Plasma Spectroscopy CubeSat: A demonstration of on-orbit electric propulsion system diagnostics

Jennifer Hudson and Kristina Lemmer
Department of Mechanical and Aerospace Engineering, Western Michigan University
1903 West Michigan Ave., Kalamazoo, MI 49008

ABSTRACT

New sensing assets are needed to characterize and assess electric propulsion systems in the space environment. Recent research has shown that visible and near-infrared spectral measurements of electric propulsion plasma plume emissions can be used to determine electron temperature, density, and propellant type. From these measurements, analysts can assess thruster health and diagnose causes of anomalous behavior. Propellant signature detection can also be used to identify thruster type. Spectral measurements taken by ground-based instruments are limited by transmission losses through the atmosphere and by the viewing angles and availability of telescopes. A new CubeSat-based optical emission spectroscopy (OES) system is proposed to perform electric propulsion system diagnostics from a low-cost, space-based platform. The Plasma-Spectroscopy (P-Spec) CubeSat is currently in development for a first flight test. P-Spec's OES payload will collect inter-satellite spectral measurements of the plasma plume from a hollow cathode with xenon propellant over a range of distances up to 1 km. An overview of the spacecraft design and mission plan are presented, and the use of OES spectral measurements for thruster health diagnostics and Space Situational Awareness applications are discussed.

1. MOTIVATION

Electric propulsion (EP) systems, such as Hall thrusters and ion engines, have come into widespread use in recent years. These propulsion systems provide high specific impulse and long thruster lifetimes, which make them well-suited for station-keeping and maneuvering during long-duration missions. However, EP systems on operational satellites occasionally exhibit unexpected behaviors on orbit. Thruster performance and durability in space may be less than expected due to uncertainties in ground-based vacuum chamber testing. For example, Intelsat-33e recently experienced unexpectedly high fuel consumption by its arcjet thrusters used for north-south station-keeping [1]. There is significant ongoing research related to the effects of experimental facilities on the performance of Hall thrusters [2,3,4,5,6]. To accurately assess EP thruster performance, diagnostic measurements must be performed when the thruster is operating in the space environment.

Evaluating EP systems in space – and determining the cause of any anomalous behavior – is challenging. Diagnostic instruments may be placed onboard the spacecraft, but they must be located outside the plasma plume to avoid interfering with thruster efficiency. In the event of a thruster malfunction, most spacecraft are not equipped with these instruments. Ground-based observations are hindered by the presence of the atmosphere, and they are contingent on the locations and availability of telescopes during thrust events. Near-infrared (NIR) emission profiles travel better through the atmosphere than visible wavelengths; however, this limits the number of emission lines that can be studied to those between 800 and 1000 nm. Most inexpensive spectrometers (such as the Ocean Optics Flame-S) have lower light detection at NIR wavelengths than at visible wavelengths. Previous studies have concluded that NIR wavelengths transmission loss through the atmosphere ranges from 0.5 dB at the zenith to about 2.5 dB near the horizon [7].

The Plasma Spectroscopy (P-Spec) mission aims to demonstrate a new system for space-based plasma plume diagnostics using a low-cost, responsive, CubeSat platform. The P-Spec CubeSat is a technology demonstration satellite in development at Western Michigan University. P-Spec will demonstrate on-orbit optical emission spectroscopy (OES) of a plasma plume from a separate, co-orbiting satellite. An OES system with a charged coupled device (CCD) camera will measure an EP system's light emission as a function of wavelength at distances from 100 m to 1 km.

The P-Spec satellite is a 6U (30×20×10 cm) CubeSat, which will separate into two independent CubeSats – Plasma-Sat and Detector-Sat – after deployment in low Earth orbit. Plasma-Sat will house a xenon feed system, propellant tank, and hollow cathode, which will emit a plasma plume representative of an ion thruster. Detector-Sat will contain the optical emission spectrometer system to measure light emission from Plasma-Sat.

The P-Spec program has completed Preliminary Design Review and is preparing for Flight Selection Review in the Air Force Research Laboratory's University Nanosatellite Program. This paper provides an overview of the satellite design and mission plan. It also discusses the data products that are expected from this mission and how they can be used to identify plasma plume composition and assess thruster performance.

2. MISSION OVERVIEW

The first orbital flight test of the P-Spec satellite will be a demonstration of the OES sensor on a plasma plume that resembles an EP system. The mission goal is to demonstrate the sensor's ability to collect spectral measurements of a plasma discharge using a separate CubeSat platform. The 6U P-Spec spacecraft will be launched into low Earth orbit as secondary payload. It will undergo its initial mission phases, including detumbling and initial ground communications, in the 6U configuration. The OES system will collect ambient light samples to be used in post-processing the experimental data. Then, at the start of the experimental phase, the spacecraft will separate into the 2U Detector-Sat and the 4U Plasma-Sat. The OES sensor onboard Detector-Sat will collect spectral measurements of the plasma plume emitted by Plasma-Sat.

Initially, the two satellites will operate in close proximity, but they will drift apart due to the separation mechanism force, differences in drag properties, and the micro-thrust provided by Plasma-Sat's hollow cathode. The two satellites are expected to reach a relative separation distance of 1 km within 24 hours. Throughout this period, Detector-Sat will collect light emission data sets while employing active attitude control to maintain sensor pointing toward Plasma-Sat. After completion of the data collection phase, when Plasma-Sat's propellant is fully depleted, Detector-Sat will transmit all spectral measurement data to the ground station for post-processing and analysis of diagnostic results.

The long-term goal of the P-Spec program is to develop the 2U Detector-Sat as an independent diagnostic spacecraft. In this configuration, the spacecraft will be equipped with both the OES system and a micro-propulsion system to allow the diagnostic satellite to perform rendezvous maneuvers with client satellites. Several CubeSat-class propulsion systems are currently in development with sufficient ΔV capabilities for this type of maneuver, including small ion thrusters, small Hall thrusters, and electrospray devices [8].

The future P-Spec mission concept is illustrated in Fig. 1. If an operational satellite experiences an EP thruster anomaly on orbit, the P-Spec diagnostic CubeSat could be launched as a small, low-cost payload into a neighboring orbit and maneuver to within a safe operational distance of the client. The OES instrument will be able to collect spectral data on the client's plasma plume and relay this information to the ground. The CubeSat could then de-orbit using any remaining onboard propellant.

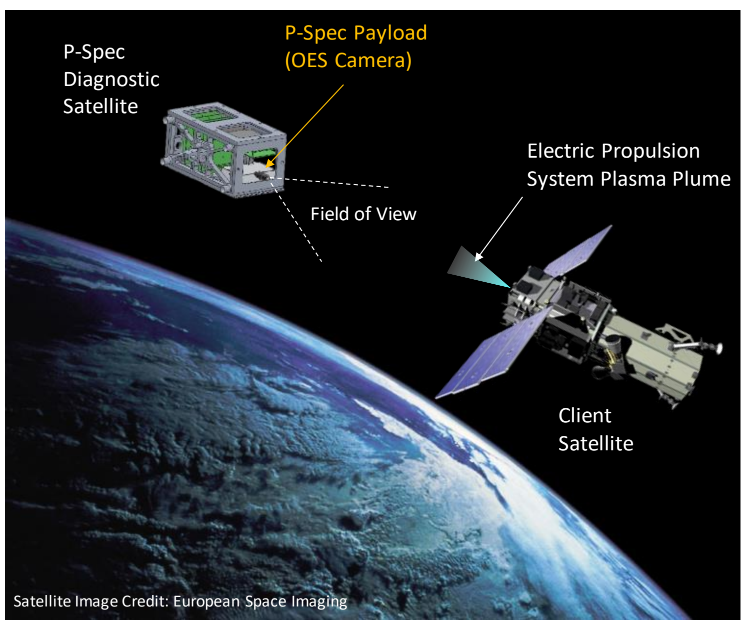

Figure 1. Plasma-Spectroscopy spacecraft operational concept

3. PLASMA-SAT PAYLOAD

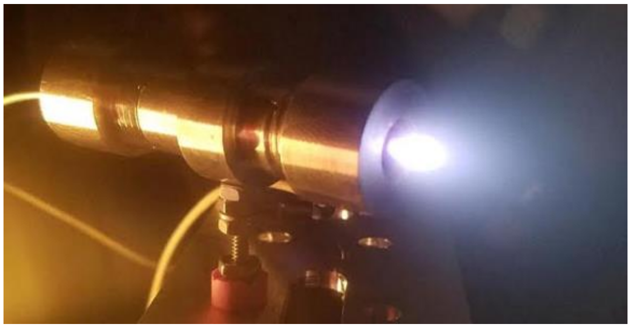

Figure 2. Cathode testing in ALPE vacuum chamber

For the first flight test, the Plasma-Sat payload will generate a plasma plume with light emission properties that resemble an EP system. A hollow cathode (Fig. 2) will generate the plasma. The cathode is a 5 W heaterless hollow cathode from Plasma Controls, LLC. It will be operated with xenon propellant. The cathode is undergoing experiments at Western Michigan University in the Aerospace Laboratory for Plasma Experiments (ALPE). Initial experiments show that xenon ions and excited neutrals at several energy levels prominent in Hall thrusters are detected in the plume from the Plasma Controls cathode using the OES instrument. The wavelengths include 460.3, 484.43, 823.16, 828.01, and 881.94 nm. Figure 3 shows the emission intensity versus wavelength curve from the cathode operating at 7 W.

The cathode must be started with a pulse of xenon flow and a high voltage (~600 V). Once started, the voltage and flow rate are reduced. To extract more plasma from the cathode, a magnetic nozzle or extraction grid may be implemented. The propellant feed system will consist of primary and secondary propellant storage tanks and micro solenoid valves to regulate line pressure and provide the pulse of propellant required for startup. The two-tank system maintains a relatively constant flow rate for the duration of the experiments in orbit.

To meet typical safety requirements for launch as a secondary payload, the propellant tank pressure is limited to 100 psi. The Plasma-Sat propellant tank has a volume of 150 cm^3, which will allow the hollow cathode to run continuously for up to 5 hours. This estimate does not include the fixed propellant volume that is needed to start the cathode; this is the subject of ongoing testing. Propellant capacity is the active constraint that limits the duration of the experimental phase. The hollow cathode is expected to produce a thrust of less than 10^{-6} N.

4. DETECTOR-SAT PAYLOAD

The OES payload onboard Detector-Sat consists of an Ocean Optics Flame-S spectrometer. It is capable of collecting light emissions with wavelengths in the range of 300-1000 nm with 1 nm resolution. A long-range collimating lens with a 25° field of view will be used to transfer light to the spectrometer. The wide field of view allows Detector-Sat to operate with relatively low attitude control requirements. The exposure time for each measurement will vary with the inverse-square of the separation distance between Detector-Sat and Plasma-Sat. It is

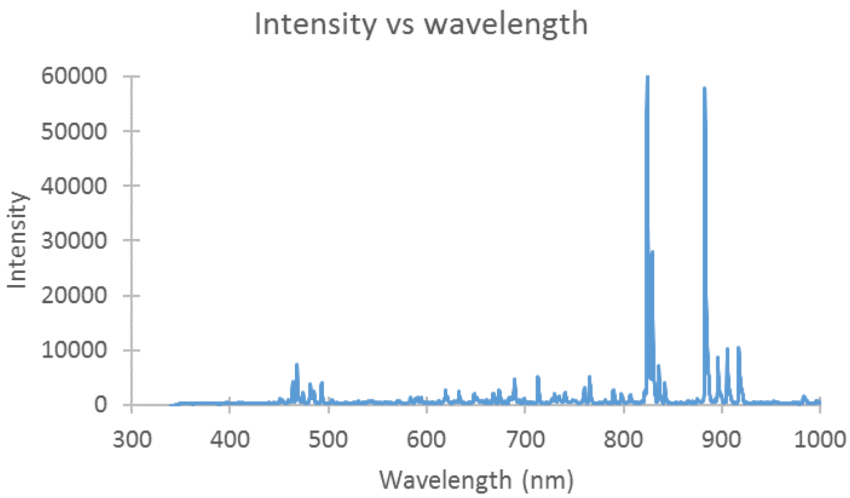

Figure 3. Xenon spectrum from Plasma Controls, LLC hollow cathode

not necessary for the measurements to maintain a constant intensity level; the OES must simply maintain the ability to measure light emission at xenon wavelengths without saturation of the CCD.

The OES system has not previously flown in space (although it is also under consideration for other CubeSat missions [9]). WMU is currently preparing the system for vacuum testing. Onboard components are being identified, and their vacuum compatibility is being determined. Components that are not rated for use in vacuum will be replaced or vacuum rated themselves. In addition, the Ocean Optics Flame-S spectrometer is under investigation to determine components that may require further structural support so the system can withstand vibration loads during launch.

5. KEY SPACECRAFT SUBSYSTEMS

5.1 Attitude Determination and Control

Due to the wide field of view of the OES instrument, the P-Spec 2U and 4U CubeSats have a high tolerance for attitude determination and control errors. Both Plasma-Sat and Detector-Sat will use the same sensor configuration for attitude determination, consisting of a gyroscope, GPS receiver, magnetometer, and Sun sensors. Detector-Sat will contain an attitude control system comprised of magnetic torque rods and one reaction wheel. This attitude control system will control the complete 6U P-Spec satellite during the initial detumbling and experimental preparation phases, and it will continue to control the 2U Detector-Sat with +/-5° pointing accuracy after separation.

Plasma-Sat will not contain any active attitude control hardware. After separation, it is expected to tumble with an angular velocity of approximately 6 deg/s. The cathode will be located off the center of mass of Plasma-Sat, as shown in Fig. 4, so that its thrust induces rotation of the spacecraft body. This will prevent Plasma-Sat from reaching a stable spin state with the cathode pointing away from Detector-Sat. As Plasma-Sat tumbles, the cathode is expected to be visible to Detector-Sat intermittently; the OES instrument on Detector-Sat will operate continuously to collect xenon spectral measurements whenever the pointing alignment is favorable. The OES system on Detector-Sat is able to measure light emissions when the pointing angle of the cathode onboard Plasma-Sat is within +/- 90° of the relative position vector.

5.2 Communication

Plasma-Sat and Detector-Sat will communicate in a parent-child configuration. Detector-Sat will communicate with both Plasma-Sat and the ground, while Plasma-Sat will only communicate with Detector-Sat. Two XBee SX Pro tranceivers will be used for inter-satellite communication; these can communicate at a range up to 100 km and a data rate of 110 kb/s at 1 W power. Detector-Sat will use the Astrodev Lithium-1 radio, which has flight heritage on several CubeSats, for ground communications.

5.3 Power

Plasma-Sat and Detector-Sat will each operate on individual, isolated power system for all mission phases. Solar panels will be located on all exposed spacecraft faces. 18650 lithium ion batteries will be used to store energy from the solar panels. Plasma-Sat will have negative power generation after the cathode is ignited. As described in Section 3, the bantam cathode payload on Plasma-Sat requires high voltage to start, but less than 1 W power for continuous operation.

5.4 Separation Mechanism

The P-Spec spacecraft will launch as a 6U CubeSat and then separate into a 4U and a 2U spacecraft at the start of the technology demonstration phase. The separation mechanism (Fig. 4) is composed of two plates and an ejector release mechanism (the TiNi Aerospace ERM E250), which will actuate the separation of Plasma-Sat and Detector-Sat with an initial separation velocity of approximately 8 cm/s.

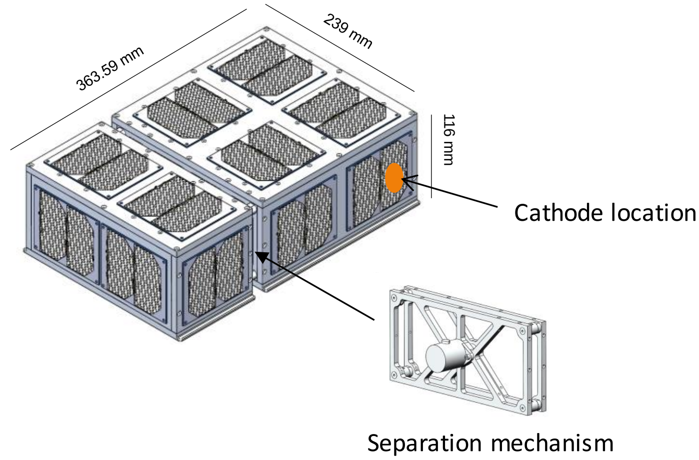

Figure 4. P-Spec spacecraft structure and separation mechanism

6. OES ANALYSIS OF PLASMA PROPERTIES

EP plasma emissions produce spectral signatures that are unique to the propellant used. Xenon propellant causes a plasma plume with peak light intensity at wavelengths of 460.3, 484.43, 823.16, 828.01, and 881.94 nm. Fig. 5 shows a comparison of the emission profiles from a Hall thruster (left, BHT-200) [10] and the Plasma Controls, LLC hollow cathode (right). Prominent xenon emission peaks for each spectrum are found at 823.16, 828.01, and 881.94 nm. Both spectra show the same peaks, indicating the plume from the cathode is representative of that from a xenon Hall thruster.

Hall thrusters have also been operated on Krypton with prominent peaks at 758.74, 826.32, 829.81, and 877.67 nm and the 810.44/811.29 nm doublet [7,11]. Spectral measurements taken by Detector-Sat's OES instrument on future missions would allow analysts to distinguish between xenon and Krypton propellants in Space Situational Awareness applications. Research is also being performed on other types of EP propellants that could be identified by their optical emission signature, including iodine, bismuth, zinc, and magnesium.

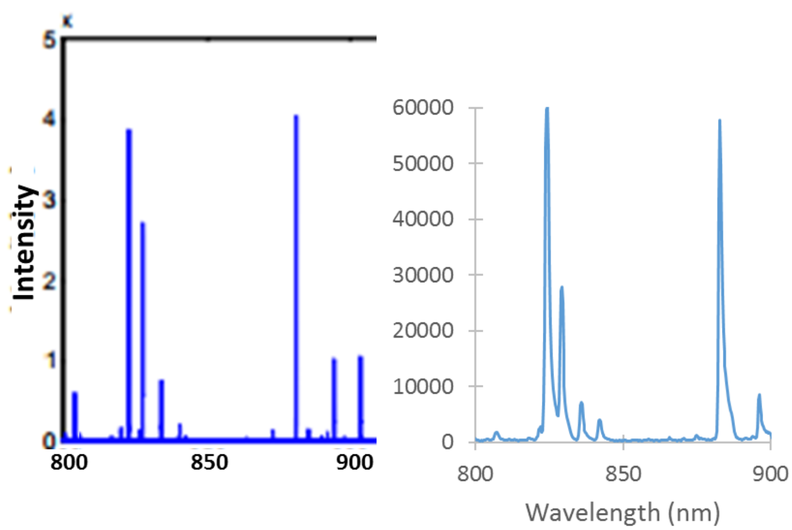

Figure 5. Emission spectra from a xenon Hall thruster (BPT-200, left) and a Plasma Controls, LLC. 5 W hollow cathode (right). Spectra show the same prominent emission peaks indicating xenon emission.

Electron temperature can also be determined from the NIR spectral measurements of xenon and krypton emission by using a collisional radiative model (CRM) [12]. Electron temperature measurements can provide information regarding the efficiency of a Hall thruster. This could indicate whether an observed propulsion system problem, such as over-consumption of propellant, is due to a thruster efficiency problem or another cause, such as unmodeled disturbance torques.

7. CONCLUSIONS

Optical emission spectroscopy is an emerging tool for Space Situational Awareness that can enable identification and diagnosis of EP systems. Spectroscopic analysis does not require contact with plasma; therefore, it can be performed from a safe distance using a diagnostic satellite. The emission intensity of light measured using spectroscopy as a function of wavelength can provide information regarding the plasma temperature, species, density, and operating stability. This can help in the assessment of thruster performance for a cooperative or malfunctioning spacecraft, and it can be used to identify the propellant and thruster type on an unknown object.

The P-Spec mission aims to demonstrate they key technologies needed for CubeSat-based EP diagnostics. The first flight test will demonstrate the OES instrument in space using a hollow cathode with xenon propellant in a mother-daughter CubeSat configuration. This flight test will demonstrate the viability of inter-satellite, optical plasma plume analysis from a CubeSat platform and assess the range of standoff distances over which plasma plume spectral measurement is possible.

8. ACKNOWLEDGMENTS

This project is supported by the Air Force Research Laboratory University Nanosatellite Program. The authors would also like to thank Nagual Simmons and the Western Aerospace Launch Initiative team for their work on the spacecraft design and development.

9. REFERENCES

1 Henry, C. Intelsat-33e propulsion problems to cut service life by 3.5 years, *SpaceNews.com*, September 1, 2017. http://spacenews.com/intelsat-33e-propulsion-problems-to-cut-service-life-by-3-5-years/

2 Passaro, A., Vicini, A., and Biagioni, L., Plasma Thruster Plume Simulation: Effect of Vacuum Chamber Environment, 35th AIAA Plasmadynamics and Lasers Conference, Fluid Dynamics and Co-located Conferences, Portland, Oregon, 2004.

3 Hofer, R. Peterson, P. and Gallimore, A., Characterizing Vacuum Facility Backpurssure Effects on the Performance of a Hall Thruster, in International Electric Propulsion Conference, Pasadena, 2001.

4 Tighe, W.G., Spektor, R., Diamant, and K., Kamhawi, H., The Effect of Background Pressure on SPT-100 Hall Thruster Performance, in: 34th Int. Electr. Propuls. Conf., Kobe, Japan, 2014: pp. IEPC–2015–152. doi:10.2514/6.2014-3710.

5 Spektor, R., Tighe, W.G., Stoltz, P.H., and Beckwith, K.R.C., Facility Effects on Hall Thruster Performance Through Cathode Coupling, in: 34th, Kobe, Japan, 2015: pp. IECP–2015–309.

6 Byers, D. and Dankanich, J., A Review of Facility Effects on hall Effect Thrusters, in International Electric Propulsion Conference, Ann Arbor, 2009.

7 Wheeler, P. et al. Satellite propulsion spectral signature detection and analysis through Hall effect thruster plume and atmospheric modeling. *SPIE Optical Engineering + Applications*. International Society for Optics and Photonics, 2016.

8 Hudson, J., Spangelo, S., Hine, A., Kolosa, D., and Lemmer, K., Mission Analysis for CubeSats with Micropropulsion, *Journal of Spacecraft and Rockets*, Vol. 53, (2016), pp. 836-846.

9 SORA: Spectrometry Observation for Reflectivity Analysis, University of Buffalo, https://ubnl.space/sora/

10 Murat, C. Ph.D. Thesis, MIT, Experimental and Computational Studies of Thruster Plasma Radiation Emission, May 2007.

11 Prince, B.D., Bemish, R.J., and Chiu, Y., Emission-Excitation Cross Sections Relevant to Krypton-Propelled Electric Thrusters, *Journal of Propulsion and Power*, Vol. 31, No. 2, March-April 2015; DOI: 10.2514/1.B35306

12 Karabadzhak, G. F., Chiu, Y., and Dressler, R.A., Passive optical diagnostic of Xe propelled Hall thrusters. II. Collisional-radiative model. *Journal of Applied Physics* 99.11 (2006): 113305.