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Micro High Energy Upper Stage

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ABSTRACT

Deep space capabilities – beyond Earth's orbit – are possible on existing small launch vehicles. As the CubeSat class and small satellite utility increases, an evaluation of the options to service significant science objectives in this class need to be assessed. Pegasus and Minotaur I are small launch vehicle systems that when coupled with the appropriately designed and sized upper stage provides affordable access to high energy trajectories for small satellites.

The Micro High Energy Upper Stage (MHEUS – pronounced "muse") is a small satellite launch vehicle system that provides high energy access to space for the small satellite community. Lessons learned from the Pegasus Interstellar Boundary Explorer (IBEX) mission, the Minotaur V Lunar Atmospheric and Dust Environment Explorer (LADEE) mission, as well as current Orbital work on advanced upper stages using ATK solid rocket motors provide the technical foundation for MHEUS.

This paper provides an overview of the technologies being integrated into the MHEUS, and systems that have been adapted for use.

Figure 1: MHEUS on Pegasus

INTRODUCTION

CubeSats and other small satellites are becoming more and more capable. With the evolving capability of the smaller satellites it is necessary to have a compatible launch system to support the needs of the high energy small satellite mission.

The Micro High Energy Upper Stage (MHEUS) is an upper stage that when coupled with a flight proven launch vehicle such as Pegasus or Minotaur I, provides an affordable dedicated small satellite high energy launch option. The MHEUS and launch vehicle system has a Technology Readiness Level (TRL) of 9 – fully mature and currently utilized in the manner to which we plan on using it (based on the extensive flight pedigree of the Pegasus and Minotaur I launch vehicles and the STAR 27H upper stage).

TECHNOLOGY OVERVIEW

Core Assumptions

To meet the TRL requirement assumption, the MHEUS system will be put into low earth orbit by a mature flight proven space launch vehicle system (Pegasus or Minotaur I). The Pegasus launch vehicle performance capability is defined by its performance to a targeted parking orbit ranging from 150 to 200 km in altitude. Due to the unique nature of the Pegasus air launch platform any inclination could be targeted in support of the mission specific Declination of Launch Asymptote (DLA) requirement. A zero degree inclination using an equatorial launch location is the baseline for the Pegasus performance in this concept design.

The Minotaur I will use a higher parking orbit to take advantage of its greater performance capability.

To maximize performance, the total upper stage is minimized in mass -- a design goal that turned out to be one of the limiting features of the system.

Primary Propulsion

Once in the parking orbit, the primary propulsive energy source for the MHEUS is the Alliant Techsystems (ATK) STAR 27H solid rocket motor. This motor was used by the satellite in performing the Pegasus Interstellar Boundary Explorer (IBEX) mission for NASA in 2008. At 369 kg fully loaded, the STAR 27H represents the largest catalog common solid rocket motor that could be reasonably integrated onto Pegasus and still have capability to accommodate stage control systems and a payload. It had a good propellant to inert mass fraction and performance similar to other high performance solid motors. Offloading the motor was not considered due to the wish to maximize performance, but could be utilized for targeting or to accommodate higher mass payloads to less energetic orbits.

The IBEX mission itself was not to an escape orbit, but was to a highly elliptical orbit that provided the sensors the orbit required for the mission. The IBEX satellite exceeded the mass that the STAR 27H can accelerate to escape velocity.

Mass Limiters

The use of the STAR 27H also set a minimum mass for the total inert material (including payload) on MHEUS. In its current form, there is a design constraint of ~22G's on the motor. This can be improved through design alterations, but was considered high enough to be a design driver on other MHEUS systems, as well as the satellites. The CubeSat standard does not currently require the satellites to meet this level of sustained acceleration – this would be a design driver on very light payloads. The maximum acceleration combined with the STAR 27H thrust profile (as currently designed and flown) meant that the total inert mass could not be less than 106 kg. This will be the starting complete system burn-out weight (with payload but also with full trim/nutation control system tanks) and we will count down to zero. Assuming a 12U satellite mass of 24 kg (the current definition by Planetary Systems 12U CubeSat mass[1]) or similar multiple smaller CubeSat and dispenser masses, the rest of the system could not weigh less than *82 kg*. With the STAR 27H case weight of 27 kg[2], the rest of the MHEUS, including structure, trim/stability propulsion, separation systems, avionics, etc., could not weigh less than *55 kg*. These are the mass limiters – of minimum, not maximum mass. The mass goal was set. We did extend the total mass to energy curve with heavier payloads – knowing adding weight and the corresponding decrease in acceleration is never much of a challenge to a satellite system.

SYSTEMS OVERVIEW

Including the prime energy source, the STAR 27H motor, a trim kit to control dispersion, and energy to provide nutation control are needed. The MHEUS combines the nutation and trim systems into a single liquid system with three axially located thrusters for both nutation control and final dispersion adjustment. Pegasus and Minotaur currently use a similar, albeit much larger optional liquid upper stage called the Hydrazine Auxiliary Propulsion System, or HAPS.

To maximize performance, we assumed a spinning system. To despin the system, a scaled yo-weight from the Minotaur V fifth stage flown on LADEE is assumed.

Guidance and communications for the upper stage is based on Orbital's Modular Avionics Control Hardware (MACH) launch vehicle avionics set. The MACH avionics have been used on multiple Orbital launch systems including orbital and suborbital systems.

Structure is several scaled and optimized versions of the lattice structure that RUAG supplied to Orbital for the LADEE mission.

Trim/Dispersion Control

Using lessons learned from famous targeting failures in the past, when going to high energy orbits, the injection must be accurate, or one will miss the intended target. Accuracy includes both direction and velocity, which are closely related. While the STAR 27H has a flawless flight heritage, any solid rocket motor does have burn-out dispersions. Since the payload we are assuming is very small and may not be expected to carry adequate velocity reserves to handle the MHEUS inherent dispersions, MHEUS will have the responsibility for trimming out the STAR 27 dispersions, allowing any velocity capabilities the satellite has to be used for final course corrections and other post-injection functions.

Using an ATK/Orbital heritage formula for typical solid motor dispersions, the amount of final stage velocity that needs to be compensated for could be as high as 64 m/second (this is assuming lowest total inert mass/highest final stage velocity). On a mass-independent basis, this could have been in total stage energy rather than velocity as the velocity would decrease in significance with higher total system masses.

With 64 m/sec required, one interesting solution presented itself. The liquid system being baselined for the SkyBox satellite constellation, as presented in last year's Small Sat conference[3], and built by the E-CAPS organization, was sized nearly ideally to handle the 3-sigma dispersions, as well as have margin to trim out nutation from the spinning STAR 27H during powered flight. Of fortunate coincidence, the dry mass of the MHEUS system is very similar to the SkyBox satellite flight mass – the velocity capabilities of the system referred to in the reference could be used directly. It should be noted that nutation trimming may not be necessary, depending on the spin balance and mass property characteristics of the final stage. These could not be predicted at this stage of total system/payload maturity, so the nutation system was retained as a fortunate, but unsized inherent capability of the velocity trim system.

By placing three thrusters in aft-facing direction as is currently flown on the Pegasus/Minotaur I HAPS system, both nutation control and velocity trim will be obtained from the same system.

Added benefits of the E-CAPS system, using LMP-103S monopropellant, is that the propellant is environmentally friendly, has low toxicity, and has a higher Isp and energy density than standard monopropellant hydrazine. A version of this system has been flying on the Swedish PRISMA satellite for more than 3 years. Its toxicity and hazard rating of 1.4S, mean that it can be air-transported in passenger carriers – a strong benefit when your launch vehicle first stage is the manned Lockheed L-1011 aircraft used by Pegasus.

The off-the shelf mass used for the E-CAPS system on SkyBox was 8.5 kg of propellant and dry system weight of 14.2 kg, for total system weight of 23 kg. Mass remaining for minimum system mass for the structure, sep system, avionics, and spin control system is *32 kg*.

Spin Control

The MHEUS baselines spin stability during STAR 27H powered flight. The initial system spin-up is provided by the launch vehicle upper stage. Pegasus spun up the IBEX satellite/STAR 27H payload stack prior to ignition, and has also been used to provide much higher spin rates for spin stabilized satellites – providing a spin of nearly 120 RPM for the first Brazilian SCD satellite. Minotaur 1 upper stage similarities with Pegasus mean it has virtually the same payload spin capabilities. The maximum mass assumed for flight with the MHEUS with largest payload weighs much less than the IBEX/STAR 27H upper stage stack, guaranteeing the capability exists on both the Pegasus and Minotaur I rockets for spinning up the stack.

Despin is assumed to use a yo-weight, scaled off the yo-weight successfully used during the LADEE flight. The MHEUS/payload mass weight (designed for launch

from a Pegasus/Minotaur I) has much less rotational inertia than the STAR 37/LADEE payload stack (designed for launch off a Minotaur IV+/V), so the yo-weight mass was scaled down proportionally.

The 3.7 kg LADEE yo-weight system mass was cut by 70%. The mass of the combined LADEE satellite, stage assembly, and burn-out STAR 37 was more than 5 times the dry inert weight of the minimum mass MHEUS/satellite (burn out STAR 27H), however some parts of the de-spin system do not scale linearly. With a total mass of 1 kg, the total minimum mass left to ballast the STAR 27 thrust profile to allowable limits was *31 kg*.

Attitude Control

With the exception of despin/roll control through yo-weights, and pitch/yaw control through the three E-CAPS systems thrusters, there is no attitude control assumed on the stage. Velocity will be as accurate as the avionics guidance system coupled with the E-CAPS liquid system can provide, but payload pointing and separation dynamics are not implied, as is typical with CubeSat deployments. The satellite must accept launch vehicle random separation attitude dispersions and an uncontrolled separation, or the additional mass of a post-burnout attitude control system will need to be added as payload mass.

This elimination saves the weight of a post-burnout stability control system. MHEUS will insert the satellite into a specified direction, and at a specified speed, but any post injection tumble/roll residuals must be removed by the satellite.

The uncontrolled separation does not imply risk of collision between the satellite and MHEUS, though. Post-payload separation collision and contamination avoidance maneuver will be accomplished through differential thrusting of the E-CAPS system thrusters to remove the upper stage from payload vicinity and passivate the stage (even though the stage is in a trajectory beyond earth's orbit and not subject to the standard orbital debris guidance).

Guidance and Communication

A minimized set of Orbital's workhorse MACH hardware is baselined for MHEUS. Taking the LADEE hardware avionics set, and removing all hardware not needed for the additional features that LADEE required (stage spin-up, cold gas attitude/nutation control), and scaling down the required cabling for a much smaller stage, drove the total system avionics mass (including batteries) to 18 kg, which includes lithium ion batteries to power the MACH stack and payload separation, a navigation system for vehicle control and guidance

(such as is needed for a spin-stable system), control interface hardware for the E-CAPS trim/nutation system, a simple communication system for telemetry, and electrical switch gear for all of the above. The entire flight sequence will happen in low earth orbit – ground telemetry connection details (through TDRSS or a ground based system) would depend on the final trajectory assumed.

With an 18 kg total avionics system mass estimate, the minimum mass left to the structure, separation systems, and other flight hardware is *13 kg*.

Structure

There are two primary structures required for MHEUS. One is a simple cone and supports the entire STAR 27H MHEUS motor, payload and associated stage systems on the front of the launch vehicle. The second is a much more complex but smaller structure and supports the avionics, liquid trim/nutation systems, and payload off the front of the motor.

The first structure would remain with the launch vehicle. It would have a non-separating aft interface with the 98 cm bolted front flange of Pegasus/Minotaur avionics section. A separation system would be attached to the aft end of the STAR 27 motor and the forward end of this cone, with bare minimum mass remaining for carriage to final insertion orbit. An anisogrid composite lattice conical structure is baselined to minimize inert structure mass and maximize launch vehicle performance to parking orbit. One of these remarkable structures was built by RUAG for the LADEE mission, however was designed to support many times more mass than the combined MHEUS and payload would weigh. There would be an additional lateral load imparted by the Pegasus XL standard horizontal carriage and launch vehicle/carrier aircraft drop transient that LADEE did not have. This lateral load would not exist for Minotaur I launches. Taking these factors into account, scaling off the LADEE structure, the entire weight of the Stage ¾ payload cone for MHEUS and payload is less than 9 kg – less than the weight of a normal Pegasus/Minotaur 97 cm payload separation system. An additional 9 kg would be needed for the STAR 27/MHEUS support structure separation, 40% of which (4 kg) would stay with the upper stage.

This MHEUS support structure is not MHEUS mass and only applies to parking orbit mass that must be lifted by the launch vehicle. The forward end of the separation system would remain with MHEUS. At a 4 kg mass carried, *9 kg* remains available for the upper stage structure mass.

The second structure is similarly extremely small – mounting to the small upper payload support flange of the STAR 27H solid rocket motor, and supporting the liquid ECAPS system plumbing and propellant tanks, E-CAPS thrusters, the MACH avionics hardware suite, cabling, and payload. While much smaller than the base MHEUS support structure with less load carrying requirements, a 5 kg weight has been estimated – due to the increased number of hardware interfaces, the need for extended carriage of the offset E-CAPS system thrusters, etc. This leaves a total mass of *4 kg* for balance weights, the secondary structure/CubeSat separation device, and other hardware not accounted for elsewhere.

PERFORMANCE SUMMARY

The performance to C3 results for both the Pegasus and Minotaur I launch vehicles with MHEUS options are included in the following tables.

Pegasus

To summarize Pegasus performance using MHEUS, there is no attempt to specify and target any additional orbital requirements that are usually necessary for high energy targeting – DLA, RLA, etc. Pegasus launch flexibility allows movement of the launch point to optimize performance for mission specific orbit targeting. The initial parking orbit for the MHEUS ignition location was lowered when the total system mass exceeded Pegasus capability to circular orbit (lowered from 200 km to 150 km).

Table 1: Pegasus Performance

Payload Mass (kg)	C3 (km2/sec2)	Parking Orbit (km)	Max Acceleration (G's)
24	18	200	23
45	9	200	19
55	6	150	18
60	4	150	17

Minotaur I

The Minotaur I launch point is assumed to be LC-46 at Cape Canaveral Air Force Station in Florida. Using the greater lift capacity of the Minotaur I launch vehicle, additional upper stage options may be available for increasing performance, however for a direct comparison with the above high energy Pegasus performance numbers, the same MHEUS was assumed.

Table 2: Minotaur I Performance

Payload Mass (kg)	C3 (km2/sec2)	Parking Orbit (km)	Max Acceleration (G's)
20	24	690	23
30	19	660	22
40	15	628	20
50	11	595	19
60	8	555	18
70	4	525	17

Using the same assumptions as were used to create Table 2, Table 3 represents the results of non-parking orbit targeting – what we will call direct inject to final orbit, with its inherent shortcomings and advantages.

Table 3: Minotaur I Performance with Direct Satellite Injection

Payload Mass (kg)	C3 (km2/sec2)	Max Acceleration (G's)
20	33	23
30	27	22
40	22	20
50	17	19
60	13	18
70	9	17
80	5	16
90	2	15

TARGET

What can a CubeSat or small satellite do with this energy state? What of value can justify the cost of building and launching your hardware?

Near Earth Objects (NEO's)

Near Earth Objects, or NEO's are those objects that have the potential of hitting earth in the near future and have become the target of political note – leading Congress to instruct NASA to "plan, develop and implement a Near Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of NEO's equal or greater than 140 meters in diameter…."

While the MHEUS may provide the satellite the energy to get to the target, the deceleration energy, rendezvous energy, etc., would need to come from the satellite. NEO's are generally from .9 to 1.3 Astronomical Units (AU) to perihelion and aphelion and thus requiring rendezvous energies of less than 0 to less than 10 km^2/sec^2. Some definitions of NEO's

extend all the way to the asteroid belt, and would require rendezvous launch energies of 21 km^2/sec^2.

Asteroid Rendezvous Mission (ARM)

The Asteroid Rendezvous Mission (ARM) that has so much interest in NASA has looked at asteroids in the primary asteroid belt, which puts the rocks at 2 to 4 AU. Rendezvous energy for these objects ranges from 20 to over 60 km^2/sec^2. ARM is generally not specifically targeted as possible earth impactors, but for other scientific objectives.

Deep Space Targets

Things get interesting when you start talking other targets. The actual energy varies greatly based on when you launch, and the corresponding positions of all the players – earth, rendezvous/swing by planets, and the target. With all the options, the list is extremely long, however, to list just a few – Mars – from C3 of 9.8 to 16 km^2/sec^2 without any planetary swing-bys, depending if you want a quick or extended rendezvous. Titan can be reached with a C3 of just 11.5, however it takes a trajectory that loops around earth, then Venus, Earth, Venus, and Earth one more time before reaching Saturn (Titan), many years later. Enceladus, that newest of interesting moons? It's another Saturn trajectory.

SUMMARY

Small satellites can be put to Earth escape trajectories without resorting to ridesharing with a much larger launch vehicle to a potentially comprised orbit. The systems illustrated here exist, and all have flight heritage in direct or derivative forms.

What can you do with a small mass capability to a high energy state? It can be reached with systems available now, without resorting to sharing a ride on another vehicle and without complete system development overhead and risk.

CAVEATES

This stage is a preliminary engineering assessment based on scaled performance from past missions, engineering work done on much larger stages, systems flown, and public literature. Nothing contained within should be considered a promise or commitment of performance.

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References

1. Planetary Systems Corporation "2002367, Rev A", 6 August 2013.

2. "ATK Space Propulsion Products Catalog", September, 2012.

3. Jonny Dyer, Aaron Dinardy, Kjell Anflo, "First Implementation of High Performance Green Propulsion in a Constellation of Small Satellites," 27th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2013