Form 442, Technical Question 6 Response

Momentus X1 MET Mission Experimental Program - Spectrum Utilization Details

6a. *Description of Research Project*:

6a.1: *Introduction:*

6.a.1.i: *Applicant:* Astro Digital US, Inc. (Astro Digital) is a private U.S. satellite company headquartered in Santa Clara, California. We design, construct, and operate small satellites. The company is authorized by the FCC and NOAA to operate an Earth-imaging satellite system (Landmapper) and distribute images and many other data products derived from our imaging database, on a commercial basis.[1]

6a.1.ii: *Mission Summary:* The Momentus X1 microwave electrothermal thruster (MET) spacecraft mission is a commercial demonstration of a propulsion system to exhibit its applicability to small spacecraft. The mission is not a part of the Landmapper system, although information from the testing may support changes to that system in the future. The mission will demonstrate the reliability, longevity, performance, and utility of the microwave-based plasma propulsion system, which utilizes water as a propellant. A propulsion system suitable for 16U CubeSat vehicles or larger that is cost-effective enables more orbital maneuverability for a large class of space vehicles. Areas where this could be of benefit include orbital debris removal missions, collision avoidance, beyond-LEO missions, and smallsat deorbiting.

6a.2: *Satellite Physical and Orbital Characteristics:* The satellite is depicted in the following figure:

[1] *See* IBFS File SAT-LOA-20170508-00071 (granted in part and deferred in part, August 1, 2018).

Momentus X1 Satellite Platform

6a.2.i: *Dimensions and Mass:* The satellite is a rectangular solid shape with dimensions of 454 mm (Z) x 246.3 mm (X) x 246.3 mm (Y), which is approximately a 16U CubeSat vehicle. The satellite mass is 24 kg with fuel. Of this mass 23.85 kg is spacecraft inert mass and 150 grams is propellant (H_2O).

6a.2.ii: *Overview of Propulsion System:*

The Vigoride propulsion system is a microwave electrothermal-based system that uses water vapor as a propellant. In this style of propulsion, a plasma is formed from microwave energy imparted to a resonant cavity. Further microwave energy raises the temperature of the plasma, which transfers energy to the rest of the propellant. This heat is turned into thrust by a converging-diverging nozzle. The Vigoride propulsion system contains a diaphragm-based tank at low pressure and uses a pump feed system to raise the pressure of the system to the working pressure of the thruster. Flow is metered by solenoid valve control, and delivered to a vaporizer, which injects the water vapor into the chamber of the thruster. A voltage-controlled oscillator paired with a solid-state power amplifier provides the microwave power to the propulsion system. All electrically actuated components are governed by a thruster control unit providing logic and timing to the system. In general, the specific impulse and thrust characteristics of the system fall between a traditional chemical propulsion system and an electric propulsion system that operates using electrostatic or electromagnetic forces. The Vigoride propulsion system, based on available microwave power and mass flow rate, can provide between 280-500s of ISP and 3-20 mN of thrust.

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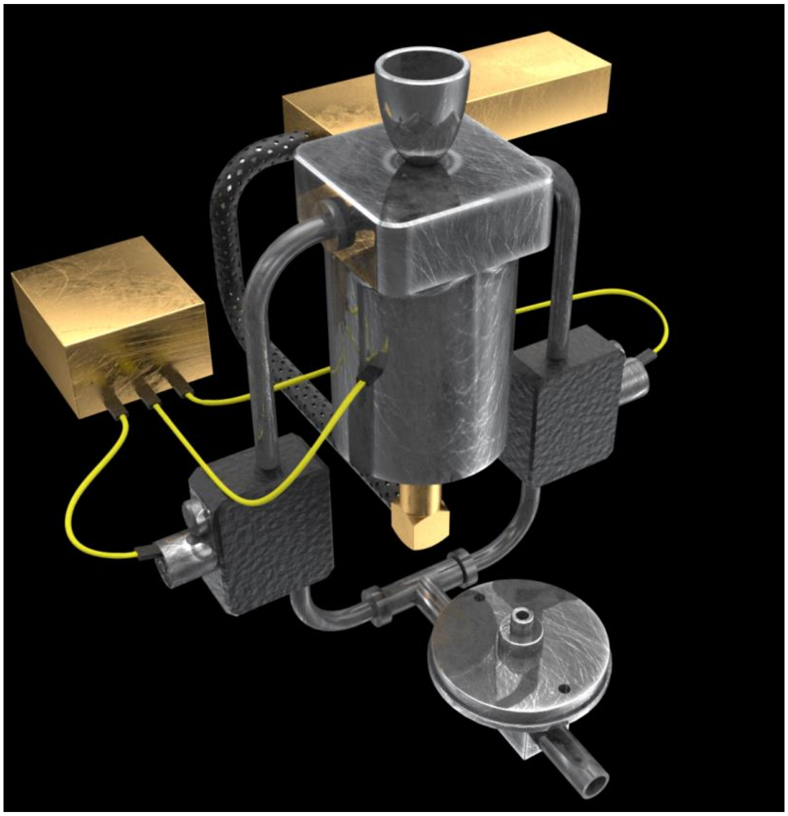

Momentus X1 Propulsion System

6a.2.iii: *Initial (Deployment) Orbit:* The injection orbit of the Momentus X1 Mission is anticipated to be as follows:

Orbit Altitude: 450 – 585 km Circular (585 km nominal)
Inclination: 98.00° ± 0.60°
Local Time of Ascending Node (LTAN): 15:05 (local time) nominal.

Momentus X1 will use a secondary payload launch opportunity. Thus, it is possible that the injection orbit parameters could be different, as we could be re-assigned to fly on the launch of a different primary satellite system. AD will advise the Commission should such an event occur. However, in no event will the injection orbit altitude exceed 585 km.

6a.2.iv: *Radio Frequency Characteristics of the MET Thruster:* Momentus X1 has an RF generator that generates an ISM-like signal at a power level of 45 watts (16.53 dBW). This generator uses a GaN solid-state device in order to efficiently produce this level of power output, which, in turn, is delivered via a specially shielded coax cable directly to the thruster injector. The emission frequency generated by the RF Power Module (RPM) can be adjusted over the frequency range 10.25 to 10.60 GHz. The frequency generator uses a crystal controlled reference oscillator with a frequency accuracy of 0.28 PPM and the synthesizer employed is adjustable over the output frequency range just given, with a resolution of better than 1 kHz. Prior measurements have confirmed that emissions radiating outside of the injector cavity are suppressed by in excess of 100 dB below the maximum generated power output of the RPM. EMI emission levels from the flight thruster payload will be measured in an anechoic facility in order to assure that radiated levels will not exceed an RF power level of greater than -50 dBm within the vicinity of the MET thruster (measurements at 1 meter from the propulsion system) and that all emissions are contained within a bandwidth of no greater than 5 MHz. We note that such a set of conditions would be anticipated to produce a PFD at the Earth's surface (at closest possible range to the satellite) of < -270 dBW/m^2/Hz. This frequency band is used on a primary basis by RADIOLOCATION, FIXED and MOBILE services and is used on a secondary basis by the Amateur Radio Service (in all three ITU Regions) according to the ITU Table of Frequency Allocations.[2] We believe that, at these emission levels from the MET thruster and within the band we have selected for operation, no emissions will be detectable by radar, mobile, fixed or amateur systems (and by a very large margin). We further note that all other emissions from our MET thruster (e.g., harmonics and sub-harmonics) will be attenuated by at least an additional 20 dB below the emission level given above.

6a.3: *Mission Operations:* AD plans to use the Momentus X1 spacecraft propulsion system in order to modify the orbital parameters of the initial spacecraft orbit. The total ΔV produced by the MET thruster is approximately 17 m/sec. The

[2] 47 CFR §2.106, page 48, Revised April 6, 2018.

total impulse of the thruster is estimated to be 370 N-sec. Mean I_{sp} of the thruster is expected to be 300 sec. The duration of the Momentus X1 demonstration mission is estimated to have a nominal duration of 9 months. The operation of the MET thruster will be carried out in multiple burns with each burn/orbit equal to approximately 10 minutes duration. We note, in particular, that the thruster will not be used to increase the apogee of the orbit without a prior reduction in perigee. In that regard the thruster's performance will never contribute to attaining an orbital lifetime greater than 22 years.

6a.3.i: *Planned Orbital Maneuvers:* The following maneuvers are currently planned using the Vigoride MET thruster:

1. Orbit Perigee Lowering by up to 25 km from nominal spacecraft separation values.
2. Orbit Apogee Raise by up to 30 km from nominal spacecraft separation values.
3. Inclination change of up to 0.13° from nominal 98° initial inclination

One or more of these options will be selected based on the assessed initial observed performance of the MET thruster. However, maneuver 2 above will not occur without first accomplishing maneuver 1. Following these maneuvers, the thruster will then be used to lower the orbit perigee by as much as possible with available propellant, and then relieve any residual pressurized consumables, and transition the spacecraft into an end of life mode.

6.a.3.ii: *Orbital Debris:* AD has provided a standard Orbit Debris Assessment Report (ODAR) which is attached with our Form 422 submission. We hereby summarize the findings of our ODAR document.

6a.4: *ODAR Submission:*

6a.4.i: *Human Casualty Risk:* Our debris analysis shows that, as our reentry is uncontrolled, we are compliant with ODAR Requirement 4.7-1 regarding human casualty risk using the "Atmospheric Reentry Option (a) as the probability of human casualty is less than 0.0001. DAS v2.0.2 has been used and reports that the Momentus X1 spacecraft is COMPLIANT with the requirement.

6a.4.ii: *Propulsion System Failure vs. Orbit Altitude:* The Momentus X1 propulsion system will only be used as stated above in Section 6a.3.i. Thus, if, during the operation of the thruster it should fail to produce further thrust, the orbital lifetime will not increase beyond the lifetime of the worst case expected orbit, which will be 560 km x 615 km (worst case). The orbital lifetime of our spacecraft, in accordance with our ODAR submission, is not greater than 22 years. AD has determined that if the satellite is dead on arrival at an injection orbit altitude of 585 km, it will have an orbital lifetime of less than 22 years.

6a.5: *Radio Frequency Characteristics*

6a.5.i: *TT&C Frequencies:* TLM and CMD data transmission from/to the spacecraft are proposed at the following frequencies:

Link Direction	Frequency Band (MHz)	Bandwidth Occupied (kHz)	Max. Data Rate (kbps)
Uplink (command) Downlink (telemetry)	402.88 – 402.92 400.48 – 400.52	40 40	38.4 38.4

The occupied bandwidth of the radio system is 40.0 kHz (at -3 dBc) and employs a very steep skirted bandpass filter to limit its output bandwidth. GFSK modulation is employed on the downlink.

The CMD uplink utilizes EESS spectrum (Earth-to-space) in accordance with ITU Table of Frequency Allocations - within the band 402.0 to 403.0 MHz. In this application we are using this link in the category of service, Space Operations. While we do not comply with US Footnote 384 (as we are not transmitting to a US Gov. spacecraft) we have been mindful of the utilization made by the NOAA GOES DCS system and have avoided the use of those uplink frequencies, as discussed below.

6a.5.ii: *Coordination Status of UHF Frequencies:* The government agency using the allocation between 402 and 403 MHz is NOAA. It is used for the GOES DCS system and by NOAA radiosondes operating in the *Meteorological Aids* category of service. Astro Digital has previously coordinated satellites with NOAA on precisely the same frequencies (under both Part 5 and Part 25 of the Commission's rules).[3] With this filing we will, once again, initiate coordination with NOAA regarding this additional experimental use of the same frequencies for Earth-to-space transmission. The conditions for use are essentially identical to our current operations within this band. And, as we expect to carry out and conclude the operations of this mission before December 2019 (nominal), we do not anticipate issues with this coordination process. We will, of course, keep the Commission apprised of our coordination efforts.

Regarding the TLM Downlink, we have recently coordinated with all the federal agencies regarding use of this frequency channel for the Astro Digital Landmapper system and anticipate no issues with coordinating use of this frequency for the Momentus X1 satellite.

[3] *See supra* note 1.

6a.5.iii: *Ground Station Location and Characteristics:*

There are two ground stations associated with the Momentus X1 mission these are situated in Santa Clara, California, USA and Littleton, Colorado USA. The specific locations are as given in our Form 442. However, for ease of review, these are repeated here:

- Santa Clara, CA Earth Station: Lat: 37.380000°, Long. -121.96111° Altitude: 32.8 ft (AMSL)

- Littleton, CO Earth Station: Lat: 39.573201°, Long: -105.133683°, Altitude: 5835 ft (AMSL)

As described in our Form 442, our emissions from this ground station are as follows:

- Command Transmitter Power Output: 50 watts
- Command Antenna Gain: 21.5 dBi
- Command System EIRP: 37.8 dBw

6b. *Specific Objectives of the Research Project*:

The research objectives of this project are:

a) To demonstrate that microwave electrothermal thrusters provide cost-effective high delta V capability to SmallSats via orbital maneuvering. This mission will show that this particular system is mature enough to be used by the small satellite market, and can be quickly and easily integrated with CubeSats as well as larger, more capable spacecraft. This provides an immediate low-cost mechanism for a wide range of space vehicles to integrate with a low risk profile.

b) To demonstrate that the thermal control design of this medium power thermal propulsion system has sufficient maturity and that the commercial components used in its design have been adequately tested and proven for flight. Thermal data taken for the duration of the mission will show that the system is well-isolated from the rest of the spacecraft, allowing the propulsion unit to be integrated with a range of buses without further thermal design consideration from a bus provider.

c) To show that the performance of this propulsion system is consistent across a performance window of several months; with total burn time of the system exceeding 50 hours and extreme thermal cycling, the choice of materials and mechanical / thermal design will be shown to adequately withstand a space environment. By demonstrating consistent performance, mission budgets for de-orbiting can be accurately predicted; spacecraft employing this propulsion system would be able to safely de-orbit.

While the maturity of the system can be demonstrated via performance tests, thermal tests, and other key environmental criteria, there is no substitute for running a space propulsion system in a space environment. Therefore, the utilization of a Part 5, Experimental License is appropriate and this project is in the public interest.

6c. *How will the program of experimentation demonstrate a reasonable promise of contributing to the development, expansion or utilization of the radio art, or is along a research line not already investigated?*

Astro Digital will use a state-of-the-art transmitter technology as part of the propulsion system. The MET uses water as a propellant and uses microwave energy in a band from 10.25 to 10.60 GHz to heat and then ionize the water - first as a vapor and then as a plasma. As discussed in Section 6a.2.iv, our design effectively will ensure that no RF energy reaches the Earth or is radiated by the system. While this system has been demonstrated in several university settings,[4] there has never been a space-based demonstration of this technology and water has never been proposed for an MET demonstration as a "safe" propellant.

This propulsion system is an ideal candidate technology for placement on small (or even large) spacecraft in order to be utilized to mitigate collisions with other space objects, to maintain accurate orbital characteristics and, most importantly, it can allow a controlled, timely and safe re-entry of a spacecraft upon mission completion. Given the Commission's Federal mandate to control the debris of non-Federal space stations and given the public interest in this matter, we believe our demonstration is in line with the goals and objectives of the Commission's experimental licensing program. Further, we note that because of the safe properties of water as a propellant we believe the reduced cost and risk of using MET technology is also very much in the public interest.

[4] M. M. Micci, S. G. Bilén, and D. E. Clemens, "History and current status of the microwave electrothermal thruster," in EUCASS Proceedings Series – Advances in AeroSpace Sciences (Array, ed.), vol. 1, pp. 425–438, 2009.