate for Precise Thrust Control in Colloid Electrospray Propulsion", accepted *Journal of Propulsion and Power*
[15] Alexander,M.S., Paine, M.D. and Stark, J.P.W. "Pulsation Modes and the Effect of Applied Voltage on Current and Flow Rate in Nanoelectrospray" *Anaytical Chemistry* 2006, 78, 2658-2664
[16] Wilm, M.S. and M. Mann, "Electrospray and Taylor-Cone theory, Dole's beam of macromolecules at last?" *Journal of Mass Spectroscopy and Ion Processes*, 1994. 136: p. 167
[17] Sobott, F., Robinson, C. V., "Characterising electrosprayed biomolecules using tandem-MS - the noncovalent GroEL chaperonin assembly", *International Journal of Mass Spectrometry*. Vol. 236, 2004, pp. 25-32
[18] Ganan-Calvo, A.M. and J. Davila, "Current and droplet size in the electrospraying of liquids - scaling laws". *Journal of Aerosol Science*, 1997. 28: p. 249.
[19] Hruby, V., et al, "Micro Newton Colloid Thruster System and Development" *27th International Electric Propulsion Conference*, Pasadena 2001
[20] Gamero-Castano, M. and J. Fernandez de la Mora, Direct measurement of ion evaporation kinetics from electrified liquid surfaces. *Journal of Chemical Physics*, 2000. 113n2: p. 815.