REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE Technical Papers	3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
1011

5e. TASK NUMBER
0011

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Leilani Richardson
Unclassified	Unclassified	Unclassified	A		19b. TELEPHONE NUMBER (include area code) (661) 275-5015

3 separate items are enclosed

MEMORANDUM FOR PR (In-House/Contractor Publication)

Please clarify Alok Das reference # 2, see below! Thanks A.B.

FROM: PROI (TI) (STINFO)

5528

08 November 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-FY99-0046**
Schilling, J.H. (SPARTA), Spores, R.A., Spanjers, G.G. , "Micropropulsion Options for the TechSat21
Space-Based Radar Flight"
AIAA Journal of Propulsion and Power   (Statement A)

Micropropulsion Options for the TechSat21 Space-Based Radar Flight

John H. Schilling[*], Ronald A. Spores[†], and Gregory G. Spanjers[‡]
Air Force Research Laboratory, Propulsion Directorate
Edwards AFB, CA 93524

Abstract

An assessment of current micropropulsion concepts and their applicability to a new Air Force mission called TechSat21 is given. The goal of TechSat21 is to demonstrate the critical technologies for a formation-flying constellation of satellites that will perform space based radar. The propulsion system must accomplish an initial ascent, 10 year stationkeeping and drag makeup, and end-of-life deorbit. Major constraints on the propulsion system are total mass, minimum impulse bit, and contamination or other interference with the constellation. Due to its technical maturity, high performance, ease of integration, and potential for improved performance over the next couple of years, the recommended propulsion system is the conventional Pulsed Plasma Thruster (PPT) for primary propulsion and the Micro-PPT for stationkeeping. A low-power Hall thruster (~200 W) for primary propulsion and Micro-PPT for stationkeeping is also a strong candidate. Electrodynamic tethers for the deorbits offer a means for further reducing the propulsion mass, albeit at the expense of increased developmental and integration costs. If significant developmental risk is acceptable, the Micro Field Ionization Thruster (MFIT) offers the lowest propulsion system mass, however it is not expected to be available in the timeframe required for the TechSat21 mission.

[*] Research Engineer, SPARTA Inc., Member AIAA
[†] Chief, AFRL Spacecraft Propulsion Branch, Member AIAA
[‡] Leader, AFRL Electric Propulsion Group, Member AIAA

1

20021119 104

I. Introduction

A greater interest by government agencies in reducing the size of their satellites is evidenced by the increasing number of government small-satellite programs. MightySat is an Air Force program utilizing small satellites for space experiments. The New Millennium Deep Space series of satellites, and the Spartan bus for Shuttle deployed satellites are examples of NASA small satellite programs. The National Reconnaissance Organization (NRO) likewise has a strong program to reduce the size of its space assets,[1] while DARPA is funding a wide range of MEMS (Micro Electro-Mechanical Systems) programs that are applicable to microspacecraft. One of the newest government efforts employing small satellites is the Air Force Research Laboratory (AFRL) TechSat21 mission,[2] which will demonstrate enabling technologies for a formation-flying constellation version of Space Based Radar (SBR).

There are strong advantages for going to small satellites. One benefit is the substantial reduction in the overall life-cycle cost by making satellites less costly to construct, due to fewer components and the potential for mass production techniques. In addition, smaller satellites have greatly reduced launch costs. For the formation flying concept of TechSat21, using small satellites enables the aperture of the system to essentially be the diameter of the constellation (~100m) yielding much greater spatial resolution. Further, the utilization of many smaller satellites lends itself to a graceful degradation of the system capability as individual satellites are lost. The constellation can reconfigure itself for maximum resolution in range and doppler shift of the target with the reduced number of satellites.

2

The Space Based Radar mission objective is to detect moving ground targets and/or airborne targets from space. This concept has been proposed for over 20 years, however the cost of deployment has been considered prohibitive. The TechSat21 approach of employing small satellites could make this long awaited DoD goal a reality. The TechSat21 program plans to launch a three-spacecraft formation in 2003, shown in Fig. 1, to test the critical technologies. This flight will be followed by a larger formation of ~12 spacecraft in 2007 to demonstrate the space-based radar concept.[2] The critical technologies that will be validated are: 1) ionospheric effects on radar, 2) interferometric radar signal processing from multiple transmitters/receivers, 3) orbital mechanics of a formation flying constellation, and 4) spacecraft micropropulsion. Advanced micropropulsion concepts are critical for this mission due to the requirements for significant ΔV and minimal propulsion system mass.

A wide range of micropropulsion concepts is currently being developed for an equally broad spectrum of future DoD and NASA missions. Cold gas thrusters based on MEMS technology are being investigated by several research groups.[3,4] Small Hall thrusters down to 200 W have been developed by Russian and American groups while here in the U.S. development is ongoing for a 50 W thruster.[5] Field emission class thrusters, that generate both individual ions and charged droplets, are being developed in a wide range of different concepts by many different groups.[4,6] Two groups are developing a MEMS concept consisting of an array of small digital chemical microthrusters, up to 10,000, on a single chip. A turbopump driven chemical bi-propellant thruster on a chip is presently being pursued at MIT[7]. A Micro Pulsed Plasma Thruster (Micro-PPT) is being developed by the Air Force Research Laboratory which

3

lends itself to easy integration into small satellites[8]. This paper will focus on micropropulsion concepts with higher specific impulse, which appears to be enabling for the TechSat21 mission. With a TechSat21 satellite mass near 100 kg, miniaturized versions of conventional thrusters can be used for primary propulsion whereas MEMS type thrusters are very attractive for attitude control. At the next level of ~10 kg spacecraft, expected in a fully deployed space-based radar formation, MEMS thrusters may be the only viable propulsion solution.

Each TechSat21 spacecraft serves as one transmit/receive element of a distributed phased-array antenna, with an operational system consisting of a dozen or more spacecraft in a formation approximately a hundred meters across. In space processing of the signals returned from each spacecraft allows detection of air and moving surface targets with search performance equal to a monolithic radar with a power-aperture product equal to the power-aperture of a single component satellite times the square of the number of satellites in the formation, and with spatial resolution nearly equal to that of a single antenna having a diameter equal to that of the entire formation.

This SBR mission represents a substantial deviation from the traditional constellation model, in which multiple satellites are used to provide global coverage, but each spacecraft operates essentially independently within its coverage area and the distance between spacecraft is several thousand kilometers. The microsatellite formations proposed for the space-based radar application would involve multiple spacecraft operating in close proximity, as shown in Fig. 1. No single spacecraft has any independent mission capability. The requirement for cooperative action imposes constraints on many aspects of spacecraft design and operations. Of particular

FIG. 1 DOES NO SHOW CLOSE PROXIME

4

importance is the stringent stationkeeping requirement associated with maintaining the formation. The individual spacecraft within the formation each have slightly different orbital elements, and thus naturally respond differently to various perturbations. In order to maintain the relative positions of the spacecraft within the formation these differential perturbations, which are principally from the orbital J2 perturbation, must be corrected by periodic stationkeeping maneuvers.

II. TechSat21 Design

The individual spacecraft for the TechSat21 mission are currently in the conceptual design phase. The proposed design, shown in Fig. 2, collapses into a 0.3 cubic meter volume for launch, then deploys a 7-meter boom and 2.5 meter antenna on orbit. As shown in Table 1, the total mass of the spacecraft is ~100 kg, of which ~10 kg is available for the propulsion system. Approximately 1 kW of electric power is produced by solar panels on the boom section, almost all of which is available for the propulsion system during the ascent and deorbit phases of the mission. No estimate is available for the amount of power available for stationkeeping propulsion when the propulsion system must compete with the radar transmitter for available power, but as the stationkeeping thrust requirement is small compared to the ascent requirement, any propulsion system capable of performing the ascent mission with < 1 kW of power will almost certainly be able to perform the stationkeeping mission with minimal impact.

The proposed TechSat21 spacecraft is passively stabilized by gravity gradient using the extended solar array boom, with magnetic torquers for attitude control. No momentum wheels or other precise three-axis attitude control system is planned, and

neither gravity-gradient stabilization nor magnetic torquing is likely to provide sufficient pointing capability for propulsive maneuvers. Therefore, we will assume that an attitude control capability will be required of the propulsion system during the ascent and deorbit phases of the mission, as well as during any stationkeeping maneuvers involving the use of the main propulsion system. Presuming propulsive burns are confined to the X-Y plane, which is certainly the case for ascent and descent, only a very limited pitch and roll control capability will be required, primarily for damping oscillations about the stable position.

The propulsion requirement specified by the TechSat21 program is a 390 m/s total ΔV broken down as follows:

- Ascent ΔV of 50 m/s

- Drag makeup ΔV of 20 m/s over 10-year life

- Stationkeeping ΔV of 200 m/s over 10-year life

- Deorbit ΔV of 120 m/s at end of life.

No thrust or trip time requirement has been specified yet, though it can reasonably be assumed that ascent times of more than a few months may be unacceptable, and less than one month preferred. For analysis, a 30-day trip time for the ascent will be assumed unless the performance of any particular propulsion system demands otherwise. The satellites will initially be dropped off at 750-km altitude. The first mission of the propulsion system is to carefully increase the orbital altitude to that of the constellation at 800 km and insert the satellite in phase with the rest of the existing constellation.

Also unspecified by the stated requirements is the approximate magnitude and number of stationkeeping burns associated with the 200 m/s stationkeeping requirement.

However, a positioning requirement of +/- 5 meters is specified, which allows an estimate of these parameters. Assuming the stationkeeping process can be approximated as a constant-velocity drift within a ten-meter cell δ, with a thruster firing to reverse the perpendicular component of velocity at each wall encounter, the total number of thruster firings is

$$N \sim (T \, \Delta V_{tot} / \delta)^{1/2},$$

= ~80,000 firings for T = 10 year mission life, ΔV_{tot} = 200 m/s, and δ = 10m.

Similarly, the thrust impulse per stationkeeping burn is

$$I_{burn} = M_{sat} \, \Delta V_{tot} / N,$$

= ~0.20 N-s for satellite mass, M_{sat} = 100 kg, ΔV_{tot} = 200 m/s, and N = 80,000 .

A thrust impulse of this magnitude can be reasonably provided by most propulsion systems capable of meeting the ascent and deorbit requirements, and presuming the stationkeeping burns required can be largely confined to the spacecraft's X-Y plane the rotational symmetry of the spacecraft should allow the main propulsion system to meet most of the stationkeeping requirements. At a minimum, however, a dedicated attitude control system will be required to rotate the spacecraft into position for each stationkeeping burn. Assuming that, on average, a 90-degree rotation is required between each burn, and noting that τ = ~4000 second average time between burns, the attitude control system will be required to provide a rotation rate of at least

$$\omega = 0.5 \, \pi / \tau$$

= ~4×10^{-4} radians/second for τ = 4000 seconds

in order to position the spacecraft for each burn. Estimating the spacecraft's moment of inertia, I, about the Z-axis at 15 kg-m^2 and noting that the geometry favors a 0.425 meter

moment arm, L, for Z-axis attitude control thrusters, the thrust impulse required to both establish and later halt this rotation is

$$I_{burn} = 2 \omega I / L$$

$$= \sim 0.03 \text{ N-s for } \omega = 4 \times 10^{-4} \text{ radians/second, } I = 15 \text{ kg-m}^2, \text{ and } L = 0.425 \text{ m}.$$

By selecting appropriate thrusters for the rotation burns, those thrust impulses can also contribute to the translational stationkeeping requirement. Thus, only about 15% of the total stationkeeping requirement, or 30 m/s ΔV would need be met by dedicated stationkeeping thrusters while 85%, or 170 m/s, could be supplied by the main propulsion system. This gives a minimum thrust of 10 μN for each element of the dedicated attitude control & stationkeeping system, and 50 μN for the main propulsion system's contribution to the stationkeeping mission. However, the thrust requirement for a 30-day ascent is approximately 2 mN, and will thus dominate the design of the main propulsion system.

The overall system requirements are thus a thrust of 2 mN and a total ΔV of 360 m/s for the main propulsion system, a thrust of 10 μN for each element of the dedicated stationkeeping/ACS system, and a total ΔV of 30 m/s for the total stationkeeping/ACS system.

III. Micropropulsion Options

Traditionally, on-orbit propulsion for spacecraft has been provided by chemical rockets. Solid-propellant rockets are the simplest propulsion system available, but are suitable only for the ascent and de-orbit portions of the mission, and cannot be used for stationkeeping due to the inability to repeatedly turn them on and off. Liquid propellant

rockets are more versatile, and offer greater performance, albeit at the cost of increased complexity. Cold-gas thrusters offer sufficient versatility for stationkeeping in a simpler package than liquid rockets, but have extremely limited performance. All three categories will be considered for the TechSat21 mission in their conventional forms, with the liquid-propellant system serving as a baseline against which other candidate propulsion systems will be measured. In addition, a novel form of miniaturized chemical rocket propulsion system, the digital MEMS thruster, is suitable for spacecraft in the 100kg and under size class and is included in the analysis.

Unfortunately, no chemical propulsion system can offer a specific impulse greater than ~550 seconds, and systems suitable for use on small spacecraft are limited to approximately 220 seconds. While chemical systems will be considered in this analysis, their low specific impulse is likely to result in unacceptably high propellant mass values. However, electric propulsion systems are available which offer much higher specific impulse at the expense of a substantial electric power requirement. As the proposed TechSat21 spacecraft has a substantial solar-electric power capability for the radar payload, while the mass budget for the propulsion system is rather tight, electric propulsion is likely to be preferable for the TechSat21 mission.

Two general categories of electrical propulsion system will be considered for the TechSat21 mission, electrostatic propulsion and electromagnetic propulsion. The former is characterized by the generation of charged particles, usually heavy ions, which are accelerated by an applied potential to velocities in excess of ten kilometers per second to produce thrust. One type of electrostatic system is the ion thruster, in which the applied potential is provided by a series of charged grids, with the ions provided by a separate

discharge chamber. Conventional ion thruster designs do not readily scale down to the size and power levels required for TechSat21 due to discharge chamber physics, but novel ion sources currently under development may allow micro-scale ion thrusters (e.g., field emission electrostatic propulsion (FEEP), micro colloid thruster) to meet the TechSat21 mission requirements. Another type of electrostatic propulsion system is the Hall-effect thruster, also known as the stationary plasma thruster (SPT). In this design, the accelerating potential is provided by forcing a discharge current through a transverse magnetic field. There are several demonstrated SPT designs suitable for the TechSat21 mission.

Electromagnetic propulsion involves the acceleration of a current-carrying plasma by an applied or self-generated magnetic field, rather than by an electrostatic potential. The requirement for a strong magnetic field limits steady-state electromagnetic thrusters to extremely high power levels, which is unacceptable for the TechSat21 mission. However, pulsed operation allows for arbitrarily low average powers, with the high peak power requirement being met by a capacitive discharge, and the pulsed plasma thruster (PPT) is a leading candidate for the TechSat21 mission. The PPTs use of an inert solid propellant with no moving parts is a particularly desirable feature for a system intended for use in a small, low-cost spacecraft.

Several interesting microthruster concepts are not addressed in this analysis, such as the Vaporizing Liquid Microthruster (JPL), a Free-Molecular Micro Resistojet (AFRL), and other electrothermal devices. The high thrust of these devices makes them attractive for several microsatellite missions, however their low specific impulse results in an excessive wet mass for the specific TechSat21 mission parameters. For an eventual

full SBR deployment, this class of microthruster may be enabling for a fast deployment of the microsatellite formation.

A. Chemical Micropropulsion

Liquid-propellant rockets have been the standard for on-orbit propulsion throughout the history of space travel, and no introduction will be given. Due to the limited mass budget of TechSat21, and the implied requirement for simplicity, only monopropellant systems are considered, with the baseline monopropellant being hydrazine. The numerous handling difficulties of hydrazine notwithstanding, hydrazine monopropellant thrusters and propellant feed systems are mature, commercial products and can be integrated with the TechSat21 spacecraft with little difficulty. For the purposes of this analysis, the Primex MR-111 and MR-103C thrusters were specified, though numerous other manufacturers offer equally suitable systems.[9,10] These represent the smallest commercially available chemical thrusters, and while somewhat larger than optimal for TechSat21 are still reasonable for the mission.

While hydrazine monopropellant thrusters may offer insufficient specific impulse for this application, other monopropellant options are available. The Air Force Research Laboratory is currently developing a series of monopropellants based on hydroxyl ammonium nitrate (HAN), which promise to deliver up to 25% greater specific impulse than hydrazine. The high combustion temperature of these propellants requires the use of new materials for thruster construction, and there are also concerns regarding the long-term stability of the new propellants. Nontheless, we will consider an AFRL advanced monopropellant formulation, RK-315A, for the TechSat21 mission. Thrusters designed

11

for use with RK-315A will be assumed 25% heavier than comparable hydrazine thrusters due to design requirements imposed by the high chamber temperature.

Solid-propellant rockets are often used where cost and simplicity are major concerns, which is certainly the case with TechSat21. Again, this is a well-established commercial technology, and no general description will be given. Due to the lack of throttling capability for solid rocket motors, they are wholly unsuitable for the stationkeeping mission, and a secondary propulsion system would need to be provided for that purpose. In addition, the high thrust of solid motors would require a correspondingly high-torque attitude control system during the ascent burn, and uncertainty regarding the exact length or impulse of the ascent burns requires the ability to correct for such errors with the stationkeeping propulsion system. So while solid rockets do offer the potential for simple, inexpensive main propulsion for TechSat21, the increased demands on the secondary propulsion system will likely negate that advantage. A system based on the commercially available Thiokol Star 5* and Star 6* motors is considered here; again, other manufacturers offer competitive systems.

Cold-gas thrusters are the simplest throttleable thruster available, and thus the simplest propulsion system suitable for the stationkeeping and attitude control requirements. Unfortunately, the combination of extremely low specific impulse and heavy, high-pressure propellant tanks results in unacceptably high total propulsion system mass values even though the thrusters themselves can be quite small. Cold gas thrusters cannot meet the ascent or de-orbit mission requirements, and are only marginally capable of performing the stationkeeping mission. However, they do have the advantage of using an inert, gaseous propellant and thus do not contaminate exposed

spacecraft surfaces. Because of the threat of mutual contamination when spacecraft operate propulsion systems in close formation, the combination of cold-gas thrusters for stationkeeping and a similarly non-contaminating main propulsion system will be considered, with the Moog 58-102 thruster baselined for analysis.[11]

While all of the aforementioned chemical propulsion systems can be obtained in sizes suitable for the TechSat21 mission, they begin to suffer from scaling effects at that level. Chemical propulsion would be largely unsuitable in future microsatellite missions with mass budgets an order of magnitude smaller. To meet the microsatellite requirement, several institutions have proposed the Digital MEMS (Micro ElectroMechanical System) thruster. This device uses semiconductor manufacturing techniques to etch thousands of extremely small (~500 μm) cavities and nozzles into a silicon wafer. Each cavity is filled with a propellant charge and serves as a one-shot microthruster at need.[12] The specific impulse and propellant mass fraction suffer in comparison with conventional chemical rockets, but the ability to scale down to arbitrarily small sizes is desirable for the microsatellite application. The availability of small discrete thrust impulses is particularly advantageous for stationkeeping and attitude control. Both TRW and Honeywell presently have programs to fabricate digital MEMS thrusters and have tested the necessary igniter arrays. Test firings with full propellant loads are expected soon, and while there are still substantial technical challenges associated with the concept it will be considered as an option for TechSat21, using the performance estimated by TRW and Honeywell.

B. Electromagnetic Micropropulsion

The Pulsed Plasma Thruster (PPT)[13] generates thrust through a surface discharge across the face of a solid Teflon™ propellant. The solid propellant is converted to vapor and partially ionized by ohmic and radiative energy from the arc. Acceleration is accomplished by a combination of thermal and electromagnetic forces to create usable thrust. The solid propellant is attractive for the small SBR satellites since it significantly reduces the thruster mass and volume by eliminating the propellant tankage and valves. In addition, eliminating the valve seals and flow regulation, which become increasingly problematic at small sizes, increases the engineering reliability of the PPT compared to gaseous or liquid propellant thrusters. The only moving part on the PPT is a spring, which passively feeds the propellant. The inherent engineering advantages of the PPT design have enabled the thruster to complete several space missions over the past 30 years with no failures.[14,15] Presently, the PPT is scheduled to fly in 1999 on the NASA EO-1 satellite[16] and is being considered for the New Millennium Deep Space 3 mission scheduled to launch in 2003.[17]

The last flight-qualified design,[18] for the LES 8/9 satellite in 1974, operating at 20 W power achieved a thrust of 300 μN, specific impulse of 1000 s, and thrust efficiency of 6.4%. For the LES 8/9 PPT two electrode assemblies were used with their thrust vectors canted 30 degrees in order to provide 2 thrust vectors for attitude control. A modern PPT, developed by Primex Aerospace for NASA, is presently being qualified for EO-1. The EO-1 PPT operates between 5 to 40 J per discharge to create 100 to 700 μN-s impulse bit with a specific impulse near 1200 s. Two electrode assemblies are again used, however the thrust vectors are pointed 180 degrees apart.

For the TechSat21 mission, a somewhat different PPT electrode configuration is proposed with four electrode sets directed towards a common thrust vector. The four electrode sets are fed from one common capacitor as was done for both the LES 8/9 and EO-1 PPTs. Each electrode would be fired at 20 J, 2 Hz for a total power level of 160 W. Use of four electrode sets eliminates the gimbal requirement, since the firing rate can be adjusted between the four units for thrust vector control. This minimizes the configuration mass and uses a design requiring minimal change from the commercially available design. The electrode redundancy also reduces the length of the breech-fed propellant to approximately 6" simplifying the spacecraft integration. Performance is conservatively assumed to be 1000 s specific impulse, 10% efficiency, and 700 μN at 40 W for each electrode set. This performance level is slightly degraded from that measured for EO-1 using a 40 J discharge, and slightly better than that measured at 20 J for LES 8/9. Due to a recent resurgence in PPT funding, significant progress has been made in improving PPT performance and engineering. Laboratory model PPTs, with reasonably flight-like designs, have been demonstrated to achieve thrust to power levels 3 to 4 times above the flight models.[19] The next-generation of PPTs are also expected to use a coaxial geometry which may reduce the radiated EMI and lessen the spacecraft interaction. These advanced PPTs could easily be available for both TechSat21 missions.

The Micro Pulsed Plasma Thruster (Micro-PPT) is a simplified, miniaturized version of the PPT developed at the AFRL. The Micro-PPT uses a high-voltage discharge that is applied across the face of a coaxial propellant bar. Both pulsed and DC application of the high-voltage has been tested. The discharge ignites through a self-breakdown thus eliminating the PPT sparkplug and the associated mass, complexity, and

energy requirements. Pulsed Micro-PPT voltage application generally tends to require lower voltage and hence reduced shielding mass. DC voltage application eliminates the mass of the semiconductor switches and voltage amplification electronics. The propellant modules consist of annular Teflon™ propellant with inner and outer copper ⟵——— electrodes. Module diameters of 0.110", 0.140" and 0.250" have been tested. Typical breakdown voltages for the 0.110" propellant is under 3000 V for a pulsed discharge. Thus the Micro-PPT can be energized from the trigger circuit of a standard PPT, effectively eliminating the PPU mass of the stationkeeping propulsion system. Micro-PPT discharges are typically in the 1 J regime and are estimated to create 10 μN of thrust μN for a 1 Hz firing rate. Thrust levels are estimated since no measurement capability presently exists at the low thrust levels required for microsatellite stationkeeping.

For applications on space based radar microsatellites, the radiated EMI from the propulsion system poses a serious concern. For the PPT, GHz radiation from the spark ignitor discharge can interfere with the primary transceiver frequencies. EMI radiation from the main PPT discharge can interfere with the radar frequency shifts in the MHz range. Although it is still a topic of current research, it is believed that the new generation of co-axial PPTs will better confine the EM radiation.

C. Electrostatic Micropropulsion

The high specific impulse, high efficiency, and modest mass have made SPTs the electric propulsion system of choice for many future missions at power levels of 1 kW or above. Recent tests in the 50-200 W range suggest that they are applicable to the

TechSat21 mission as well. SPTs were developed in the former Soviet Union during the 1960s and 1970s, and have been flown in over a hundred successful missions. The relatively high mass of even the smallest SPTs, though, renders them marginal at best for stationkeeping and attitude control despite the potential savings associated with the use of a common power processing unit and propellant feed system. For purposes of this analysis the 200 W Hall thruster developed by Busek Corp. is considered for primary propulsion.

Another electrostatic thruster proposal under consideration is Field-Effect Electrostatic Propulsion (FEEP). This is an ion thruster using a field emission ion source, in the form of a narrow slit anode through which cesium propellant is passed and ionized by the geometrically-enhanced electric field. This offers a more compact and efficient ion source than the traditional electron-bombardment ionization chambers used with ion thrusters, allowing the extension of electrostatic propulsion to smaller spacecraft than previously possible. FEEP systems have been demonstrated in the laboratory, and a FEEP thruster is scheduled for a shuttle flight experiment in 1999. These systems offer extremely high specific impulse values at reasonable efficiency, but specific power and thrust is low. It may, therefore, be necessary to relax the 30-day ascent time requirement for a FEEP-based propulsion system. For the purpose of this analysis, several combinations of the Centrospazio 120-watt FEEP thruster with complimentary ACS thrusters will be considered.

The basic physical principles of the FEEP thruster can be scaled down to the true micropropulsion regime, resulting in the micro colloid thruster. As with the digital chemical microthruster described earlier, this system consists of a large number of

17

discrete thrusters micromachined into a silicon wafer. The thruster elements consist of microvolcano field-emission ion sources, in which a propellant is fed through a small, sharp needle, which serves as an anode similar to the Spindt-type microcathode. The field enhancement associated with the sharp tip of the needle results in the emission of charged micron-scale droplets of propellant. The droplets are accelerated by an applied electric field and neutralized by an external electron source, or perhaps by a parallel microthruster element operating at the opposite polarity. Systems proposed by Phrasor Scientific and MIT use doped glycerol propellants and are predicted to achieve specific impulse values of order 1000 seconds at reasonably high efficiency. As yet, only limited progress has been made in fabricating thruster subassemblies and testing representative components, and no actual thruster has been constructed or tested, so there would be a high degree of technical risk associated with the use of micro colloid thrusters in TechSat21.
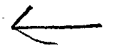
Closely related to the micro colloid thruster is the Micro Field Ionization Thruster (MFIT) from SRI, inc. This also uses microvolcano field ion sources, but with a metallic propellant, typically gallium or indium. These materials melt at or near room temperature, which allows for a relatively simple feed system, while having a low ionization energy and surface tension results in the emission of single ions rather than charged clusters or droplets.[20] The resulting high charge to mass ratio allows higher specific impulse values to be achieved with reasonable accelerating voltages, and the ionization mechanism is considerably more efficient than that of conventional ion thrusters. The current proposal calls for a specific impulse of 15,000 seconds or higher, with a correspondingly low thrust-to-power ratio, though it is likely that the specific

18

impulse can be substantially reduced if necessary to meet thrust requirements. With a fixed ionization energy requirement, power efficiency will of course drop at lower specific impulse values, and the thruster is best used for moderate to high-Isp missions. The development of MFIT thrusters is at a very early stage, and readiness for the 2003 TechSat21 mission is doubtful, but the potential benefits of such a compact, high-Isp system for later stages of the program cannot be ignored.

D. Electrodynamic Tether

One further technology is considered for the primary propulsion requirements, the electrodynamic tether. However due to the immaturity of this technology and lack of understanding of the fine control for maneuvering, the tether was only considered for the specified de-orbit requirement for TechSat21. Several kilometers of thin wire can be deployed from a spacecraft and, by gravity gradient effects, oriented vertically with respect to the Earth. Orbital motion of this wire in the Earth's essentially stationary magnetic field will generate an electric potential along its length, and if a plasma contactor is placed at each end a current will flow. The JxB force produced by the interaction of this current with the magnetic field tends to decelerate the spacecraft, and can perform the deorbit mission in a matter of months.[21]

Unfortunately, TechSat21 is likely to operate in a polar orbit, whereas electrodynamic tether systems require motion perpendicular to the Earth's magnetic field to produce thrust. Since the Earth's magnetic pole and the true North differ by 11.5 degrees a small force is still generated, however there is concern as to the length of time required to remove the satellite from the constellation. There is also a strong concern

regarding deployment of the tether within the dynamic constellation and potential tangling with adjacent spacecraft. One approach that will be further investigated is the option of simply turning off the propulsion system of a failed satellite, allowing the J2 perturbation to drift the vehicle out of the constellation, and then from a "safe" distance away from the constellation deploying the electrodynamic tether. These, plus general concerns regarding the technical maturity of tether systems at present, argue against recommending a tether de-orbit system for TechSat21, but the option is considered for comparative purposes.

E. Electric Power Processing

It should be noted that for all of the electric propulsion systems described, dedicated power processing hardware is required. The TechSat21 spacecraft will have ample electric power available from the solar array boom, but the main bus can be expected to operate at less than 100V, while the various electric thrusters require anywhere from 300 V to 10 kV. Also, few of the systems have been tested in a simple direct-drive configuration. Traditionally, voltage- or current-regulated switching power supplies are used, which tend to outweigh the thrusters they drive by a factor of two or three. We assume that such conventional power supplies will be used with the macro-scale Hall thruster, but for the various micropropulsion systems a solid-state DC-DC converter seems a more reasonable choice. A Micro-PPT has been operated using such a system at AFRL, and it will be assumed that similar systems can be used with the colloidal and MFIT systems. With PPTs, a trigger unit and a discharge capacitor must also be provided, and are included in the system weight estimate. Notwithstanding the

requirement for a power processing unit, such systems are rightly considered separately from the thrusters themselves, as a single PPU can serve a substantial number of distinct thrusters in stationkeeping or attitude control operation. In the case of the PPT, it is fortuitously possible for the PPT trigger circuit to also serve as the entire power-processing unit for an associated Micro-PPT system.

A comparison of the thruster proposals described above is given in Table 2. As can be seen, electric propulsion systems generally offer specific impulse values of 1000-1500 seconds and chemical systems approximately 200 seconds. Electric propulsion is thus quite likely to offer lower overall system mass, presuming the thruster and PPU masses can be kept to acceptable levels. Thrusters can also be divided into micro- and macro scales, with the macro thrusters being small versions of conventional spacecraft propulsion systems and the microthrusters developed specifically for microsatellite applications, often using semiconductor-style, commonly referred to as MEMS, fabrication. The macrothrusters, with masses of order 1 kg, are generally suitable for the main propulsion application, but are too heavy to be used in the numbers required for the stationkeeping/ACS application. The microthrusters, at approximately 100 grams, can meet the stationkeeping/ACS requirement but lack the thrust needed for main propulsion of the 100kg TechSat21 vehicle unless used in clusters. Some combination of the two is likely required.

III. Analysis

Given the extremely tight mass budget set for the TechSat21 spacecraft, any comparison of propulsion options must center on predictions of propulsion system mass.

To address this issue, detailed mass estimates for propulsion systems using the various proposed technologies were constructed. A total of seventeen propulsion options were considered, with each of the potential main propulsion systems matched with one or more compatible stationkeeping systems. Mass estimates for each system were broken down into five categories - thruster, PPU, propellant, propellant feed, and miscellaneous - with one or more line items in each category as appropriate.

The thruster category includes the main propulsive thruster or thrusters and the stationkeeping thrusters. The size and/or number of main thrusters was set by the ~2 mN thrust requirement for a ~~thirty~~ 30-day ascent, except in the case of the MFIT system where a relaxed 60-day requirement was allowed due to the MFITs low thrust-to-power ratio. In some cases, such as the Hall thruster or any of the chemical systems, a single thruster of the smallest reasonable size provided an ascent period of less than one day. For attitude control and stationkeeping, a total of ten ACS thruster elements with a minimum thrust of 15 μN were required. Any special mounting hardware required was also included in this category.

For electric propulsion systems, a high-voltage DC power-processing unit is invariably required, as previously described, and the use of semiconductor DC-DC conversion has been postulated in most cases. Also included in this category are any necessary high-voltage or high-current cables. In the case of PPTs, an energy storage capacitor and a pulse trigger generator are also required. If the main and ACS systems incorporate different electric propulsion technologies, separate power processing systems are generally required. The principal exception to this rule is the ability of a PPT trigger

pulse generator to serve as the entire power processing system of a Micro-PPT attitude control system although additional switching is required.

Sufficient propellant was provided to meet the specified mission ΔV requirements of 320 m/s for the main propulsion system and 50 m/s for the ACS. In some cases, it was deemed advantageous to provide separate propellant storage for each ACS thruster element rather than a feed system from a central tank. For these cases the requirement is set at 1 kN-s total impulse per element (100 m/s total ΔV for the ACS) to account for possible non-uniform propellant usage by the ACS. The propellant feed system includes tankage for main and ACS propellant, feed lines, valves, and flow control systems.

Ten percent of the propulsion system net dry mass is specified for structures and general mounting hardware. An additional five percent is specified for control systems and wiring harnesses using standard spacecraft design practice.[22] This is exclusive of any high-voltage distribution system incorporated in the PPU category. Finally, a fifteen percent margin is set aside for unexpected system growth. This total of 30% of net dry mass constitutes the miscellaneous category.

For each of the enumerated items, commercial off-the-shelf hardware was specified whenever possible, preferably space-qualified but in the case of some PPU or propellant feed system components, ground or aviation hardware meeting relevant military specifications was used as a baseline. The intention is to reliably estimate the mass of a flight system rather than to actually design such a system. In some cases, commercial systems of different power levels were scaled linearly over a modest range to meet specific TechSat21 requirements. For experimental thruster concepts, flight-like

laboratory test hardware was considered, and in the case of some technologies which have not yet reached even the test stage, the best estimates of the authors regarding developed system weights were used.

Space precludes giving the detailed mass breakdowns for all propulsion system options here, though a representative sample is given in Table 3. Figure 3 is a schematic layout of the same system, indicating the major components. While specific to the all-PPT propulsion option, other propulsion systems will have a similar configuration. Six ACS thrusters in a trilateral arrangement are specified for X-Y stationkeeping and yaw control, rather than the traditional eight-thruster orthogonal arrangement. While this does result in a small (< 13%) reduction in efficiency due to cosine losses, the ease of integration with the hexagonal TechSat21 bus and the ~25% reduction in thruster dry mass more than compensates for non-orthogonal losses, and leads to the recommendation of the trilateral system for this application.

Table 4 provides a comparative breakdown of all the concepts included in this study. It is apparent that only systems incorporating the MFIT thruster can meet the specified 9 kg propulsion system mass budget. However, a number of electric propulsion systems offer total masses in the 10-15 kg range which, in light of the technical immaturity of the MFIT system and the lack of other alternatives, must be considered acceptable. The conventional chemical monopropellant baseline, at more than twice the budgeted mass, is not a reasonable candidate for the mission.

Factors other than propulsion system mass must also be considered in comparing TechSat21 propulsion options. In particular, the technical maturity of the various systems is a major concern. Only the chemical monopropellant baseline system, already

24

rejected on mass grounds, could be constructed using existing flight-qualified hardware. The FEEP, low-power Hall, PPT, and µPPT thruster systems have at least been demonstrated in the laboratory, and are based on existing flight-qualified systems operating at higher power levels. Less tested systems such as the MFIT, digital MEMS, and colloidal microthruster are higher risk, and therefore may suffer increases in mass and cost while developing a flight unit.

Also relevant are the ascent trip time and power requirement, though it is clear that any of the proposed systems can achieve acceptable performance in these regards. In particular, with a power budget of 1 kW the TechSat21 propulsion system is likely to be mass-limited rather than power-limited. Power processing units capable of handling the full kilowatt of available power would be excessively heavy (6+ kg for the PPU alone for a 1 kW class SPT-100 thruster). All of the electric propulsion systems found competitive for TechSat21 operate at power levels of only a few hundred watts.

Table 5 lists these parameters and issues for all studied propulsion system options. The systems fall into three general categories. The all-MFIT system is the clear winner in terms of mass and simplicity, with reasonable ascent time and power requirements, but involves substantial technical risks. A range of combinations using PPT or Hall Thrusters for main propulsion with a variety of ACS systems deliver propulsion system masses in the 10-15 kg range, with the main propulsion systems at least having been demonstrated in the laboratory. These options differ primarily in the details of their attitude control systems, which have a minor impact on overall system mass and a major impact on technical risk. Chemical-propulsion options have uniformly high overall masses, and cannot be considered even where the technical risk is low.

IV. Conclusions

Based on the analysis above, the all-PPT system seems the best overall choice for the TechSat21 mission. The original specification of a 9 kg propulsion system mass cannot be met without depending on the MFIT propulsion system, which is at a very early stage of development and is unlikely to be ready for the TechSat21 mission. At an estimated 11.90 kg, the combination of PPT thrusters for ascent and descent and μPPT modules for attitude control offers the lowest total system mass for any propulsion option using demonstrated technologies. The use of a common technology for main and ACS propulsion also simplifies the design and integration of the propulsion system, and allows weight savings through the use of common components. This presently appears to be the best technology combination of reasonable system mass, simplicity, and technical maturity , which is not offered by any other combination studied. It should also be noted that near-term advances in PPT technology and performance can easily reduce the all-PPT propulsion mass to within the 9-kg allotment.

Worthy of attention, however, is the combination of Hall thrusters for main propulsion and μPPT modules for stationkeeping. The use of two distinct propulsion technologies results in a substantial increase in complexity and a modest increase in mass, but again all relevant technologies have been demonstrated. As the predicted total mass for the Hall-μPPT system is less than 15% higher than that of the all-PPT system, it is possible that future improvements in Hall thruster system design, or unexpected

difficulties with PPT development, may shift the balance in favor of the Hall thruster for main propulsion. It is also likely that the higher specific impulse of the Hall thruster will work to its advantage in later operational missions with potentially higher ΔV requirements.

Two other propulsion systems that cannot be ruled out are the electrodynamic tether and the micro field ionization thruster. If the MFIT can be brought to flight-ready status at even a fraction of its claimed performance, it outclasses any other system for microsatellite main propulsion or ACS applications, and while this is unlikely to occur in the timeframe of the first TechSat21 mission, it should be kept in mind for follow-on missions. The electrodynamic tether can enable a substantial reduction in the propulsion system mass for the early TechSat21 missions. While the performance of tether systems in polar orbits is substantially degraded, it may nonetheless be able to perform the deorbit mission for TechSat21. In this case, the propellant savings will more than compensate for the added mass of the tether system, resulting in a complete propulsion system mass of approximately 11 kilograms. Additional study of the performance of tether systems in polar orbits, and of the general technical maturity of tether systems in the near future, is strongly recommended.

References

[1] Ferster, W., "NRO Delays New Spy Fleet Amid Questions Over Cost," *Space News*, Vol. 9 No. 21, 1998, pp. 6-20.

[2] Das, A., "Overview of the AFOSR/AFRL TechSat21 Microsatellite Program," *Micro/Nanotechnology for Micro/Nanosatellites*," AFOSR, Albuquerque, 1998 Section 4.

[3] Janson, S.W., and Helvajian, H. "Batch-Fabricated Microthrusters: Initial Results," AIAA Paper 96-2988, July, 1996.

[4] Mueller, J., "Overview of Micropropulsion Workshop," Jet Propulsion Library, Pasadena, CA, 1997

[5] Khayms, V. and Martinez-Sanchez, M., "Design of a Miniaturized Hall Thruster for Microsatellites," AIAA Paper 96-3291, July, 1996.

[6] Fehringer, M., Rudenauer, F. and Steiger, W., "Space-Proven Indium Liquid Metal Field Ion Emitters for Ion Microthruster Applications," AIAA Paper 97-3057, July, 1997

[7] Breuer, K., "Chemical Microturbines & MEMS-based Micronozzles," *Formation Flying and Micropropulsion Workshop*, AFRL, Lancaster, 1998, chapter 27

[8] Spanjers, G. G., Schilling, J. H., et al, "The Micro Pulsed Plasma Thruster," submitted to the Journal of Propulsion and Power Special Issue on Micropropulsion, Jan. 1999

[9] Mueller, J, "Thruster Options for Microspacecraft: A Review and Evaluation of Existing Hardware and Emerging Technology," AIAA Paper 97-3058, July 1997.

[10] Rocket Research Company, "Rocket Thrusters," *Hydrazine Handbook,* Olin Defense Systems Group, Redmond, WA 1995, chapter 3.

[11] Moog Space Products Division, "Cold Gas Thrusters," *Moog Space Products,* Moog, Inc, Aurora, NY, 1993, section 4.

[12] Janson, S.W., and Helvajian, H. "Batch-Fabricated Microthrusters: Initial Results," AIAA Paper 96-2988, July, 1996

[13] Burton, R. L. and Turchi, P. J., "Pulsed Plasma Thruster," J. Propulsion and Power Vol. 14, No. 5, 1998, p. 716 – 735.

[14] Brill, Y., Eisner, A., and Osborn, L., "The Flight Application of a Pulsed Plasma Microthruster; the NOVA Satellite," AIAA Paper 82-1956, Nov. 1982.

[15] Guman, W. J., and Williams, T. E., "Pulsed Plasma Microthruster for Synchronous Meteorological Satellite (SMS)," AIAA Paper 73-1066, Oct. 1973.

[16] Meckel, N. J., Cassady, R. J., Osborne, R. D., Hoskins, W. A., and Myers, R. M., "Investigation of Pulsed Plasma Thrusters for Spacecraft Attitude Control," 25th International Electric Propulsion Conference, Paper 97-128, Aug. 1997.

[17] Blandino, J. J., Cassady, R. J., and Peterson, T. T., "Pulsed Plasma Thrusters for the New Millenium Interferometer (DS-3) Mission," 25th International Electric Propulsion Conference, Paper 97-192, Aug. 1997.

[18] Vondra, R. J., "Flight-qualified Pulsed Electric Thruster for Satellite Control," J. Spacecraft, Vol. 9, 1974, p. 613.

[19] Burton, R. L., Bushman, S. S., Antonsen, E. L., "Arc Measurements and Performance Characteristics of a Coaxial Pulsed Plasma Thruster," AIAA 98-3660, July 1998.

[20] Fehringer, M., Rudenauer, F. and Steiger, W., "Space-Proven Indium Liquid Metal Field Ion Emitters for Ion Microthruster Applications," AIAA Paper 97-3057, July, 1997

[21] Forward, R.L. and Hoyt, R.P., "Application of the Terminator Tether Electrodynamic Drag Technology for the Deorbit of Constellation Spacecraft," AIAA Paper 98-3491, June, 1998

[22] Larson, W.J., and Wertz, J.R., "Spacecraft Design and Sizing", *Space Mission Analysis and Design*, 2nd ed., Microcosm, Torrance, CA, 1993, chapter 10.

Table 1 – Proposed Mass Budget for TechSat21 Spacecraft

Subsystem	Mass, kg
Radar Payload	20.0
Attitude Determination and Control System	3.8
Propulsion	1.7
Telemetry, Tracking and Command	4.0
Command and Data Handling	2.4
Structure	6.6
Power	29.3
Thermal	3.3
Propellant	7.0
Contingency	15.2
TOTAL	93.3

Table 2 – Thruster Performance Comparison
Values for Typical Microsatellite Installation

Type	Isp	η	Mass	Thrust	Power
Cold Gas Thruster	75 s	95+%	0.01 kg	5 mN	N/A
Solid Rocket Motor	185 s	90+%	1.60 kg	100+ N	N/A
Digital MEMS	200 s	~75%	0.04 kg	50 mN	N/A
Hydrazine Monopropellant	220 s	95+%	0.32 kg	2 N	N/A
Advanced Monopropellant	290 s	95+%	0.40 kg	2 N	N/A
Colloidal Microthruster	500-1500 s	~50%	0.08 kg*	20 μN	0.2 W
Pulsed Plasma Thruster	1000 s	~10%	0.25 kg*	700 μN	40 W
μPPT	1000 s	~5%	0.12 kg*	40 μN	4 W
Hall Thruster	1500 s	~35%	1.00 kg*	10 mN	200 W
FEEP	8,000 s	~25%	3.50 kg*	800 μN	120 W
MFIT	15,000 s	~90%	0.15 kg*	1.5 mN	300 W

* Values for EP systems do not include power processing unit

η = total system efficiency (thrust power output to chemical or electrical power input)

Table 3 – Representative Propulsion System Mass Estimate
(PPT thruster with μPPT ACS)

Component	Type	#	Unit Mass	Total Mass
Main Thruster	Primex PPT or similar	4	250 gm	1000 gm
Propellant	Teflon bars	4	875 gm	3500 gm
Capacitor	Maxwell MDE series	1	1800 gm	1800 gm
Striplines	5cm x 0.5mm Aluminum	2	175 gm	350 gm
Power Processing Unit	Semiconductor DC-DC	1	640 gm	640 gm
Trigger Pulse Unit	AFRL PPT trigger unit	1	200 gm	200 gm
ACS Thrusters	AFRL μPPT modules	10	120 gm	1200 gm
ACS Propellant	Teflon rods	200	3 gm	600 gm
High-Voltage Cable	RG-58 or equivalent	13.5 m	40 g/m	540 gm
SCR Switch Modules		14	20 gm	280 gm
Structures & Mounts			10% of Dry Mass	600 gm
Controls & Wiring			5% of Dry Mass	300 gm
Design Margin			15% of Dry Mass	900 gm
Total				**11.90 kg**

Table 4 – Propulsion System Mass Comparison

| Propulsion Type | | | System Mass Breakdown | | | | | |
Ascent	ACS	Deorbit	Thruster	PPU	Propellant	Tankage	Misc	Total
MFIT	MFIT	MFIT	0.40 kg	0.85 kg	0.25 kg	0.20 kg	0.45 kg	2.20 kg
PPT	MFIT	PPT	1.55 kg	3.25 kg	3.50 kg	N/A	1.45 kg	9.75 kg
Hall	MFIT	Hall	2.30 kg	2.30 kg	2.40 kg	1.70 kg	2.00 kg	10.70 kg
PPT	μPPT	Tether	2.95 kg	3.00 kg	3.30 kg	N/A	1.85 kg	11.10 kg
PPT	μPPT	PPT	2.50 kg	3.55 kg	4.10 kg	N/A	1.80 kg	11.90 kg
Hall	Colloid	Hall	3.00 kg	2.40 kg	2.60 kg	1.90 kg	2.20 kg	12.10 kg
Colloid	Colloid	Colloid	6.15 kg	0.85 kg	3.50 kg	0.50 kg	2.15 kg	13.20 kg
Hall	μPPT	Hall	3.70 kg	2.70 kg	3.00 kg	1.70 kg	2.45 kg	13.55 kg
PPT	MEMS	PPT	3.30 kg	3.00 kg	6.50 kg	N/A	1.90 kg	14.70 kg
Hall	MEMS	Hall	4.20 kg	2.00 kg	5.40 kg	1.70 kg	2.40 kg	15.70 kg
Hall	Hall	Hall	6.20 kg	2.15 kg	2.60 kg	1.95 kg	3.10 kg	16.00 kg
HAN	HAN	HAN	4.40 kg	N/A	12.75 kg	5.75 kg	1.95 kg	21.20 kg
FEEP	Colloid	FEEP	7.80 kg	8.60 kg	0.65 kg	0.85 kg	5.15 kg	23.05 kg
Hall	C. Gas	Hall	2.50 kg	2.00 kg	6.40 kg	10.35 kg	4.45 kg	25.70 kg
FEEP	μPPT	FEEP	9.00 kg	9.20 kg	1.45 kg	0.65 kg	5.65 kg	25.90 kg
N_2H_4	N_2H_4	N_2H_4	3.60 kg	N/A	17.55 kg	3.05 kg	2.00 kg	26.20 kg
Solid	MEMS	Solid	11.00 kg	N/A	17.60 kg	N/A	3.30 kg	31.90 kg
MEMS	MEMS	MEMS	13.20 kg	N/A	19.80 kg	N/A	3.95 kg	36.95 kg

Table 5 – Propulsion System Comparison

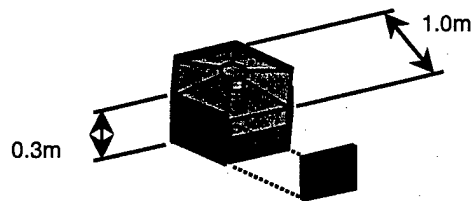| Propulsion Type							
Ascent	ACS	Deorbit	Propulsion Mass	Ascent Time	Ascent Power	Technology Status	Notes
MFIT	MFIT	MFIT	2.20 kg	60 days	300 W	Research	No moving parts
PPT	MFIT	PPT	9.75 kg	30 days	160 W	Research	
Hall	MFIT	Hall	10.70 kg	10 days	200 W	Research	
PPT	μPPT	Tether	11.05 kg	30 days	160 W	Demonstrated	
PPT	μPPT	PPT	11.90 kg	30 days	160 W	Demonstrated	
Hall	Colloid	Hall	12.10 kg	10 days	200 W	Research	
Colloid	Colloid	Colloid	13.20 kg	30 days	15 W	Research	No moving parts
Hall	μPPT	Hall	13.55 kg	10 days	200 W	Demonstrated	
PPT	MEMS	PPT	14.70 kg	30 days	160 W	Research	
Hall	MEMS	Hall	15.70 kg	10 days	200 W	Research	
Hall	Hall	Hall	16.00 kg	10 days	200 W	Demonstrated	Zero contamination
HAN	HAN	HAN	21.20 kg	< 1 day	N/A	Demonstrated	Advanced Chemical
FEEP	Colloid	FEEP	23.05 kg	60 days	240 W	Research	
Hall	C. Gas	Hall	25.70 kg	10 days	200 W	Demonstrated	Zero contamination
FEEP	μPPT	FEEP	25.90 kg	60 days	240 W	Demonstrated	
N_2H_4	N_2H_4	N_2H_4	26.20 kg	< 1 day	N/A	Flight Ready	Chemical baseline
Solid	MEMS	Solid	31.90 kg	< 1 day	N/A	Research	No moving parts
MEMS	MEMS	MEMS	36.95 kg	< 1 day	N/A	Research	No moving parts

Figure Captions:

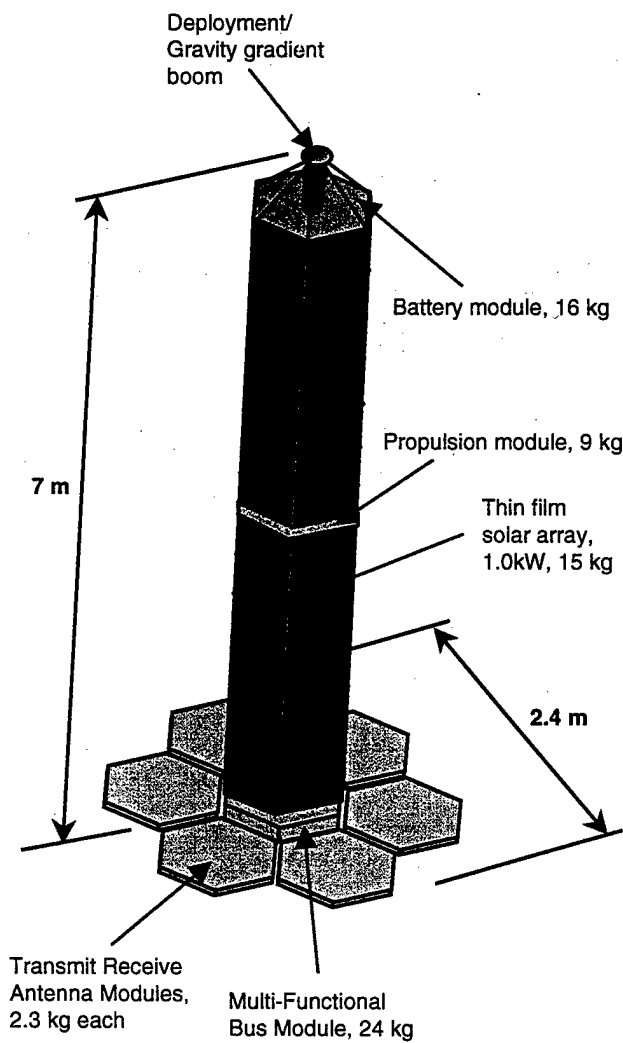Fig. 1 Satellite formation for the 2003 TechSat21 flight using 3 spacecraft.

Fig. 2 Proposed design for the individual TechSat21 spacecraft. 2a) The spacecraft in the stowed configuration for launch, and 2b) the spacecraft fully deployed.

Fig. 3 Representative propulsion system layout on a TechSat21 spacecraft. PPTs are shown for primary propulsion with Micro-PPTs for attitude control. 4a) Overall spacecraft propulsion system layout, and 4b) Detail of the propulsion module.
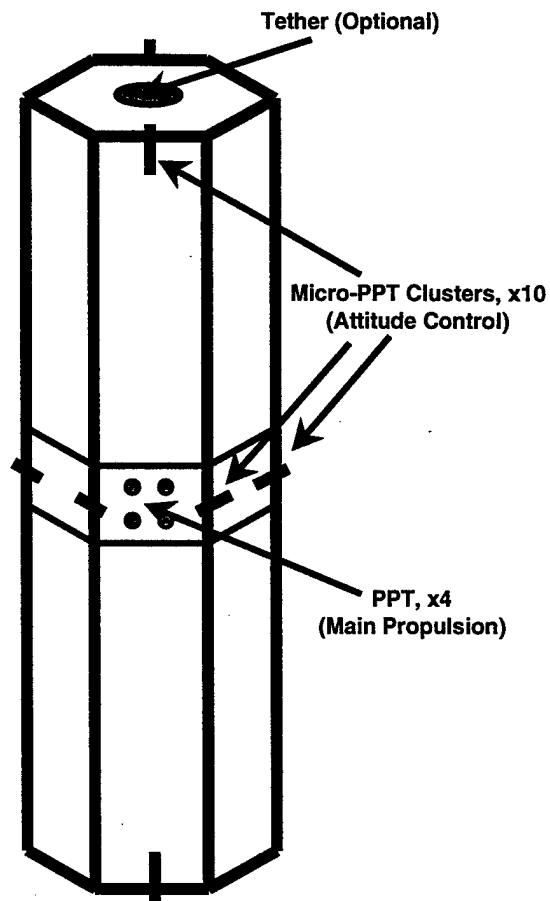
7 m

2.4 m

1.0m

0.3m

a) Stowed

Deployment/
Gravity gradient
boom

Battery module, 16 kg

Propulsion module, 9 kg

Thin film
solar array,
1.0kW, 15 kg

7 m

2.4 m

Transmit Receive
Antenna Modules,
2.3 kg each

Multi-Functional
Bus Module, 24 kg

b) Deployed

Schilling et al., J. Propulsion and Power, Fig. 2 of 3

Tether (Optional)

Micro-PPT Clusters, x10
(Attitude Control)

PPT, x4
(Main Propulsion)

a) Spacecraft propulsion system layout

Micro-PPT Clusters, x6
(Attitude Control)

Transmission
Line

SCR, x10

Micro-PPT
Pulser

Capacitor

PPT, x4
(Main Propulsion)

b) Propulsion Module

Schilling et al., J. Propulsion and Power, Fig. 3 of 3