Proposal Cover Page

Opportunity Title: Announcement of CubeSat Launch Initiative
Solicitation Number: NNH20ZCQ001O
Respondent: Brown Space Engineering (undergraduate student group at Brown University)

Proposal Title Page

Title: Perovskite Visuals and Degradation eXperiment (PVDX)

Mission Parameter Tables

Table 1. *CubeSat Mission Parameters*

Mission Name	Mass (g)	Cube Size	Desired Orbit		Acceptable Orbit Range	400 km @ 51.6 degree incl. Acceptable	Ready for Dispenser Integration Date	Desired Mission Life
PVDX	2750	3U	Altitude	400 km	400-500 km	Yes	Mid 2024	~1 year
			Inclination	51.6º	>42°			

In order for PVDX to be active during the school year (to allow us to perform more local outreach), an optimal launch would occur in the fall or winter, or alternatively have at least a year of orbital lifetime. More information about the expected development cycle, and general information about project management, can be found in Appendices D & E.

Table 2. CubeSat Project Details

Focus Areas	Student Involvement	NASA Funding		Sponsoring Organization(s)	Collaborating Organization(s)	
		Yes or No	Organization		List	International
Technology Demonstration and Educational Outreach	Yes	Yes	RI Space Grant Consortium	Brown University School of Engineering	N/A	No

Points of Contact

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Proposal Abstract

Contemporary solar cells have experienced remarkable advances in the past few decades. One emerging solar cell technology is perovskite solar cells (PSCs), which feature a unique crystal structure that allows them to achieve properties such as bandgap tunability, high power per mass (specific power), low cost, resistance to radiation, low-light capabilities, self-healing, and manufacturability in space. Low-cost, high specific power, radiation tolerance, and self-healing properties make PSCs promising candidates for use in space. Further, low-light and low-temperature capabilities mark them for use in deep-space missions, and their bandgap tunability allows them to be optimized for missions to specific planetary bodies. Additionally, the potential for them to be transported to space in liquid form makes PSCs especially viable for in-space manufacturing.

Recent research and literature[1] from the NASA Glenn Research Center[2] have also pointed to PSCs as potential candidates for use in CubeSat missions; however, PSCs have never been tested on a satellite before. The Brown Space Engineering (BSE) team's 3U CubeSat, Perovskite Visuals and Degradation eXperiment (PVDX), will serve as the first extended flight test of PSCs. The team will work with Dr. Nitin Padture of Brown University's Materials Science Department to develop and test PSCs of a range of compositions. PVDX will test around 30 PSCs and use gallium-arsenide cells as a control group. Additionally, the conditions experienced by the cells will be monitored with temperature and light sensors.

The performance of PVDX's PSCs will be analyzed by collecting Current Density vs. Bias Voltage (J-V) curves throughout the satellite's lifetime. Over the course of a year, Dr. Padure projects that a 20% loss in efficiency may occur. Therefore, in order to characterize PSCs in space, it is also necessary to monitor this degradation and identify its causes. J-V curve analysis and visual imaging will be used to diagnose degradation. The measured J-V curves will distinguish between some categories of degradation; however, perovskite-specific chemical degradation in PSCs and mechanical degradation result in the same J-V curve trends. In order to differentiate between them, PVDX will utilize a camera mounted on a simple robotic arm to periodically identify the color of the cells since chemical degradation alone results in cell discoloration.

While PVDX's primary mission is technical, the BSE team also aims to make space more accessible to people of all backgrounds. To this end, the secondary focus of PVDX's mission is education and engagement. Our aim is to offer ways for students, particularly those from historically underrepresented groups, to connect with space. We plan to accomplish this by providing hands-on experiential learning to Brown undergraduates, empowering student engagement with space, and making aerospace design more accessible. Our team's first CubeSat, EQUiSat, was a 1U spacecraft that sought to enable public interaction with space and test $LiFePO_4$ batteries in flight. Deployed in July 2018, it continues to operate nominally after more than two years. The designs, documentation, and experience our team developed through this process have offered us insight into challenges of CubeSat development. PVDX will offer us an opportunity to build on this foundational knowledge and experiment with improved approaches to design. This project, like EQUiSat, will be run entirely by Brown University undergraduates.

[1] https://ieeexplore.ieee.org/document/8981392
[2] https://data.nasa.gov/dataset/Perovskite-based-Photovoltaics-A-New-Pathway-to-Ul/ja3w-xvxg

To facilitate student engagement, PVDX will utilize its camera-carrying robotic arm and an externally mounted programmable display. BSE will provide tools so students can "program" PVDX to display images and enable them to observe the effects through the photos sent back down to Earth. Students around the United States will be encouraged to control an object in space, send it a set of instructions, and see the results. Our team aims to specifically promote STEM engagement by pairing this interactive exercise with education sessions and programming tutorials for middle school students.

Finally, PVDX will continue BSE's on-orbit validation of student-made, open-source, affordable space design. Although CubeSat development costs have decreased significantly, the field remains dominated by prefabricated kits that present a barrier to groups with access to fewer resources. We aim to offer student groups an alternative: our designs, technical documentation, and codebase, which will be freely available on our website as a resource. Our designs will allow these groups to minimize costs and empower them to realize their own research ambitions, thereby improving the accessibility of CubeSat development.

PVDX fulfils NASA's Strategic Objectives by investigating a low-cost technology that can improve the performance and affordability of spacecraft power systems, facilitating public engagement with space, and advancing access to aerospace design both for undergraduate students at Brown and the wider CubeSat community.

Proposal Detail

Primary Focus Area: Testing Perovskite Solar Cell (PSC) Technology

Our satellite's primary mission is to test and characterize a novel photovoltaic technology in space: perovskite solar cells (PSCs). PSCs are an emerging photovoltaic (PV) technology that has the potential to revolutionize aerospace PVs. They are particularly well suited for aerospace applications because of their chemical tunability, high specific power, low cost, resistance to radiation, low-light capabilities, self-healing properties, and potential to be manufactured in space. These unique qualities give PSCs the potential to enable new NASA missions. Our primary mission therefore addresses NASA's Strategic Objective 3.1 by developing revolutionary photovoltaic technologies that can help further enable the exploration of space.

PSCs' unique characteristics originate from the perovskite crystal structure AMX_3, where A and M are cations and X is an anion. These cations can include transition metals and anions can include halogens, but the A cation may also be swapped out for organic molecules; this versatility gives material scientists the ability to fine tune various properties of perovskites, including temperature stability, resistance to radiation, mechanical properties, and their bandgap. The following sections will discuss the advantages of PSCs in space applications and discuss why this technology will facilitate space exploration.

Advantages of PSCs

Tunability

The bandgap of a semiconductor determines the theoretical maximum power-conversion efficiency of a single-junction solar cell made from that semiconductor. Pure silicon crystals have a band gap of 1.1 eV, which cannot be tuned, while the band gap of perovskites can be tuned between 0.8 to 3 eV. The tunable bandgap of perovskites enables optimization for various radiation spectrums that is not cost efficient with other types of PV technologies, such as multi-junction cells. For example, perovskites could be tuned specifically for near-surface radiation on Mars, which experiences shorter wavelengths of light relative to Earth[3].

Specific Power, Efficiency, and Power Per Area

PSCs have a specific power of around 29 W/g[4], much larger than GaAs (3 W/g) and Si (1 W/g) cells[5]. PSC efficiency has increased exponentially over the past decade, from <4% in 2009 to a record 25.2% in 2019. This efficiency is still increasing, and is comparable to GaAs cells' 30%[6] and Si cells' 27%[7] efficiencies. PSCs have a power per area of 140 W/m^2[8], which is

[3] https://solarsystem.nasa.gov/system/downloadable_items/715_Solar_Power_Tech_Report_FINAL.PDF
[4] https://pubs.rsc.org/en/content/articlelanding/2019/ta/c8ta10585e#!divAbstract
[5] https://www.sciencedirect.com/science/article/pii/S2542435120303226
[6] http://photonetc.com/gaas
[7] https://www.nature.com/articles/s41598-019-48981-w
[8] https://www.sciencedirect.com/science/article/pii/S2542435120303226

less than GaAs cells (300 W/m^2) but comparable to Si cells (150 W/m^2)[9]. Overall, PSCs have a higher specific power relative to Si and GaAs solar cells, while maintaining comparable efficiency and power per area. Therefore, PSCs can enable missions where low mass is critical, which is true for aerospace applications.

PSCs' high specific power, along with their flexibility and tunability, could extend the capabilities of the helicopters and other aero vehicles NASA plans to send to Mars over the next decades. For helicopters, the efficiency enabled by the tunability could shorten recharge times between flights, ultimately allowing more flights—and so more data collection—to be squeezed into the same mission. Similarly, for airplanes not designed to descend all the way to the surface, greater efficiency and specific power could extend the lifetime of the mission and allow more to be allotted to scientific instrumentation. In addition, flexible, thin-film perovskites could be fitted to the wings and fuselage of the aircraft as part of a light-weight, aerodynamic power system[10].

Low-Cost

PSCs are low-cost due to their low mass (lower launch costs) and cheap manufacturing process. PScs cost 10-20 cents per watt, less than the 75 cents per watt for Si cells[11] and $2 to $400 per watt for GaAs cells[12]. The affordability of PSCs is especially attractive to designers of UAVs and small satellites, which tend to work with tighter budgets than do more substantial space and aerospace missions[13]. PSCs' low cost also aligns with BSE's mission of broadening participation in space engineering by demonstrating low-budget designs.

Resistance to Radiation

Another advantageous characteristic of PSCs for space applications is their ability to resist damage from radiation. While traditional spacebound silicon solar cells must be shielded from high-energy radiation by a cover glass—which comes with a mass penalty—recent testing of the effect of charged-particle radiation on perovskites' performance has led researchers to conclude that perovskites "might require dramatically less...radiation shielding to operate reliably in space".[14] Other studies have also found that perovskites' radiation tolerance compares favorably to traditional cells, concluding that PSCs are resistant to levels of radiation that would destroy silicon or GaAs solar cells.[15] [16]

PSCs' radiation tolerance could facilitate new deep-space missions. A study investigating the suitability of PSCs to environments that would be faced by spacecraft orbiting Mars, Jupiter, or Saturn has yielded further encouraging results, finding "no evidence of a phase change" which

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9 http://www.nanoflexpower.com/pdf/150406%20NanoFlex%20Investor%20Deck%20(website).pdf

10 https://solarsystem.nasa.gov/system/downloadable_items/715_Solar_Power_Tech_Report_FINAL.PDF

11 https://www.nextbigfuture.com/2019/02/first-commercial-perovskite-solar-late-in-2019-and-the-road-to-moving-the-energy-needle.html

12 http://www.nanoflexpower.com/pdf/150406%20NanoFlex%20Investor%20Deck%20(website).pdf

13 https://www.sciencedirect.com/science/article/abs/pii/S2211285520305966?via=ihub

14 https://ieeexplore.ieee.org/document/8366410

15 https://pubs.acs.org/doi/10.1021/acs.jpclett.9b02665

16 https://www.sciencedirect.com/science/article/pii/S2589004218300294

would indicate deformation and so permanent degradation of the perovskite crystal lattice[17]. While perovskites will inevitably suffer limited degradation on the way to deep space—for example from the trip through the Van Allen belts and high-temperature thermal cycling while still relatively close to Earth—these degradation processes halt upon leaving the damaging conditions.

Low-light capabilities

PSCs' unique ability to harvest low-intensity solar energy has the potential to enable new deep-space missions. During the PSCs' only test in space (on a rocket), scientists noticed "these solar cells managed to soak up energy even when they were turned away from the Sun" indicating that "they...harvest the weak light reflected back from the surface of the Earth" – something that traditional solar cells...don't do.[18] Scientists determined that PSCs can generate power at low light intensities found around Jupiter and Saturn, making them a promising candidate for missions into the outer solar system.

Self-Healing

There is research that suggests PSCs have self-healing properties: cracks in perovskite crystals caused by bending stresses can be healed when restoring pressure or moderate heat is applied.[19] This makes the PSCs extremely promising for space applications, given that solar array failure causes approximately 40% of satellite failures[20]. Self-healing properties could be useful in repairing damage sustained during the rigors of launch; this was the source of damage that caused a string of failures in Space Systems/Loral satellites costing nearly half a billion dollars[21].

Manufacturability in Space

PSCs can be stored as a liquid and manufactured by depositing or electrospraying them on a substrate to generate solar power.[22] This makes manufacturing of PSCs in space viable, which would prevent damage from launch and save storage volume. A 1 MW solar array would require only one liter of solution.[23]

Previous Testing of PSCs in Space

Though PSCs are advantageous for extra-terrestrial applications, there are many challenges that must be overcome to make their use a reality. The most important challenge PSCs currently face is the dearth of information on how they perform in space, as they have never been tested on a satellite before.

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[17] https://pubs.acs.org/doi/pdf/10.1021/acsaem.8b01882
[18] https://newatlas.com/energy/perovskite-organic-solar-cells-space/
[19] https://www.sciencedirect.com/science/article/pii/S1359645420300653
[20]https://www.nts.com/wp-content/resources/Testing%20the%20Reliability%20of%20Satellite%20Power%20Systems.pdf
[21] https://spacenews.com/33046spate-of-solar-array-failures-on-ssl-satellites-traced-to/
[22] https://www.sheffield.ac.uk/news/nr/spray-on-solar-cells-1.392919
[23] https://www.nasa.gov/feature/glenn/2019/building-solar-panels-in-space-might-be-as-easy-as-clicking-print

Prior to 2020, the highest altitude test of PSCs was the Optical Sensors based on CARbon materials (OSCAR) high-altitude balloon mission[24]. OSCAR's PSCs experienced a severe loss in power efficiency (5%) over the duration of their flight due to encapsulant failure under low pressure.[25] [26] Additionally, while OSCAR collected valuable data on the performance of PSCs at high altitude, it did not study PSC performance in the space environment, as BSE proposes to do. Their experiment was fundamentally different for two reasons. Firstly, the spectra of incident photons—a key factor in the performance of solar cells—is different in orbit. Secondly, OSCAR did not reach heights where the PSCs would experience full vacuum; no conclusions could be made about PSCs' viability in space.

In September 2020, PSCs reached another milestone: they were flown on a rocket flight for the first time[27]. Cells' JV curves were measured during the rocket's 6 minute flight time, some of which was in low earth orbit. The PSCs reached power densities of 140 W/m^2, comparable to silicon PVs, with no loss in power efficiency during flight. Although this experiment demonstrates PSCs' viability as promising candidates for use in space, it cannot determine the long-term effects the space environment may have on PSCs.

PSC Testing on PVDX

PVDX's mission is a logical next step to test the suitability of PSCs in the radiation spectrum, thermal conditions, and near-vacuum of low earth orbit. BSE will collaborate with Brown Materials Science Professor Dr. Nitin Padture to fabricate, coat, and test PSCs. We anticipate that if PVDX remains operational for over 6 months, we will have enough data to characterize PSCs. Our previous satellite, EQUiSat, has remained operational for over two years. While such long lifetimes are not guaranteed, especially on larger CubeSats, based on consultations with Dr Padture's research team, we believe that we will collect enough data to investigate the long-term effects of the space environment on PSCs.

Specifically, PVDX will perform a phenomenological experiment that aims to 1) evaluate PSC performance in space and 2) determine the rates and mechanisms of degradation of PSCs in a low earth orbit environment. PSCs performance will be primarily evaluated using J-V curves. PSCs will be integrated—but non-critical—components of PVDX's power system, allowing us to evaluate their ability to provide power to a satellite. PVDX will also monitor PSC degradation using *J-V* curve measurement, visual inspection, and PSC environmental conditions using temperature and light sensors. Gallium arsenide (GaAs) PV cells will serve as a control for this experiment and will undergo the same characterization methods as the PSCs.

PSC current density vs. voltage plots (J-V curves) allow BSE to measure PSC performance and diagnose causes of degradation. As discussed further in the Appendix III,

[24] https://arxiv.org/ftp/arxiv/papers/1709/1709.01787.pdf
[25] https://www.researchgate.net/publication/325821336_Methodology_of_the_first_combined_in-flight_and_ex_situ_stability_assessment_of_organic-based_solar_cells_for_space_applications
[26] https://www.researchgate.net/publication/321098135_BEXUS_23_OSCAR_Solar_Cell_I-V_Monitoring_System_for_Space_Environments
[27] https://www.sciencedirect.com/science/article/abs/pii/S2542435120303226

Section A: Additional Technical Documentation ('Payload, Using JV Curves to Diagnose PSC Failures'), J-V curve parameters serve as indicators for different types of PV cell degradation. These include open circuit voltage, short circuit current density, maximum power point, and fill factor; changes in these parameters can implicate different causes of degradation (e.g. thermal stress or glass corrosion).

However, J-V curves alone cannot distinguish between chemical decay (e.g. deterioration of the light-absorber in the PSC) and mechanical decay (e.g. glass corrosion, microcracks, or uncoupling of layers). However, the former results in a visible change in the color of the PSCs from black to yellow/brown, while the latter does not. Thus, the J-V curves and imaging data of PSCs will allow BSE to identify the cause of degradation.

Both J-V curve measurement and visual inspection will be performed around 3-4 times per day. Since PSCs experience a 20% decrease in efficiency over 1 year terrestrially, taking this measurement frequency will provide sufficient time resolution to characterize degradation.

Secondary Focus Area: Education and Engagement

PVDX's secondary mission focuses on promoting access to and interest in space. In doing so, the project aligns with Strategic Objective 3.3 by contributing to the advancement of STEM education in three ways:

I. Offering experiential learning to BSE team members
II. Empowering middle school students to interact with space
III. Improving the accessibility of CubeSat design for other student groups

In approaching the design of our mission, we hoped to incorporate ways to share our excitement with students across the country who could be encouraged by our example while contributing to our own community at Brown.

I. *Experiential Learning for Undergraduates*

PVDX will offer undergraduate students at Brown University and the Rhode Island School of Design the opportunity to engage in hands-on aerospace engineering. For members of our team, designing and prototyping PVDX systems is their first, most comprehensive exposure to space systems and experiential learning in engineering. It allows them to complement theoretical knowledge acquired from classes with practical application. Undergraduate students design all satellite subsystems, select and acquire components, and implement all aspects of construction, integration, and testing.

II. *Platform for Middle School Students to Interact with Space*

PVDX will serve as a platform for direct interaction with space for middle-school students. One small face of the satellite will feature an LED display. Users can upload "programs" to the satellite that represent a pattern to be displayed through our website and mobile applications. The camera mounted on the robotic arm can then take a picture of the display. We envision this interaction as an approachable way for students to understand how communicating with and controlling a satellite works. We hope to conduct education sessions at neighbouring schools to talk about the work our team does, and show students how they can get involved in aerospace design and engineering at the college level.

We plan on complementing these sessions with programming tutorials. Computer Science education ties particularly well with PVDX's mission; we will develop an associated curriculum to empower students to write and run the programs to display images, and learn basic algorithms. These sessions and tutorials will also lay the groundwork for interactive satellite exhibits and talks that can be implemented at schools, observatories, libraries, museums, or events for students and scout groups.

We have a commitment to collaborate with White Mountain Science (WMS), an organization that develops STEM programs for schools in New Hampshire. After conducting a Merit Review of our proposal, Dr. Kim Arcand of the Harvard-Smithsonian Center for Astrophysics (CfA) expressed interest in our education efforts, and invited us to collaborate with the institution's Science Education Department. Her team will guide us through the following:

1) Curriculum development: CfA currently offers curricula, courses, activities and a digital catalog for schools. Our curriculum will be designed in consultation with CfA staff to complement existing resources.
2) Formative evaluations: CfA will help us test our curricula and applications with focus groups of students, so we can improve our offering over time.
3) Implementation: Our curriculum will be integrated with the CfA catalog; we will run workshops in collaboration with CfA and their partner institutions.

Signed commitments from WMS and Dr. Arcand are included in Appendix II: Compliance Documentation and Commitments, Section B. We are in discussions with schools in the New England area, and hope to work with student groups at Brown that run tutoring programs at local schools to further develop education sessions prior to PVDX's launch.

III. CubeSat Design Resource for Student Groups

We seek to lower the barriers of entry to the aerospace industry for other student groups by increasing the accessibility of satellite design. Our team will use low-cost, off-the-shelf components so that our designs can be replicated by student groups with access to only a machine shop. Our website and GitHub portal provide access to all our documentation, designs, and code. The following subsections describe the various public engagement avenues we are developing to fulfil the three education goals outlined above:

Website and Tracking Apps

BSE's website (brownspace.org) and mobile applications will serve as the primary mode of engagement with students across the country. The website will serve as a hub for documentation. We will provide tutorials detailing important design motivations and procedures. These resources, coupled with our efforts to engage directly with student groups who reach out for assistance, will enable other teams to reproduce our designs. We aim to turn our website into a "one-stop shop" for those interested in CubeSat development.

We are active on social media and engage with the CubeSat and amateur radio communities through student organisation coalitions, a ground station network, and public events. In the last few years, we have offered technical assistance to 13 university CubeSat and aerospace engineering teams from eight different states based on our experience designing EQUiSat. Uploading PVDX designs to our website will enhance our ability to facilitate other student groups' engineering process.

The website and mobile applications will share the following functionality:

1) Tracking: once PVDX is on orbit, interested students will be able to use them to track the satellite, stay updated on its condition, and view downlinked telemetry. They will feature data received both from BSE's ground stations and by other amateur radio operators.
2) Interaction: users will be allowed to write short programs in a simplified programming language that we will convert to a sequence of satellite commands to be uplinked. We will collect contact information through an online form, notify users when their command sequence is run on the satellite, and send them pictures of the display after our ground stations download them.
3) Engagement: users will be able to view a gallery of downlinked images, and leave reactions including 'likes' and 'comments'

BSE is currently developing the web, iOS and Android phone applications. These will be extensions of apps previously developed to track EQUiSat. Currently, they primarily feature the 'tracking' component, including visualizations of the satellite's location, telemetry data, and a method for signing up to receive notifications as the satellite passes overhead. We hope that with the addition of interaction and engagement elements, these platforms will help build a community around tracking and executing programs on the satellite, thereby encouraging interaction with the satellite and its other followers.

Partnerships with University Student Groups

Information on affordably designing a CubeSat from start to finish is sparse. BSE aims to fill this gap. Aside from having open-source resources, we engage and host events with other undergraduate student organizations focused on aerospace projects. More details about these partnerships can be found in Appendix III, Section C: Education and Engagement Plan.

Radio and Amateur Satellite Community

The communications system of PVDX has been designed to provide easy accessibility to both the general public and amateur radio enthusiasts. Sensor data regarding the health and operations of the satellite will be receivable by amateur radio operators, so that BSE and other radio operators can learn from PVDX's function in orbit.

PVDX's RF modulation and frame encoding scheme will be easily received and decoded by members of the amateur radio community or university teams using open source software receivers designed by BSE. These decoders will be based heavily on one successfully used with

EQUiSat and will be compatible with commercially-available software-defined radios (SDRs). In addition, BSE plans to work with the Libre Space Foundation to integrate these software decoders into their global SatNOGS network of open satellite ground stations, as other CubeSat teams have done in the past. This will allow any ground station operator in the SatNOGS network to receive and decode PVDX packets, while also publishing the packets online to the SatNOGS database and BSE's website to assist in the monitoring of the satellite.

BSE will also offer a website (similar to decoder.brownspace.org made for EQUiSat) where users can upload and decode FM audio recordings of the satellite received using an SDR or handheld radio and home-made antenna. Listeners could then upload the data they received to BSE's telemetry database, allowing everyone to contribute their receptions to the PVDX website. We are exploring turning this into a workshop for middle school students; our team would walk students through the process of preparing basic receiving equipment and collecting data from PVDX. Appendix III, Section C: Education and Engagement Plan offers further information on how our communications system and image transmission protocol will be designed to enable consistent engagement with PVDX.

Summary of Compliance and Eligibility Requirements

Brown Space Engineering is a student group at Brown University. Brown University is an accredited U.S. Educational Institution. A signed certification letter can be found in Appendix II: Compliance Documentation and Commitments, Section A. Brown University's School of Engineering and the Rhode Island Space Grant have committed to providing BSE funding that will total over $8,000 per year. We anticipate this being fully adequate to perform research and development for PVDX and support public engagement activities. Letters of support outlining these funding commitments are included in Appendix II, Section B after the certification letter mentioned above. Additionally, a breakdown of anticipated yearly development costs is available in Appendix III, Section E: Project Management under 'Annual Budget'.

PVDX is being designed to satisfy all requirements laid out in the 'Launch Services Program, Program Level Dispenser and CubeSat Requirements Document (LSP-REQ-317.01B)' without the need for any waivers; detailed notes on this can be found in Appendix II, Section C.

Review Process

BSE conducted a multi-step review process of the PVDX proposal. We reached out to a panel of qualified reviewers with experience across academia, public service, and the private sector. None of the reviewers were involved with the project at the time of solicitation or when they eventually provided their review. Our committee of external Merit Reviewers included:

1) Dr Jim Newman, a former NASA astronaut and physicist who flew on four Space Shuttle missions. Newman is currently a member of the faculty at the Naval Postgraduate School, where his research focuses on using small satellites in hands-on education.
2) Dr Pete Worden, former Director of NASA's Ames Research Center. Dr Worden has served as a scientific co-investigator for two NASA space science missions and served on both the National Space Council and the Air Force Space Command. Currently, he serves as the Chairman of the Breakthrough Prize Foundation

3) Dr Jim Head, Distinguished Professor of Geological Sciences at Brown University. Dr Head trained astronauts and studied samples for the Apollo program, and has served as a lead investigator on many major international planetary investigation missions.
4) Dr Peter Schulz, Director for the Northeast Planetary Data Center and the NASA/Rhode Island University Space Grant Consortium. Dr Schultz is a Professor of Geological Sciences at Brown University, former research associate at the NASA Ames Research Center, and former Director of the Lunar and Planetary Institute Planetary Image Facility.
5) Dr Kimberly Kowal Arcand, Visualization Scientist & Emerging Technology Lead at the Smithsonian Astrophysical Observatory. Dr. Arcand has been the principal investigator for numerous NASA-funded programs. She is also a celebrated science communicator, and has experience designing STEM curricula for students of all ages.

Our committee of external Feasibility Reviewers included:

1) Dr Jon Arenberg, Chief Engineer for Space Science Missions at Northrop Grumman. Dr Arenberg has led Northrop's work on the James Webb Space Telescope, and has over 30 years of experience working on astronomical programs such as the Chandra X-ray Observatory. He has previous experience testing novel solar cell technologies and designing a gravity-gradient ACDS for small satellites.
2) Kenneth Rock, Satellite Systems Engineer at Iridium. At Iridium, Rock works as a Platform Engineer for NEXT and Legacy Block 1 Systems; he has expertise in Attitude Determination and Control, Data Handling, and Electrical and Power systems.
3) Adam Greenbaum, former Space Systems Engineer at Draper Laboratory. Greenbaum worked for 11 years on Draper's Space Systems team, and is currently a Systems Engineer/Architect at Amazon Robotics.
4) Ray Zenick, former Lead RF Engineer for AeroAstro, Inc., a small satellite manufacturer. Zenick has over 35 years of experience as a design specialist with extensive background in circuit and systems design for spacecraft.

Merit and Feasibility Review Rubrics, designed under Dr Fleeter's guidance, can be found in Appendix III, Section G: Review Board Outcomes, followed by the reviewers' written responses. The non-competitive review process was as follows: each reviewer was given the option to meet with the team virtually and/or provide written feedback. To reviewers who selected the former, we presented our mission and provided them the appropriate rubric. We then conducted a question and answer session where we noted feedback on the strengths and weaknesses of the mission. Some reviewers also provided notes from these sessions. For reviewers who chose to provide written feedback, we provided the proposal and applicable rubric. We also asked for additional, general feedback on areas we saw as critical internally.

Dr. Newman and Dr. Worden requested a presentation and provided written feedback. Dr. Head invited us to present during one of his research group's meetings. Dr. Schultz provided written feedback. Dr. Kowal requested a presentation. Dr. Arenberg requested a presentation and provided brief written feedback. All the other Feasibility Reviewers provided written comments.

The factors used to assess both merit and feasibility can be seen in the sample Review Rubrics in Appendix III, Section G mentioned above. Overall, Merit Reviewers felt that both focus areas of the PVDX mission possessed merit. Reviewers highlighted the value of PVDX's

PSC demonstration for both its direct testing of new technology and its role in influencing potential future use cases. Several reviewers praised the PVDX mission's novel and multi-faceted approach to education and engagement. Dr. Arcand's decision to offer BSE an opportunity to collaborate with the CfA speaks particularly to the merits of the education efforts.

Feasibility reviewers found the project to be feasible overall and accomplishable by BSE. They found that our subsystems generally use tried-and-tested technical solutions, and gave the mission a high probability of success. They expressed confidence that BSE had necessary expertise and financial support, and were particularly impressed by the team's past CubeSat experience with EQUiSat. Reviewers were asked to note potential sources of risk within each subsystem; their overall determination was that systems were designed according to standard protocols and sufficiently addressed development risk.

Additionally, this holistic review process gave us actionable insights regarding both areas of focus of our mission, and robust technical feedback on all major satellite subsystems. Based on the reviews, we made the following major changes to our approach:

1) Experimental design: based on feedback from Dr Newman and Dr Arenberg, we designated a set of GaA cells on the same face as the PSCs to be the control group, and set up the experimental methodology above.
2) Target groups for education: based on feedback from Dr Arcand and Dr Head, we decided to focus specifically on middle school students for our educational initiatives, instead of focusing on K-12 education broadly.

All reviewers suggested minor modifications to experimental design, education and engagement strategy, and satellite architecture; this feedback was discussed with Dr. Fleeter and addressed ahead of Proposal submission. Documentation of the alterations made based on reviewer feedback is available in Appendix III, Section H: Modifications to Design Based on Review Board Outcomes. All Reviewers offered to continue advising BSE through the development cycle. The team remains in contact with them, and plans to periodically share updated designs, progress, and any technical queries with them for further review.