

First Implementation of High Performance Green Propulsion in a Constellation of Small Satellites

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ABSTRACT

Skybox recently became the first commercial company to baseline ECAPS' High Performance Green Propulsion (HPGP) technology, implementing a propulsion system design with four 1N thrusters in their second generation small satellite platform (< 150 kg). The initial propulsion module, to be delivered in 2013, will serve to qualify the system design for use in an entire constellation of small satellites intended to provide customers easy access to reliable and frequent high-resolution images of the Earth.

Selection of the ECAPS HPGP system resulted from a system study of various propulsion options in support of Skybox's mission to provide high quality and timely earth observation data from a small satellite constellation. Two key technical requirements for the propulsion system were to provide the maximum delta-v achievable (for continued orbit maintenance and mission flexibility) within a considerably limited internal volume typical of many Small-Sats. Additionally, in light of the commercial nature of the project, the overall life-cycle cost was considered to be of utmost importance. A detailed trade study of various propulsion technologies and vendors was conducted by Skybox during the selection process. The results of that study showed that the HPGP solution selected provides nearly twice the on-orbit delta-v of the more traditional monopropellant systems, at the lowest projected life-cycle cost of the liquid propulsion technologies evaluated. The higher performance of the HPGP system will give Skybox's constellation of small satellites significantly improved mission flexibility, enabling collection and delivery of higher quality and more timely data to customers. Furthermore, the handling and transportation advantages of the environmentally benign Ammonium Dinitramide (ADN)-based LMP-103S monopropellant provide reductions in logistics costs and enable more responsive launch preparation.

This paper will present an overview of the driving propulsion performance requirements for small Earth Observation satellites such as Skybox's and discuss how the HPGP technology was selected for Skybox's imaging constellation.

I. INTRODUCTION

Skybox Imaging and ECAPS have partnered to implement ECAPS' High Performance Green Propulsion (HPGP) technology on future Skybox spacecraft, the first commercial use of a "green" monopropellant system. HPGP's high performance and low life-cycle cost are uniquely enabling in Skybox Imaging's deployment of their constellation of high resolution imaging satellites.

Skybox Imaging Overview

Skybox Imaging ("Skybox") provides global customers easy access to reliable and frequent high-resolution images of the earth through its microsatellites and cloud services. By designing, building and operating a coordinated imaging satellite constellation, Skybox aims to empower commercial and government customers to make more informed, data-driven decisions that will improve the profitability of companies and the welfare of societies around the world. Founded in Silicon Valley in 2009, Skybox is

backed by leading venture firms and comprised of internet and aerospace professionals.

ECAPS Overview

ECAPS is a world leader in the area of increased performance, reduced risk and environmentally benign (“green”) storable monopropellants. ECAPS’ High Performance Green Propulsion (HPGP) technology includes a family of Ammonium DiNitramide (ADN) based propellants, rocket engines and associated propulsion systems. HPGP technology development activities started in 1995 at SSC (formerly the Swedish Space Corporation) and were later transferred to ECAPS in 2000, when the company was established as a separate entity.

ECAPS is certified as conforming to SS-EN ISO 9001:2008 with respect to the development and manufacturing of rocket engines and propulsion systems for satellites. The propulsion team at ECAPS has extensive experience in the design, manufacture and testing of green monopropellants, thrusters, systems and related Ground Support Equipment (GSE) for space applications. ECAPS personnel have successfully delivered flight propulsion systems for a number of high-profile satellite projects, including:

- Design, procurement and testing of the SMART-1 hydrazine propulsion system including GSE
- Development of the storable, low hazardous, low toxic, HPGP liquid monopropellant (LMP-103S), space-qualified for the PRISMA mission
- Development of a 1N HPGP thruster, space-qualified for the PRISMA mission
- Development of the PRISMA HPGP system
- Design, manufacturing and testing of the PRISMA HPGP GSE and fueling cart
- Design, procurement and testing of the PRISMA hydrazine propulsion system

ECAPS’ technology development and hardware manufacturing facilities are located in Solna (a suburb of Stockholm), Sweden. The propellant LMP-103S is manufactured at EURENCO Bofors in Karlskoga, Sweden, and ECAPS’ hot-firing test facility (for thrusters ranging from 1N to 220N) is located at the Swedish Defense Research Agency (FOI) premises in Tumba, Sweden.

II. FROM SECONDARY PAYLOADS TO A CONSTELLATION

In order to get to market on a startup budget, Skybox has taken the lean startup Minimum Viable Product (MVP) approach and applied it to the design of our first two spacecraft, SkySat-1 and SkySat-2. The MVP philosophy involves a careful balancing act between

simplicity in implementation and making something capable enough that it is, in fact, viable in the market. For SkySat-1 and 2, this led the team to a design that packs an incredible Earth Observation (EO) platform in a very small ESPA-class payload volume that can be launched cheaply as a secondary payload. And while these spacecraft will serve Skybox well in proving the commercial viability of the Small-sat EO approach, the Skybox satellite team is already busy evolving the design to support the needs of the world’s first coordinated constellation of high-resolution EO satellites.

One of the critical requirements identified in the evolution towards a constellation was the need for a capable propulsion system. Adding propulsion to future SkySats enables the following capabilities:

- Constellation relative phase management – The compact size of the SkySat platform enables enormous cost savings by utilizing a single launch vehicle to launch multiple spacecraft. However, once on orbit, propulsion will be required to phase the spacecraft within each orbit plane and maintain their relative spacing in the face of orbital perturbations.
- Mission flexibility to better serve the EO market – The commercial EO market is relatively new and evolving. High performance propulsion will enable Skybox to meet market demands for increased resolution, collect volume or spacecraft lifetime by adjusting the spacecraft’s orbits.
- Launch vehicle diversity – High performance propulsion will enable Skybox to take advantage of a wide range of future secondary launch options as they become available, while maintaining tight coordination of one-off launches with the rest of the constellation.

III. SMALL-SAT PROPULSION TRADE SPACE

The propulsion options available for small spacecraft is quite large and growing, as new technologies are developed and technologies matured on larger spacecraft platforms are scaled down. In choosing a propulsion architecture for future spacecraft, Skybox executed a wide-ranging trade study of the available technologies before selecting the ECAPS HPGP system. While the results of the study were evaluated with Skybox’s mission specifically in mind, much of the results are widely applicable to many potential Small-Sat systems.

Technologies

In-space propulsion technologies can be grouped in several ways. For this study, Skybox chose to group technologies into “cold-gas”, “chemical” or “electrical”

categories, because these categories divide the performance / cost / scalability spaces fairly effectively. A brief description of each category is given below, followed by a comparison of the three categories in a Small-Sat application.

Cold Gas

Cold gas propulsion systems generate thrust by adiabatically expanding a gas through a classic convergent-divergent (or de Laval) nozzle. The energy used to accelerate gasses is generally stored in the mechanical internal energy of the propellant gas (pV energy) stored at high pressure. Variants such as liquefied cold gas and warm gas systems were also included in this category because they are largely similar to cold gas from a system complexity, cost and performance perspective. Liquefied cold gas systems store the propellant as a saturated liquid / vapor mixture which is often denser than a compressed gas. Warm gas systems add thermal energy to the propellant (generally with electric heaters) in order to improve specific impulse, I_{sp} (impulse per unit propellant mass).

The specific impulse of a cold gas, warm gas or liquefied cold gas system is generally very low due to the low specific energy content in a pressurized gas. Lower molecular weight propellants (such as helium) give higher specific impulse performance but, because gas density is (to first order) directly related to molecular weight, have very low effective mass propellant mass fractions. As Figure 1 shows, cold gas system performance will often optimize in the mid-molecular weight propellants, but is generally quite flat past the very low molecular weight gasses.

Specific impulse of cold gas systems can generally be expected to be in the 20-80s range, with system ΔV s of < 50 m/s for most Small-Sat applications. It is considered a low performance option that can be used for modest attitude control and orbit maintenance activities. Cold gas systems are generally on the inexpensive side of the spectrum and can be built with off-the-shelf components if spacecraft lifetime is limited (due to leakage).

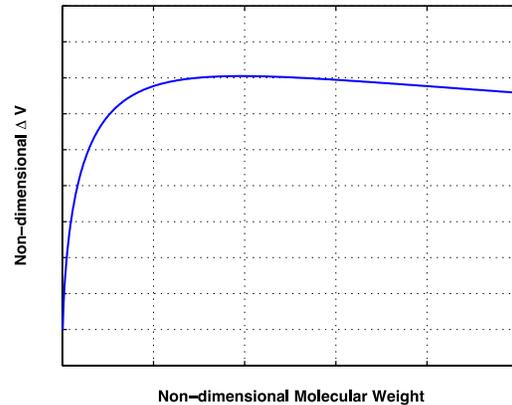


Figure 1. Non-dimensional scaling of system ΔV with propellant molecular weight - due to density's dependence on molecular weight, lower molecular weight propellants are often worse despite their I_{sp} advantage

Chemical

Chemical propulsion systems include monopropellant and bipropellant systems and, like cold-gas systems, generate thrust through thermodynamic expansion of the working propellant through a nozzle. However, chemical propulsion systems also convert stored chemical energy within the propellants into thermal energy prior to expulsion, generating much higher I_{sp} than is achievable in cold gas systems. In addition, most chemical propellants are liquid at ambient temperatures, resulting in far higher propellant densities and therefore propellant mass fractions. Monopropellants generally have I_{sp} values in the 100-220s range, while bipropellants may have I_{sp} values as high as 310s for storable and 450s for cryogenic propellants.

Monopropellants are generally simpler (and therefore cheaper) than bipropellants from a system complexity standpoint because there is only one working propellant and thus only one set of tanks, plumbing, valves, sensors, etc. Bipropellant thrusters also tend to operate at very high temperatures, making combustion chamber design difficult and requiring exotic materials. However, most monopropellants require a catalyst to initiate chemical decomposition which can be costly (due to use of rare earth metals) and fragile.

As will be shown, monopropellants can deliver ΔV s in the 50-200 m/s range for a reasonable 100kg-class small satellite and bipropellants do not offer a significant advantage in ΔV due to their increased overhead and structural mass.

Electric

Electric propulsion systems generally¹ operate in a fundamentally different way than the thermal gas-dynamic cold gas and chemical propulsion systems in that the working propellant is accelerated with an electrically induced force (electrostatic or electromagnetic). Because the energy source is separated from the propellant being accelerated, very high exhaust velocities and, hence I_{sp} (and ΔV s), are achievable. Hall-effect thrusters and ion engines are both forms of electrostatic electric propulsion and can reach I_{sp} values into the 10,000+s range. There are a wide variety of other technologies that fall into the category of electric propulsion including Pulsed-Plasma Thrusters, Magneto-Plasmdynamic (MPD), VASIMR, arcjet, resistojet and many more.

Hall effect thrusters are arguably the most successful to date and their high performance has led to their increasing use on GEO spacecraft for orbit maintenance where propellant capacity is often a life limiter. However, thrust tends to be significantly smaller than gas-dynamic propulsion systems and electrical power availability can severely limit the practicality of electric propulsion systems on small satellite platforms with relatively short lifetimes, as can be seen in Figure 2 below.

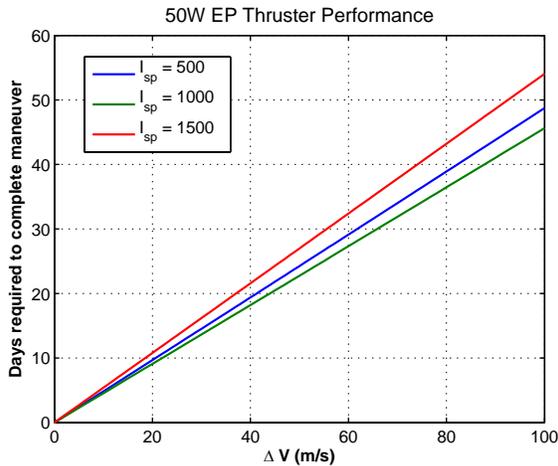


Figure 2. Firing time vs. ΔV for a 50W Hall effect thruster. Note that the y-axis is in days and that operating the thruster in this system at a lower I_{sp} (1000s) gives reduced burn times

¹ The word “generally” is used because arc-jets and resisto-jets (warm gas systems) are sometimes considered electric propulsion even though they convert thermal energy to kinetic gas-dynamically like cold-gas and chemical propulsion. The energy source *is* however separated from the propellant, like most other electric propulsion systems, so in some sense they are a bit of a hybrid.

IV. SMALL-SAT PROPULSION TRADE STUDY

A trade study of propulsion technology for a hypothetical sun-synchronous Small-Sat Earth Observation (EO) constellation mission is presented here as an example. The spacecraft is compliant with the ESPA-class (61cm x 71cm x 97cm) secondary launch envelope with a mass limit of 150kg. Design mission lifetime is 5 years at an altitude of 450km. The propulsion system is allocated an internal volume of 10% of the overall spacecraft (0.04 m³). There are three categories by which the various propulsion technologies are compared: performance, cost and maturity (or risk). Choosing the best solution for a given mission involves trading these against each other in the context of the mission-specific requirements.

Performance Requirements

A ΔV budget [Ref 1] for the mission is shown in Table 1 below:

Table 1. Mission Delta-V Budget

Component	Delta-V	Notes
Orbit phasing	10 m/s	
Drag Makeup	70 m/s	Solar F10.7 = 130
Phase Maintenance	5 m/s	
Subtotal :	85 m/s	
Margin :	15%	
Total :	98 m/s	

The mission requirement for ΔV is thus 98 m/s.

System Performance

A simplified parametric model was built to estimate the system ΔV performance of the five potential propulsion technologies considered: N₂ cold gas, hydrazine monopropellant, HPGP monopropellant, a Xenon Hall effect thruster and bipropellant nitrogen tetroxide (NTO) / hydrazine (N₂H₄). The following constraints were imposed on all systems:

- Must fit within a 0.04 m³ volume
- Power consumption
 - While Operating: < 80W
 - Idle (Survival): < 15W

Additionally, a qualitative complexity metric and logistical cost metric (from 1-5, with 1 being lowest and 5 being highest) was assigned to each technology in order to quantify cost.

Table 2 shows the key results from the trade study. As can be seen, cold gas is not even in the running from a performance perspective. Bipropellant meets the performance requirements, but the complexity, cost and difficulty of handling a second nasty propellant (nitrogen tetroxide) make it an unreasonable solution

Table 2. System Performance Analysis Assumptions

	N ₂ Cold Gas	Hydrazine	HPGP	Xenon Hall thruster [2]	NTO / N ₂ H ₄
Dry Mass	18 kg	14.2 kg	14.2 kg	20 kg	18 kg
Propellant Density	0.39 g/cc (330 bar)	1.02 g/cc	1.24 g/cc (20 °C)	1.46 g/cc (65 bar)	1.4 and 1.02 g/cc
Usable Propellant Volume	9000 cc	6500 cc	6500 cc	2500 cc	5400 cc
Propellant Mass	3.5 kg	6.7 kg	8.5 kg	3.65 kg	6.5 kg
Beginning of Life <i>I_{sp}</i>	74 s	218 s	230 s	1000 s	310 s [3]
Thrust	4 N	4 N	4 N	5 mN	40 N
Active Power	< 20W	< 20W	< 40W	80-320W	< 30W
Complexity Rating	2	3	3	4	4
Logistics Cost Rating	2	4	2	2	5
Delta V	18 m/s	94 m/s	122 m/s	280 m/s	137 m/s

for most Small-Sat missions. Looking only at ΔV , the Hall effect thruster looks very good on paper. However, the smallest commercially available hall thruster uses 80W power minimum and only produces 5mN thrust at that power level. For an EPSA class spacecraft, 80W is likely the majority of the bus’ orbit-average power and because the thrust is so low, any reasonable maneuvers will require very long burn times. Practically, this means that the thruster would likely use most or all of the spacecraft available power for long portions of the mission which is a significant operational deficiency. This leaves only the monopropellant systems (hydrazine and HPGP). While hydrazine doesn’t quite meet the performance objective using the parametric model, one could argue that it is still close enough for consideration.

V. HPGP VS. HYDRAZINE FOR SMALL-SATS

A spacecraft designer faced with the mission performance objectives outlined above would traditionally select a hydrazine monopropellant system, and indeed Skybox initially considered this approach as well. However, there are significant hazards (and thus cost) associated with hydrazine and its performance is “good” – but not great.

The need for improving the state-of-the-art of monopropellant technology was recognized at SSC in 1995 as a result of a study involving several national space research proposals. The objective was to develop a storable liquid rocket propellant for space applications which was significantly simpler and safer to handle; while also providing equal or higher performance than conventional propellants. The design goals were to

develop a new propulsion technology, which compared to hydrazine provides:

- Increased performance
- Simplified and safer handling and transportation characteristics
- Lower overall mission cost

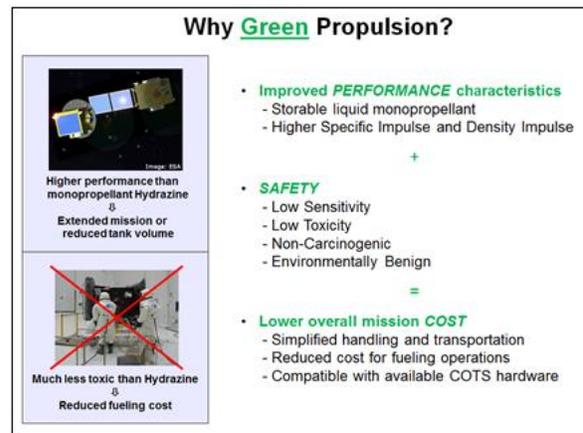


Figure 3. Benefits of HPGP to small satellite missions

The objectives pursued during the development of HPGP technology are summarized below:

1. Impose low personnel risk (low toxicity, non-carcinogenic, low sensitivity)
2. Simpler to handle, transport and store (no SCAPE required, wide storage temperature range, moderate vapor pressure, no pressure build-up, insensitive to air and water vapor as compared to other state-of-the-art liquid monopropellants)
3. Propellant, production, combustion exhaust and waste products to be environmentally benign
4. Equal or better performance (I_{sp} and density impulse; response times) as compared to hydrazine

5. Comparable operational life compared to hydrazine
6. Compatible with COTS propulsion system components
7. Minimum impact on the spacecraft or launch vehicle operations or architecture
8. Lower total mission (life-cycle) cost

By providing the features identified in Table 3, HPGP serves as an enabling technology for the replacement of hydrazine in most monopropellant space propulsion applications and is especially well suited to volume- and mass-constrained Small-Sats. The ADN-based monopropellant blend designated LMP-103S fills the performance gap between classical mono- and bipropellant space propulsion systems, due to its higher performance (I_{sp}) and higher density in comparison with hydrazine. Moreover, there are no Substances of Very High Concern (SVHCs) in the liquid propellant developed by ECAPS; hence it is fully compliant with the European REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) legislation.

Performance

HPGP has been successfully demonstrated on-orbit (on the PRISMA mission) since 2010, and shown to provide a 32% mission average performance increase over monopropellant hydrazine [4-5]. The PRISMA back-to-back in-space comparison to hydrazine demonstrates the higher performance of HPGP in most thruster firing cases, as detailed in Table 4. Overall, the HPGP system has provided an average I_{sp} increase of 8% over the hydrazine system on the PRISMA mission. The in-space comparison has been performed with the same type of sensors and according to the same process, as well as at comparable thrust levels.

Table 3. Comparison of hydrazine and HPGP characteristics

Comparison Parameter	Hydrazine	HPGP (LMP-103S)
Specific Impulse	Reference	≥ 6% higher than hydrazine
Density	Reference	24% higher than hydrazine
Stability	Unstable (reactivity)	Stable > 20 yrs (STANAG 4582)
Toxicity	Highly Toxic	Low Toxicity (due to methanol & ammonia)
Carcinogenic	Yes	No
Corrosive	Yes	No
Flammable Vapors	Yes	No
Environmental Hazard	Yes	No
Sensitive to Air & Humidity	Yes	No
SCAPE Required for Handling	Yes	No
Storable	Yes	Yes (> 7.5 yrs, end-to-end test is ongoing)
Freezing Point	1°C	-90°C (-7°C saturation)
Boiling Point	114°C	120°C
Qualified Operating Temp Range	10°C to 50°C	10°C to 50°C (allows use of COTS hydrazine components)
Operating Temp Range Capability	10°C to 50°C	-5°C to 60°C
Typical Blow-Down Ratio	4:1	4:1
Exhaust Gases	Ammonia, nitrogen, hydrogen	H ₂ O (50%), N ₂ (23%), H ₂ (16%), CO (6%), CO ₂ (5%)
Radiation Tolerance	Reference	Insensitive up to 100 kRad (Cobalt 60)
Shipping	Class 8 / UN2029 (Forbidden on commercial aircraft)	UN / DOT 1.4S (Permitted on commercial passenger aircraft)

Table 4. HPGP performance vs. hydrazine on PRISMA

Specific Impulse and Density Impulse Comparison		
Steady-State Firing: I_{sp} for last 10 s of 60 s firings	6-12 % 30-39 %	Higher I_{sp} than hydrazine Higher Density Impulse than hydrazine
Single Pulse Firing: T_{on} : 50 ms – 60 s First half of the mission	10-20 % 36-49 %	Higher I_{sp} than hydrazine Higher Density Impulse than hydrazine
Pulse Mode Firing: T_{on} : 50 ms – 30 s Duty Factor: 0.1 – 97%	0-12 % 24-39 %	Higher I_{sp} than hydrazine Higher Density Impulse than hydrazine

Small-Sat missions are able to benefit from HPGP's improved density impulse over hydrazine through two different approaches. First, replacing a pre-existing hydrazine system with a HPGP system of the same size can extend the mission life significantly. From a performance perspective, a HPGP system can provide an effective increase in overall ΔV of approximately 30% as compared to hydrazine; thus allowing for an increased mission lifetime if an equivalent tank size is employed as would have been used for a hydrazine-based design. Alternatively, HPGP can provide an equivalent mission ΔV with a smaller propellant tank size, as compared to a hydrazine-based design.

Packaging

Squeezing liquid propulsion systems into Small-Sat platforms can present a significant challenge, even for the "larger" ESPA-class missions. Just as a rough example, assuming that a maximum of ~20% of the internal spacecraft volume is able to be allocated to the propulsion system will still result in a total of only ~0.07 m³ being available on the largest possible ESPA-class satellite. In light of the difficulty of packaging any complete liquid propulsion system within such a limited volume, it's easy to understand why the increased performance provided by HPGP technology is such an important enabling factor with respect to meeting the unique requirements of Small-Sat missions. In addition to allowing for the implementation of smaller tanks without sacrificing ΔV , the demonstrated performance improvements of HPGP over hydrazine (Table 4) provide for additional, corollary mission performance increases – beyond I_{sp} and density impulse – in the form of propellant tank volume reductions, and the associated mass savings. Furthermore, beyond the direct benefit of a smaller and less expensive spacecraft, the indirect benefit of an overall reduction in the total mass at launch can also provide additional launch vehicle related cost savings to a Small-Sat mission.

Safety / Flexibility / Launch

The environmentally benign nature of HPGP enables greatly simplified transportation and handling procedures as compared to hydrazine. With significantly reduced requirements for both facility safety measures and personnel protective equipment, operations with HPGP result in reduced preparation time and costs for all pre-launch activities. Such simplified ground operations are particularly attractive to help reduce the costs of Small-Sat missions.

LMP-103S, in its 5 liter transport configuration, has received a transport classification of UN and DOT 1.4S, enabling it to be transported on commercial passenger

aircraft. This allows for the propellant to be shipped together with the satellite (as shown in Figure 4) rather than separately, further reducing the launch campaign related costs. Transport on commercial flights has already been demonstrated within Europe, to the U.S. and to Japan.



Figure 4. Shipment of HPGP propellant to the launch site together with the PRISMA satellites

Additionally, unlike hydrazine (which requires a rigorous regime of safety procedures), HPGP handling does not require any specialized safety equipment (such as SCAPE suits) or facility-related precautions (such as explosion-proof electrical outlets and air scrubbers). This is due to the fact that HPGP has very low toxicity, is extremely stable (insensitive to mechanical shock, air and humidity) and non-flammable. As a result, satellite processing could occur in almost any cleanroom-type facility, rather than in a dedicated (and more expensive) fueling hall.

Finally, during fueling activities at the launch site, the "non-hazardous" nature of HPGP operations allow for shorter launch campaigns – due to reduced processing timelines for individual satellites and the possibility to execute parallel/concurrent payload processing activities for multiple satellites simultaneously. As a result, "non-hazardous" HPGP fueling operations do not adversely impact the processing timelines of other co-manifested satellites. Furthermore, the safe and insensitive characteristics of the HPGP propellant pose significantly less risk (both physical and schedule) to a primary satellite; thus enabling propulsion systems to be included on secondary payloads where they have often previously been forbidden.

Life-Cycle Costs

HPGP's ease of handling provides opportunities for significantly simplified operations, and associated cost savings. Although it is difficult to quantify the exact level of cost savings that any specific mission would be able to realize (due to differences in flight hardware, propellant volumes, launch sites, etc.) without

performing a mission-specific analysis, the following paragraphs provide both a top-level description of the potential savings able to be achieved for common Small-Sat mission configurations, and a specific SkySat-related example.

It is important to keep in mind that although the hardware/commodity related costs for a HPGP system can be somewhat higher than those for a similar hydrazine system, the *life-cycle costs* of the HPGP solution typically provide significant savings over a hydrazine solution – due to reduced costs associated with propellant transportation, handling and fueling operations, and both pre-fueling preparations and post-fueling decontamination activities.

Simplified transportation and launch site processing translate to significantly reduced life-cycle costs [6-8] – which is always of paramount importance to Small-Sat missions. Additionally, the ability for fueling operations to be performed as “non-hazardous operations” (without SCAPE, and on a non-interference basis with a primary and/or other secondary satellites) is also an important selection criterion for many Small-Sat missions. As previously mentioned, the HPGP propellant was shipped to the launch site by air along with the PRISMA satellites and all fueling activities were declared to be “non-hazardous operations” by the Range Safety authority. As a result of the simplified transport and handling, a greater than 2/3 cost savings was realized for the HPGP transportation and fueling activities as compared to the equivalent set of activities performed for the hydrazine system that was also flown on PRISMA. (i.e. – The hydrazine transportation and handling costs were 3x higher than for the equivalent HPGP activities.)

Using their life-cycle cost comparison methodology [Ref 8] (which considers all propulsion system hardware, the propellant and its transportation to the launch site, launch campaign fueling operations, and post-fueling waste disposal), ECAPS has estimated that for the SkySat-specific implementation \geq \$400K of savings can be achieved on the launch of a single SkySat satellite and an additional \geq \$800K of savings on each subsequent constellation launch of 6 satellites, as compared to implementing a similar propulsion system design based on hydrazine.

Table 5. ECAPS’ HPGP vs. hydrazine life-cycle cost comparison

\$ Saved by HPGP over Hydrazine (assuming identical tank costs)	
Single launch (1 spacecraft)	Constellation launch (6 spacecraft)
\geq \$400K	\geq \$800K

VI. SUMMARY

The selection of ECAPS’ HPGP propulsion technology for future Skybox Imaging satellite missions will provide unparalleled mission flexibility with drastically lower life-cycle cost than an equivalent hydrazine system. Skybox and ECAPS are excited to revolutionize in-space propulsion and Small-Sat constellation capabilities together.

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