SSC18-WKIII-07

GW-Sat: GW's First Satellite with propulsive 3-axis-stabilization

Jonathan Kolbeck, Michael Keidar
The George Washington University
800 22nd St NW, Suite 3000; 202-994-6929
jkolbeck@gwu.edu

ABSTRACT

The George Washington University's proposed satellite mission, GW-Sat, was one of the 34 missions selected by NASA as part of the CubeSat Launch Initiative program. The CubeSat will be built entirely by students from different departments and schools at the university. GW-Sat is a 3 U CubeSat and its primary mission is to validate its propulsion system based on in-house built Micro-Cathode Arc Thrusters. The thrusters will be used to provide the spacecraft with 3-axis stabilization and the ability to perform station-keeping maneuvers, and therefore, increase the mission's lifetime. In addition to this, the CubeSat will be used to perform secondary science missions, which include relaying information from a remote ground station using the store-forward architecture and the effect of the thruster's plasma discharges on radio communications.

INTRODUCTION

Since the popularization of the CubeSat standard, CubeSats have allowed universities to train large numbers of students on real space missions using a hands-on approach, usually at a relatively low cost. These small satellites are used to teach students about the different spacecraft subsystems and how they all come together to form a spacecraft. Additionally, CubeSat projects are great at teaching the process of designing a spacecraft according to requirements, whether from the launch provider, NASA, or other stakeholders. Furthermore, such projects teach students how to work effectively in interdisciplinary teams, a skill that is often unpracticed in academia.

GW's proposal for a 3 U CubeSat with propulsive 3-axis stabilization was accepted by NASA as part of the 2017 CubeSat Launch Initiative call for proposals. It was one of the 34 missions accepted. Work on the CubeSat began in early 2017, when GW's CubeSat Lab was established. GW's CubeSat Team consists of approximately 30 students from different departments, most of them belonging to mechanical and aerospace engineering, followed by electrical engineering, space policy, systems engineering, computer science, physics, business, and law. The project is managed by GW's mechanical and aerospace department. The distribution of students by graduate and undergraduate is approximately 30% and 70%, respectively. The mission's management is done by graduate students only. Work on the CubeSat is on a volunteer basis, which means that students are not remunerated for their work. This is particularly challenging with undergraduate students, since they have a heavier course load.

MISSION GOALS

The overall goal of GW-Sat, and the GW CubeSat Team in general is to educate GW students using a real space mission. Additionally, the team expects to generate scientific papers to contribute to the small satellite community. Outreach is another key aspect on which the team focuses. The CubeSat Team has focused on cooperating with School Without Walls, a DC public high school in the proximity of GW's campus. Volunteers from the GW-Sat team mentor the students on a weekly basis. The following paragraphs will describe the mission goals. A more detailed explanation of the mission will follow.

Primary Mission Goal

The primary mission goal of GW-Sat is to validate the performance of the propulsion system based on Micro-Cathode Arc Thrusters (µCAT)[1-6], developed at the Micro-propulsion and Nanotechnology Lab (MpNL) at GW. The system has been previously flown on the United States Naval Academy's (USNA) Ballistically-Reinforced Communication Satellite (BRICSat-P)[7]. This 1.5 U CubeSat flew 4 µCATs to detumble the spacecraft. Additionally, this propulsion system was also flown on CANYVAL-X[8], a joint project between NASA Goddard, Yonsei University, and GW. The µCAT system is scheduled to be flown on BRICSat-2 and will launch with SpaceX's next Falcon Heavy rocket, STP-2. After initial detumbling with the magnetorquers, the spacecraft's thrusters will be tested for brief periods of time to ensure that all of them are discharging/firing and operating nominally. To validate the propulsion system, CubeSat will perform various tasks while in orbit. These tasks include:

1. Spin up the spacecraft to approximately 10 degrees per second along the z-axis using the attitude control thrusters in order to deduce the thrust produced by the propulsion system

2. Perform station-keeping maneuvers for extended periods of time to delay the orbital decay. The actual satellite orbit will be compared with model predictions assuming low, median, and high orbit perturbances to verify that the thrusters are maintaining the orbit.

3. Demonstrate 3-axis stabilization and pointing capabilities of the 3 U CubeSat under real space conditions. This will be done by commanding the CubeSat to point at a specific location on Earth and snap a picture of it. Verification of the pointing accuracy will be done by comparing the image's center (ideally the exact desired location).

4. Depending on the results of the on-orbit validation, the team may attempt to perform orbital-raising maneuvers.

5. At End of Life (EOL), the thrusters will be used to safely deorbit the thrusters.

Secondary Mission Goals

GW will partner with various universities for its secondary mission goals. These goals also have the education and training of students in the foreground. These partnerships will increase the number of students that benefit from this CubeSat. The following list describes the secondary mission goals of GW-Sat.

1. Perform on-orbit testing and validation of a novel low-cost star tracker designed by students at MIT. The device is based on a new algorithm called TETRA[9].

2. GW-Sat will function as a store-forward communications node between a remote ground station from our partner university TEC from Costa Rica and GW's ground station. This will be described in detail in a later section of this document.

3. Analyze the effect of the µCAT thruster's plasma discharges on radio communications.

STATUS OF MISSION PROGRESS

The mission is currently planned for a launch in late 2019. The team has successfully passed PDR and is headed towards CDR, currently planned for the middle of September. Originally, the CDR was planned for May, but due to loss of funding from a sponsor, the team was forced to rescope the mission and reduce the cost of the CubeSat. Additionally, there was a large exodus of seniors due to graduation and therefore, the CDR had to be rescheduled. The team is going confidently into CDR despite the rescoped mission.

SATELLITE MISSION SEGMENTS

For the CubeSat mission to be successful, it requires not only a well-designed and operational satellite (the space or Flight Segment), but also a successful launch via a Launch Segment. In addition to this, the Ground Segment, i.e. the ground stations, mission control, etc. and the Program Segment (Mission Operation) need to be well defined.

- **Launch Segment (LS)**: The launch segment is comprised of the launch vehicle, launch infrastructure, and the launch service. In the case of GW-Sat, the LS is controlled by NASA and could encompass various different launch vehicles, such as Atlas family rockets, Falcon 9 rockets, Antares rockets, Delta family launch vehicles, as well as any of the newcomers, such as Virgin One, Blue Origin, Rocket Lab's Electron launch vehicle, and Vector Space's system.

- **Flight Segment (FS)**: The FS is comprised of the CubeSat equipment, the payload, the system engineering activities and the tests.

- **Ground Segment (GS)**: The GS includes all the ground infrastructure, such as the ground stations (GW, USNA, TEC), the hardware and software used to link the FS to the GS, Mission Control Center (MCC), the data processing facilities, and the archiving facilities. GW-Sat's GS is complex in the sense that GW will be operating their own ground station to communicate with the satellite (both via VHF and UHF antennae). Additionally, the US Naval Academy will also use their ground station as part of the collaboration between GW and USNA. USNA will use this opportunity to train their Midshipmen in ground station operations. GW will be sending a group of students to USNA to participate on a one-day workshop to train them in the topic. TEC's portion of the GS includes the Remote Science Ground Station

(RSGS), which will be built and managed by TEC. GW-Sat will obtain data from the RSGS, store it, and then downlink it to either GW's or USNA's ground station.

- **Program Segment (PS)**: The PS includes project management, project coordination, product and mission assurance, interfaces, project organization and planning of resources.

GW-SAT'S PROPULSION SYSTEM

The Thruster – Basics

The thrusters are based on the physical phenomenon of vacuum (cathodic) arcs. The term cathodic refers to the fact that the discharge is produced on the cathode on so-called cathode spots. These are the source of electrons and ions, i.e. plasma, required to sustain the discharge. For this type of propulsion system, the cathode functions both as electrode for the discharge and as propellant. The μCAT (micro-cathode arc thruster) system has been designed and manufactured at GW. As of May 2016, the development stage of the thruster is at TRL-7.

Figure 1 shows an example of the circuit board with the components used to operate the μCAT system. This particular board configuration was flown on USNA's BRICSat-P CubeSat. The flight result is described in more detail below. A similar but more complex system will be flown on the GW-Sat.

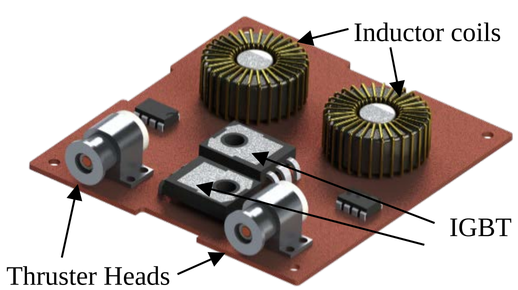

Figure 1: CAD image of the thruster control board flown on BRICSat-P

Figure 2 depicts a schematic of the circuitry used to power the μCAT devices. A DC voltage of approximately 15-25 V is applied to charge an inductor. The IGBT is set in such a way as to close Loop 1. Once the inductor is fully charged (within fractions of a second), a square-wave pulse is sent to the IGBT, which stops the flow of current through it, forcing the inductor to release its stored energy in the form of a voltage spike of hundreds of volts through Loop 2 onto the thruster head. The ceramic interface between the cathode and the anode is covered in a thin layer of graphite with a resistance in the 1000s of ohms. The resistance of the graphite causes it to heat up locally and ionize. This cloud of ionized graphite produces a highly conductive path between the cathode and the anode, allowing a high current of approximately 40 A to flow to the anode. This flow of current is known as an electric arc, and it originates in small spots on the cathode known as cathode spots. These are high temperature and high luminosity spots with a diameter of only a few micrometers and a life-span of only a few nanoseconds. These spots are known to have high current densities of up to 10^{12} A/m^2.[10] An increase in the cathode current does not further increase the current density at these spots above the aforementioned value, but rather contributes to the production of more cathode spots. The thrust produced by a system using this phenomenon is proportional to the amount of emission (cathode) spots. Therefore, it is desired to have many emission spots at the same time in order to increase thrust. While this may be beneficial from the thrust point of view, a large amount of cathode spots also increases the temperature of the cathode significantly, as these spots are known to have temperatures of over 4000 K. An increased cathode temperature leads to zones of gross melting and an increase in the production of detrimental particles called macroparticles. These particles are slow-moving molten metal droplets that do not contribute significantly to thrust but considerably increase the erosion rate of the cathode, leading to an inefficient use of the propellant.

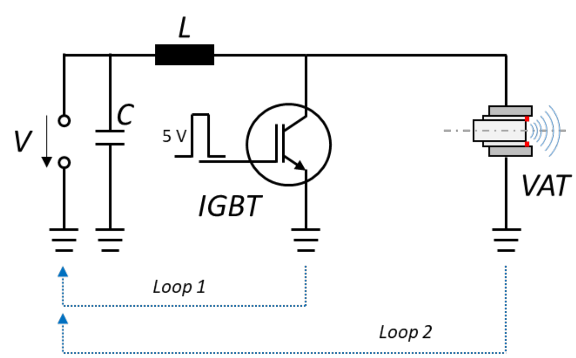

Figure 2: Thruster circuit diagram

The aforementioned cathode spots are the source of ionized cathode material (i.e. ionized propellant) and electrons, which are required to close the circuit. Acceleration of ions occurs mainly due to hydrodynamic pressure gradients in the near-cathode region[11]. The μCAT system is equipped with a magnetic coil near the exit region of the plasma. The magnetic coil has been shown to further accelerate the ions[12] by using the magnetic nozzle effect, increasing the axial momentum of the ions. This effect further increases the efficiency of the system. The magnetic coil also serves a secondary purpose. The arc discharge is heavily influenced by nearby magnetic fields. The topology of the magnetic field created by the coil on the thruster causes the arc spots to "move" in a $-j \times B$ (anti-Amperian) direction, i.e. around the circumference of the cathode. The effect is beneficial to the lifetime of the thruster as it contributes to the uniform erosion of the cathode.

Vacuum arcs are known to produce small, measurable forces; these were first observed in the late 1920s[13]. Due to the nature of the discharge, any metal can be used as a propellant, although titanium and nickel are the two cathode metals of choice at the Micro-propulsion and Nanotechnology Laboratory at GW. Titanium is a light-weight metal with an atomic mass of 47.9 u, whereas nickel has an atomic mass of 58.7 u. The choice of cathode material depends largely on the requirements set to the propulsion system. Titanium ions can be accelerated to higher speeds and therefore have a higher specific impulse than nickel ions. The use of nickel offers a higher thrust production than titanium, but at a lower specific impulse. The thrusters that will be used for GW-Sat will be thrusters with nickel cathodes and will be an improved version of the ones launched on BRICSat-P. Rather than having an aluminum casing, the new thrusters will have a PTFE housing in order to increase the quality of the electrical insulation around the electrodes. This will also prevent any interactions between the ejected plasma and the casing. A rendered image of the improved thruster can be seen in Figure 3.

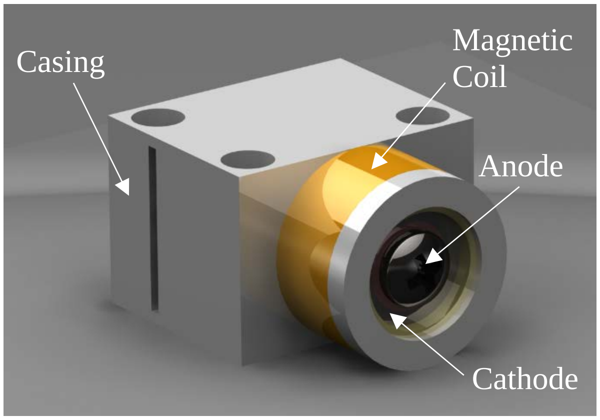

Figure 3: Rendered image of the improved µCAT system.

A list of important parameters of the µCAT system can be found in Table 1. This list includes information such as size and power consumption.

RECENT DEVELOPMENTS

In the previous months, research has been performed in order to increase the efficiency of the µCAT system. In the vacuum arc community it is known that approximately 90 % of the arc discharge current is carried by the electrons and the remaining 10 % of the current is conducted by the ions[11].

Table 1: Thruster Parameters

Thruster Parameters	
Casing Material	PTFE
Propellant	Nickel
Size	Length: 27.6 mm Width: 20.1 mm Height: 14.0 mm
Required structural opening on side panel for plume	Diameter: 14 mm
Total system mass	< 200 g
Power consumption	Approx. 1 W at 10 Hz firing rate
Firing rate	1-50 Hz
Trigger	5 V square wave signal
Charging Voltage	Approx. 15-25 V

Thrust is produced mainly by the high-velocity ions that leave the cathode, which means that the energy carried by the electrons does not contribute towards the production or increase in thrust. Therefore, the aim of the current research is to use part of the energy carried by the electrons to produce additional thrust without increasing the total energy consumption of the thruster.

As of today, the thruster only uses the cathode material to produce thrust. The anode, on the other hand, remained unused and served only the function of an electrode to close the circuit. Work performed by J. Lukas[14] focused on changing the material of the thruster's anode from titanium (and stainless steel) to a metal with a lower melting temperature. As it was mentioned before, the electrons flow to the anode to complete the circuit. Joule heating causes the anode to heat up and increase in temperature. This does not have an effect when using stainless steel anodes. When using metals with low temperatures, on the other hand, the electrons heat up the anode material and melt it locally, producing metal vapor of the anode metal. Measurements performed with an ion collector showed an increase in the total ion current for certain firing frequencies. At a firing rate of 1 Hz and 2 Hz, the measured total ion current was 45 % and 38 % higher compared to the non-ablatable anode, respectively. Further research is planned in order to find out if the increase in the ion current leads to a measurable and proportional increase in thrust. For this reason, a micro-newton thrust balance is being developed at the Micro-propulsion and Nanotechnology Laboratory at GW. Performing experiments with a thrust balance together with and ion collector will give clue as to whether the hypothesis is correct.

GW-Sat's Thruster Configuration and Diagnostics

The satellite will be equipped with twelve µCAT thrusters. These thrusters will be located at the bottom 1 U of the CubeSat, as shown in Figure 4, which shows a rendered image of the CubeSat prior to the decision of dropping the deployable solar cells from the design. The thrusters are grouped into "corner units" or "RCS units", as shown in Figure 4.

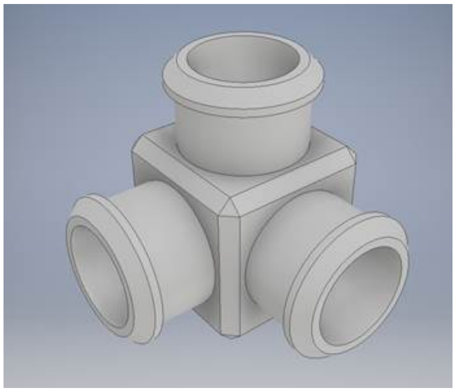

Figure 4: Schematic overview of the thruster corner units.

Four of the thrusters will point in z-direction and will be fired simultaneously during station-keeping maneuvers. Additionally, two thrusters on each face will allow the spacecraft to perform 3-axis-maneuvers such as pointing and 3-axis stabilization. The thruster power processing unit (PPU) is designed in such a way that each PPU provides power to three thrusters, but only one will be fired at a given time. The spacecraft carries four thruster PPUs, which ensures that all four bottom thrusters can be fired simultaneously. During other maneuvers, a maximum of two out of twelve thrusters will be fired simultaneously.

SCIENTIFIC MISSION

In addition to the technology demonstration character of GW-Sat's mission, the satellite will be used to perform a scientific mission in cooperation with our partner university, TEC, Costa Rica's Institute of Technology. The TEC will be launching their own satellite, Irazú, from the ISS at the beginning of 2018.

The scientific mission consists of using GW's satellite as a store-and-forward (S&F) relay node to further test the communication system of the GW-Sat, but also to obtain scientific data from a remote ground station. Store-and-forward communication consists of sending information to a receiver, which will temporarily store the data, and broadcast it after a given time. A satellite-based S&F network consists of at least three components, the broadcasting (remote) ground station, the satellite itself, and the receiving ground station. The network can be expanded to numerous broadcasting stations, satellites, and receiving ground stations. The broadcasting station can be located anywhere within the satellite's ground path and it can be used to gather data from a remote location. TEC will oversee the design, manufacture, and management of the remote ground station located in the Costa Rican wetlands.

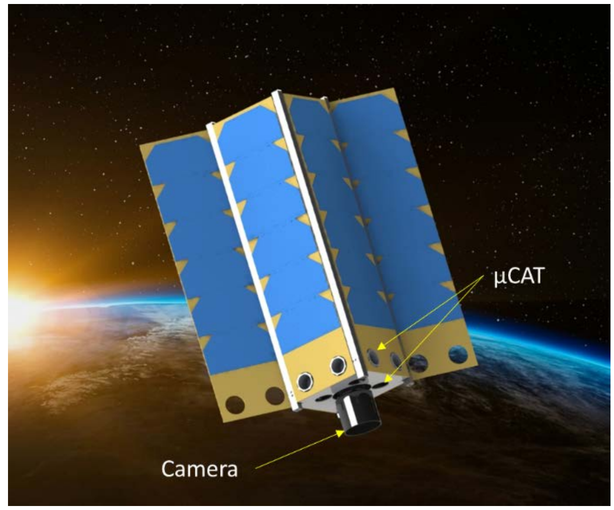

Figure 5: Position of thrusters in the CubeSat. Rendered image prior to the decision of not carrying deployable solar cells.

Wetlands are ecosystems that are rich in biodiversity and are crucial for animals and plant species that live in them, including many endangered species. They also provide benefits to humanity thanks to their ability to filter water, absorb pollutants, produce building materials and food, replenish groundwater systems, protect shorelines from erosion, mitigate flooding, and their ability to mitigate climate change as fast-acting, long-term carbon sinks. There are over 1800 wetlands within Costa Rica, wetlands may include mangroves, rivers, lakes, swamps, floodplains, estuaries, coral reefs, and peatlands. These regions cover a total area of 350,000 acres of land, and 30% of these are located in conservation areas. Twelve of these wetlands are Ramsar Convention wetlands due to their international importance for aquatic bird conservation. These ecosystems are highly vulnerable and currently in danger due to forest fires, water extraction for irrigation, water pollution, squatter villages, and invasive species.

The protection level of these wetlands is minimal, aside from the wetlands located in conservation areas. Scientific information about their hydrodynamics and their variation during the year is almost non-existent. Therefore, it becomes more difficult to create action plans for conservation based on hard data. A major reason for this is the lack of economically viable monitoring systems that can be used to monitor these ecosystems.

A system to monitor the wetlands would require, at minimum, bathymetric measurement of the wetland and water level monitoring. This would allow for the determination of the total water mass at any given point. The National System of Conservation Areas (Spanish: Sistema Nacional de Areas de Conservación—SINAC) is responsible of protecting and conserving the wetlands in Costa Rica. While SINAC's budgetary constraints do not allow them to protect the wetlands as they would like, they have a track record of success and a desire to protect the wetlands as much as possible.

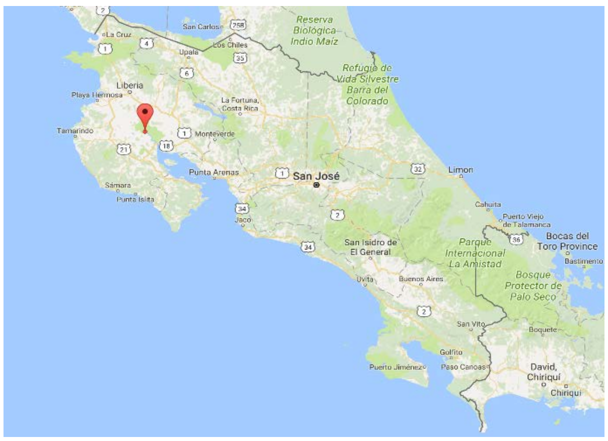

Figure 6: Location of the Humedal Palo Verde in Costa Rica.

The Costa Rican government published a document called the National Wetlands Politics 2017-2030 where they discuss the current situation of the wetlands, the current legal framework involving the wetlands, the administrative structure as well as the politics and priorities for the next years. Some of the basic tasks that need to be performed, according to the document, are bathymetry and water level measurements throughout the year. There are, of course, challenges tied to these measurements, such as:

A. Bathymetry measurements of the wetlands: This is a complex undertaking because it involves the underwater topographic measurement of the wetland. If the wetland is flooded throughout the year, this is difficult to achieve. An indirect way of performing these measurements is to frequently analyze images of the water level/flooded area and relate them to the measured water levels, and therefore, one can start associating the bathymetry of the wetland between the lowest and highest water level measured. On the other hand, if the wetland dries up during a certain season, it is possible to use a LIDAR (Light Detection and Ranging) to obtain high-precision information about the topography of the wetlands.
B. Water level measurements: These measurements are done with a high-precision sensor that measures the pressure of the water column above the sensor. The sensor transduces the pressure into a water level after the data it is compensated with the current atmospheric pressure. A challenge associated with these measurements is that usually, the sensor must be installed in the deepest part of the wetland, which can be located hundreds of meters away from the shore and could also be covered by all sorts of aquatic plants. The data from the sensors must be taken manually, i.e. by visiting the wetlands and retrieving the data. These challenges are only compounded when wetlands are in remote, difficult to access areas.

Therefore, it is necessary to envision a way of performing frequent measurements in these remote areas of difficult access. Data gathered for a period of over a year would enable the interpretation of data to produce a bathymetric model of the wetlands. This would allow scientists to understand the yearly variation in the ecosystem and would help understanding the hydrological changes it goes through.

Ideally, this would include a measurement of all the sources of water, such as rain and influx from rivers, and the sinks of water, such as water filtration through the ground, as well as outflux into rivers or through evaporation. This requires a much more extensive study of the wetlands and is not part of the scope of this study.

For conservation matters, it is required to know at least the basic information about the wetlands, such as the hydrodynamics of the wetlands and the surface area of them. This would be a first step that will be used to define further conservation efforts and would allow for a baseline measurement.

The SINAC was consulted by TEC and they recommended that the "Humedal Palo Verde" (Palo Verde wetlands) be the wetland to be analyzed as part of GW-Sat's scientific mission due to its emblematic character. SINAC is currently installing meteorological stations from Campbell Scientific in that location to start monitoring the region, which will be complementing TEC's efforts. The location of the Palo Verde conservation area is shown in Figure 4.

Figure 7: Image of Humedal Palo Verde with migratory bird species.

General Scientific Mission Statement

To contribute to the preservation of the biodiversity and hydrological equilibrium of the Costa Rican wetlands through improved monitoring.

Specific Objective

To design a wetland-monitoring prototype system that will allow the study the hydrodynamics of the flooded area and the effect of its variability in this ecosystem.

Justification

The accelerated urban growth, the increase in the environmental pollution, and the growth in irrigation agriculture are factors that affect the wetlands directly. It is therefore required to envision and design new ways and methods to measure and monitor the hydrology of the wetland ecosystems and how these are affected by the variability in the climate. The information gathered throughout this study could provide a tool for lawmakers to make political decisions about these ecosystems. This study will benefit different organizations such as The Ministry of Environment, Energy, and Telecommunications (MINAE), SINAC, as well as many National Parks and NGOs that deal with the environment.

Site Selection

As previously mentioned, Costa Rica has a large diversity of wetland ecosystems. As of today, these wetlands have only been studied by identifying their locations and their estimated region of influence. Almost nothing is known regarding their hydrodynamics. The SINAC requires a basic monitoring model and GW-Sat's scientific mission would be the proof-of-concept for a more advanced concept to test and develop a new methodology for lacustrine wetlands. Therefore, TEC and SINAC came to an agreement to select the Humedal Palo Verde, shown below in Figure 5. This site is not only a RAMSAR site, but also one of the wetlands in Costa Rica that require prioritized conservation. This wetland is of great importance for migratory bird species in the American continent, especially those birds coming from the northern hemisphere. Therefore, Palo Verde was declared a National Park for its importance and it has a Biologic Station from the Organization for Tropical

Studies (OTS). The selection of this location will guarantee that the obtained results will have a direct impact for the conservation of the site. Additionally, it is a site that will allow capacitation of SINAE functionaries, national and international students. Moreover, it is a safe location that will allow the installation of all required equipment and offers logistic facilities for the execution of the project.

Main Contribution

Generation and production of prototypes and methods to measure environmental variables in wetlands using a remote station.

To fulfil this objective, the following products will be needed:

- An autonomous electronic device will be designed to monitor water level and temperature of the wetlands.
- A functional and calibrated prototype that can measure the water level and its temperature.
- A database that includes climate data, as well as the measured water levels and temperatures to allow the study of the wetlands' hydrodynamics and its variability due to climate change.
- Bathymetry measurements of the wetland using remote sensors and data from the water level of the wetland.

A database of bathymetric information backed by satellite imagery.

OPERATION OF THE SCIENTIFIC MISSION

The operation of the scientific mission will be done by GW, TEC, and USNA. The TEC is responsible for the Remote Science Ground Station (RSGS), which is part of GW-Sat's Ground Segment. Data will be gathered by the RSGS in the Humedal Palo Verde. The radio system of the RSGS will broadcast the data at a predefined frequency in the Very High Frequency (VHF) amateur radio band (30 to 300 MHz), most likely in the 145 MHz range. Once the satellite's orbit brings GW-Sat within the communication region of the RSGS, the RSGS will start broadcasting its data to GW-Sat. The data broadcasted data will contain a specific handler that will cause GW-Sat to start "listening". The satellite will receive specific data packages in the form of ASCII text, which will be stored on-board. The satellite will then orbit Earth and once it is within reach of GW's or USNA's Ground Station, the data will be downlinked and transferred to TEC for further analysis. The scientific mission will help verify GW-Sat's radio systems, both in the space segment as well as the ground segment.

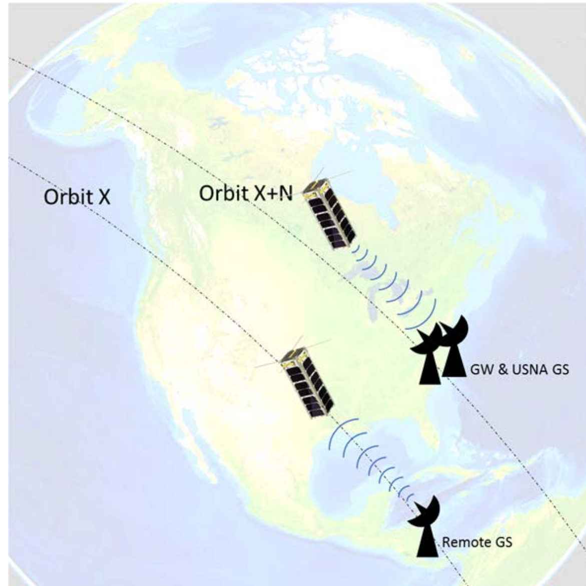

Figure 8: Overview of GW-Sat's science mission operation. The satellite will receive data from the remote ground station. Several orbits later, the data will be downlinked to either GW's or USNA's ground stations.

OUTREACH APPROACH

With the GW-Sat mission, we aim to inspire and train future STEM leaders who are passionate and committed to their work. NASA's goal is to attain "an increasingly diverse workforce with the right balance of skills and talents (…)". We expect to obtain a team of highly motivated students with different backgrounds.

In addition, our goal is to involve students from the DC school system in our project and we intend to organize different outreach events throughout the project's lifetime. In the past, GW has collaborated closely with other schools in the region, such as School Without Walls, a D.C. Public High School located on GW's campus, and we aim to continue this work. School Without Walls has been recognized as one of the most outstanding schools in the District's school system. Our hope is to help inspire the next generation of engineers and scientists, which complements the NASA CubeSat program's overall educational goals.

We plan to organize school visits, where members of the team will talk to students (K-12) about their work and about space missions, in order to educate and inspire students about STEM fields. Additionally, we would like to organize a "Send Your Name to Space" event, where students K-12 can sign up to have their name sent into space. Once the students register, we would be providing the students with a virtual "boarding pass" they can print out. This is similar to what NASA did with the first Orion mission and with the InSight mission. This event could also be made completely open to public, in order to inform the public about the benefit of CubeSat missions. In addition to school visits and the "Send Your Name to Space" event, we would like to invite classrooms to visit the facility where our CubeSat will be put together and tested. Moreover, this visit would be complemented with a presentation in our auditorium, followed by a Q&A session where students will have the opportunity to ask their questions about the project, its purpose, etc.

MISSION TIMELINE

Table 2 shows the expected date for various key milestones of the mission. Only major milestones are shown.

Table 2: Mission Milestones

Milestone	Date
Feasibility Study	Completed Late 2016
Phase 0/A	Completed Early 2017
Phase B (PDR)	Completed Oct. 2017
Phase C (CDR)	Expected Sep. 2018
Phase D (SC Ready)	Expected Dec. 2019
Phase D (Launch)	Expected Q1 2020
Phase E (Mission Op)	Expected Q1-Q4 2020
Phase F (Deorbit)	Expected Q1 2021

CONCLUSION

GW-Sat will be a novel mission designed to test the capabilities of GW's Micro-Cathode Arc Thruster propulsion system in orbit. The team hopes to gain new insights into the performance of the thrusters under real-life conditions.

Acknowledgments

The GW-Sat team would like to extend their gratitude to Raytheon Company, Philtec Inc, DHV Technologies, the NASA DC Consortium, NASA Goddard Space Flight Center, NASA Marshall Space Flight Center, and The American Institute of Aeronautics and Astronautics for their continuous support of this project, financial or otherwise. Many thanks to Dr. Randy Graves for his donation to the project. Additionally, many thanks to the student participants, in alphabetical order, Audrey Bacskai, Yash Bagla, Christopher Beauregard, Terence Bou, Juliana Curry, Andrew DaCosta, Keir Daniels, Abigail Demasi, Duncan d'Hemecourt, Jinous Ebrahimi, Allegra Farrar, Austin Fern, Drew Garza, Jordan Giacoma, Anthony Hennig, Joseph Joyce, Paul Kennedy, Cody Knipfer, Courtney Krawice, Shankar Kulumani, Cesar Laurent, Evan Linck, Christopher Mathes, Jacari Matthews, Jannik Milberg, Anishsanjay Nayak, Victoria Nilsen, Daniel Oler, Gabriel Papadatos, Colin Pate, Chandraman Patil, Thomas Porter, Katie Rabasca, Michael Re, Joel Rhine, Ryan Rice, Lauren Robinson, Andria Sperry, Benjamin Sproule, Raymond Squirini, John Stricker, Zachary Switzer, Sanjin Terzic, Joseph Torchia, Alexa Vero, Jonathan Villegas, Joshua Wolny. This section would not be complete without acknowledging our colleagues at the United States Naval Academy, TEC, and MIT.

References

1. Zhuang, T., Shashurin, A., Chiu, D., Teel, G., and Keidar, M. "Micro-Cathode Arc Thruster Development and Characterization," *32nd International Electric Propulsion Conference, IEPC-2011-266*. Wiesbaden, Germany, 2011.
2. Zhuang, T., Shashurin, A., Beilis, I., and Keidar, M. "Ion velocities in a micro-cathode arc thruster," *Physics of Plasmas* Vol. 19, No. 6, 2012, p. 063501.
3. Zhuang, T., Shashurin, A., Chiu, D., Teel, G., and Keidar, M. "Micro-Cathode Arc Thruster (uCAT) Performance and Thrust Vector Control," *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-2012-4103*. American Institute of Aeronautics and Astronautics, 2012.
4. Keidar, M., Haque, S., Zhuang, T., Shashurin, A., Chiu, D., Teel, G., Agasid, E., Tintore, O., and Uribe, E. "Micro-cathode arc thruster for PhoneSat propulsion, SSC13-VII-9," *27th Annual AIAA/USU Conference on Small Satellites*. 2013.
5. Brieda, L., Zhuang, T., and Keidar, M. "Near Plume Modeling of a Micro Cathode Arc Thruster," *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA-2013-4120*. American Institute of Aeronautics and Astronautics, 2013.
6. Haque, S. E., Keidar, M., and Lee, T. "Low-Thrust Orbital Maneuver Analysis for Cubesat Spacecraft with a Micro-Cathode Arc Thruster Subsystem," *33rd International Electric Propulsion Conference, IEPC-2013-365*. Washington, DC,, 2013.
7. Hurley, S., Teel, G., Lukas, J., Haque, S., Keidar, M., Dinelli, C., and Kang, J. S. "Thruster Subsystem for the United States Naval Academy's (USNA) Ballistically Reinforced Communication Satellite (BRICSat-P)," *34th International Electric Propulsion Conference and 6th Nano-satellite*

Symposium, IEPC-2015-37. Kobe-Hyogo, Japan, 2015.

8. Earth Observation Portal. "https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/canyval-x, Accessed on June 18, 2016."
9. Brown, J., and Stubis, K. "TETRA: Star Identification with Hash Tables," 2017.
10. Jüttner, B. "Erosion Craters and Arc Cathode Spots in Vacuum," *Beiträge aus der Plasmaphysik* Vol. 19, No. 1, 1979, pp. 25-48.
11. Keidar, M., and Beilis, I. *Plasma Engineering: Applications from Aerospace to Bio and Nanotechnology*: Elsevier Science, 2013.
12. Keidar, M., Schein, J., Wilson, K., Gerhan, A., Au, M., Tang, B., Idzkowski, L., Krishnan, M., and Beilis, I. I. "Magnetically enhanced vacuum arc thruster," *Plasma Sources Science and Technology* Vol. 14, No. 4, 2005, p. 661.
13. Tanberg, R. "On the Cathode of an Arc Drawn in Vacuum," *Physical Review* Vol. 35, No. 9, 1929, pp. 1080-1089.
14. Lukas, J., Teel, G., Kolbeck, J., and Keidar, M. "High thrust-to-power ratio micro-cathode arc thruster," *AIP Advances* Vol. 6, No. 2, 2016, p. 025311.