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A Bimodal Science Measurements for Earth Remote Sensing on a 3U CubeSat Platform

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ABSTRACT

Solar energetic events, which include solar flares and solar mass ejections affect the Earth's atmosphere. While solar energetic events have been observed to influence the chemistry of the mesospheric ozone, a comprehensive collection of quantitative data detailing the frequency, energy, and intensity of these interactions with the mesosphere have, to our knowledge, not before been collected. High-energy charged particles from solar energetic events can ionize molecules found within the mesosphere, accelerating the formation rate of reactive hydrogen atoms and nitrogen oxides. This results in reactions that catalyze the conversion of ozone back into diatomic oxygen. The Variability in Atmosphere – Solar Energetic Event study (VIA-SEEs) mission intends to utilize a 3U-CubeSat in Low Earth Orbit (LEO) to establish a singular data set for the purpose of understanding the correlation between flux in solar energetic events and variability in total reactive nitrogen oxides (NO_y) and ozone (O_3) concentrations in the mesosphere. This mission intends to produce a unique data set using a bimodal measurement scheme involving two instruments – one Variability in Atmosphere (VIA) commercial-off-the-shelf spectrophotometer for measuring NO_y and O_3 concentrations, and one in-house designed and fabricated solid-state radiation detector for observing the energy and flux of solar energetic electrons and protons.

INTRODUCTION

A critical component of the NASA Heliophysics Roadmap for Science and Technology for 2009-2030 focuses on the role of the Sun and its variability in driving terrestrial change with a special focus on the atmosphere's response to auroral, radiation belt, and solar energetic particles on mesospheric nitrous oxide and ozone concentrations.[1]

The study of the effects of radiation on the atmosphere began with the discovery of the increase in ionizing radiation with altitude by V.F. Hess[2] and the discovery of Earth's radiation belts by Van Allen et al. (1958)[3]. The first measurements of the effect of solar energetic events on the concentration of ozone were reported by Weeks et al. (1972)[4]. Two suborbital missions launched during solar energetic events in 1969 carrying an ozone spectrophotometer established a significant drop in atmospheric ozone concentration ascribed to charged particle precipitation. Subsequent measurements of backscattered UV light, obtained by the Nimbus 4 meteorological satellite in LEO during a solar energetic event confirmed the impact of radiation on ozone concentration (Heath et al. 1977).[5] Subsequently the important role of proton precipitations was established.[6] The knowledge of energetic particle effects on Earth's atmosphere and the mechanisms that affect the ozone layer climate were summarized by Miranova et al. (2015) and Rozanov (2018).[7,8]

Atmospheric scientists relate the influence of solar energetic particles on ozone depletion to the increase in ionization in several atmospheric layers, leading to the enhanced formation of odd hydrogen HOx then affecting the depletion of ozone (Solomon et al. 2022)[9]. An international research team from Japan, the United States, and Canada studied a type of aurora called an "isolated proton aurora". This type of aurora has revealed a cause of ozone depletion that comes from Earth's radiation belt. The isolated proton aurora caused a nearly 250-mile-wide hole in the ozone layer. Furthermore, the damage left behind in mesospheric ozone repairs itself more quickly than holes in stratospheric ozone. Observational studies show that radiation belt electron fallout from space around the Earth has a direct, immediate, and localized effect on atmospheric changes in the mesosphere.[10,11] Findings from our study are expected to contribute to an improved prediction of short-term changes in the Earth's atmospheric environment by considering the effects of atmospheric ionization by high-energy plasma from space.

Our data contributes to model calculations in the fields of atmosphere and space weather by providing real-time observations of various atmospheric parameters. By integrating real-time observations of various atmospheric parameters into sophisticated models, we can accurately simulate atmospheric conditions and predict weather patterns. Additionally, our data feeds into space weather models, enabling us to analyze solar events and their potential impacts on Earth's magnetosphere and technological infrastructure.

RESEARCH OBJECTIVES

Project VIA-SEEs intends to utilize one 3U CubeSat in Low Earth Orbit (LEO) to measure the direct correlation between Solar Energetic Events (SEEs) and the variabilities in the total reactive Nitrogen Oxides (NOy) and Ozone (O_3) concentration in the mesosphere, thereby enhancing our understanding of how our atmosphere changes in response to solar particle radiation.

The specific science goal/objective of VIA-SEES is to determine with precision the impact solar electrons ranging from 10-2000 keV have on the degradation of mesospheric gasses NO, NO_2, and O_3. While remote sensing data on solar energetic electrons and mesospheric composition spectra have been collected by separate missions, to our knowledge no previous mission has flown two instruments on a single spacecraft bus to collect a unified coordinated data set with high time resolution.

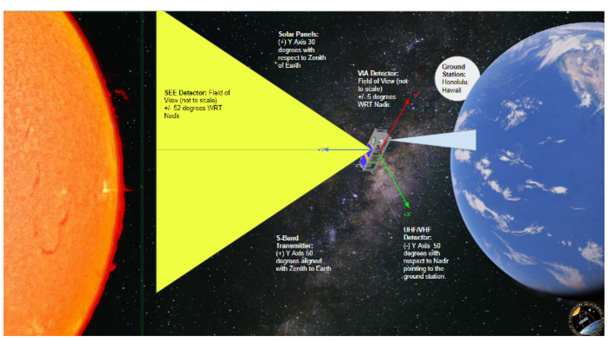

Figure 1: Spacecraft Orientation and detector FOVs

To achieve the science goals, the spacecraft must be in highly inclined LEO covering areas subject to relativistic electron precipitation and proton irradiation of the mesosphere. The proposed orbit should have an altitude of ~415 km with an inclination exceeding 85 degrees. This will allow the measurement of the UV-VIS wavelength reflectance to detect ozone, NO_x, and other atmospheric components with a spectrophotometer. At this altitude and inclination, the radiation detector can measure relativistic electrons in the range of 10 keV to 2000 keV and will also be able to measure protons of up to 80 MeV. The original design of the radiation detector was a semiconductor-based detector telescope, modeled after the REPTile I instrument.[12,13,14,15]

The optimal mission operation time frame is before, during, and shortly after a solar maximum, enhancing the probability of observing multiple solar particle events. The next solar maximum (SC25) is predicted for July 2025 but could be as early as between the last quarter of 2023 and last quarter of 2024.[16,17] This will place both programmatic opportunity and constraints on mission development, for spacecraft delivery, mission lifetime, and launch date.

For the VIA-SEEs project, we have combined two heliophysics roadmap science goals into one science objective which requires two instruments that simultaneously measure atmospheric gas concentrations and precipitating solar energetic event particles that are known to affect them.[1] The relationship between the science goals, the science objective, and desired science measurements are provided in in Table 1. To achieve our science the mission payload must measure atmospheric gasses and precipitating radiation simultaneously.

Title	Explanation
Science Goals	Understand the Earth's atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on Nitric Oxide (N_2O) and ozone. Understand the role of the Sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects.
Science Objectives	Determine the baseline levels of atmospheric ozone in non-SEP intervals and the size of ozone depletions, before, during, and after solar energetic particle events.
Science Measurement Requirements (VIA): Physical parameters, and Observables.	Define the variability in nitric oxide (N_2O), total reactive nitrogen oxides (NO_y), and ozone (O_3) production and depletion before, during, and after solar energetic particle events. The instrument shall be able to distinguish between the reflectance spectra of ozone, nitric oxides, and other gasses found in the mesosphere. (200-500 nm range)
Science Measurement Requirements (SEE): Physical parameters and Observables.	The instrument shall distinguish between electrons, and solar protons, before, during, and after solar energetic particle events. Define the local energy flux of 10-2000 keV electrons, <80 MeV protons. Observe auroral electrons 10-30 keV, medium energy electrons 30-300 keV, and relativistic electrons 300-2000 keV.

Table 1: Science Goals and Objectives

The VIA-SEEs he mission's success is dependent on measurements during at least three solar energetic events while the spacecraft is in Earth's polar regions.

The optimal mission operation time frame is before, during, and shortly after a solar maximum. A launch in Q1-2025 with an expected mission lifetime of six months or more would provide opportunities of observing multiple solar energetic particle events as the next solar maximum is in July 2025 .[16,17] Most atmospherically effective particle precipitations occur in polar and circumpolar regions. Therefore, the mission must be in a highly inclined LEO at ~415 km to cover the areas of interest.

High-fidelity data sets collected by two instruments, a UV-VIS spectrophotometer, and a particle spectrometer, are anticipated to provide valuable data inputs into quantum chemistry models, atmospheric models, and general statistical models.

SCIENCE INSTRUMENTATION

Variability In Atmosphere (VIA) Detector

The Variability In Atmosphere (VIA) detector is necessary to understand the atmosphere's response to auroral, radiation belt, solar energetic particles, and their associated effects on nitrous oxide and ozone. To study this relationship, our mission must be equipped to measure UV-VIS scattering or reflectance. The spacecraft will have a spectrophotometer onboard that will measure photons released by the molecular dissociations caused by solar electrons in the mesosphere. The variability in both nitrous oxide and ozone production, and depletion, before, during, and after solar energetic particle events will be measured. Because the reflectance spectra of nitrous oxide are at 195-230 nm and ozone spectra are at 200-350 nm, our instrument will need to be able to analyze within the UV range of the electromagnetic radiation spectrum as shown in Figure 2.

The VIA detector is a COTS complementary metal-oxide semiconductor (CMOS) spectrophotometer from Avantes AVASpec Compactline, model AVASpec-Mini2048CL, which has previously flown onboard a 3U CubeSat mission out of UC Boulder in 2017 (Radiance 2017) currently possessing a TRL of 6. The AVASpec-Mini2048CL can collect spectra within ultraviolet and visible light ranges with a usable range between 200-1100 nm and is, therefore, able to measure the ozone and nitrous oxide reflectance spectra that we seek surrounding solar energetic particle events. The AVASpec-Mini 2048CL can be seen in Figure 3.

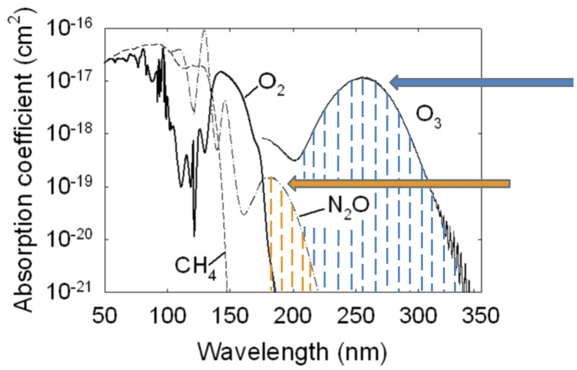

Figure 2: Absorption Spectra of N_2O and O_3 , Segura et al., (2005)[18]

Figure 3: AvaSpec-Mini 2048CL

The AvaSpec-Mini2048CL is 9.5 x 6.8 x 2.0 cm and will be placed flush along the far internal nadir side wall of the spacecraft, providing maximum clearance for the SEE detector which will be placed adjacent to the spectrophotometer, this configuration allows for both instruments to suitably fit within the 1U payload bay for this application. Placement of the instrument can be seen outlined in Figure 5 on the most updated CAD model for the spacecraft.

VIA Detector Calibration

The VIA-SEEs mission aims to utilize a spectrophotometer (AvaSpec-Mini2048CL) capable of measuring UV-VIS reflectance spectra of the atmosphere in conjunction with a solid-state radiation detector telescope (SEE). The instrument calibration process is critical to determine whether the detector's ability to measure the desired spectra, absorption or reflectance peaks from the atmospheric gasses in particular ozone and nitrous oxide. The calibration will also identify if the atmospheric components can interfere with ozone and nitrous oxide. The measurements are intended to provide data to answer atmospheric chemistry questions, whether there is a distinct correlation between SPEs and ozone concentrations in the mesosphere. The testing apparatus has been designed and built in a calibration chamber that can hold the gasses in an airtight dark environment. The testing chamber is installed with the gas input/output, fiber optic cable, and a light source. The collected data from the calibration experiment will help determine whether the instrument could function properly and is able to obtain absorbance and reflectance spectra in the wavelength zone of ozone and nitrous oxide. The research data are useful to support the VIA-SEEs project and other atmospheric research missions with CubeSats.

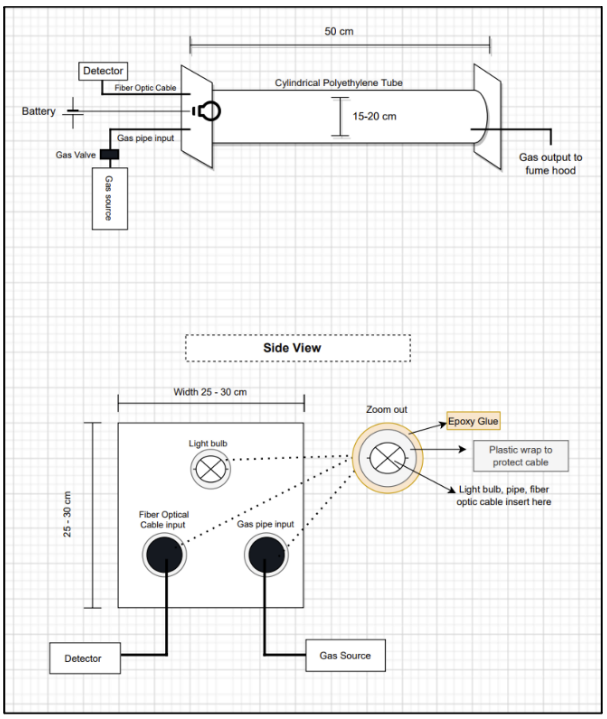

Figure 4: Calibration chamber for VIA detector

The VIA-SEEs mission aims to utilize a spectrophotometer (AvaSpec-Mini2048CL) capable of measuring UV-VIS reflectance spectra of the atmosphere in conjunction with a solid-state radiation detector telescope (SEE). The instrument calibration process is critical to determine whether the detector's ability to measure the desired spectra, absorption or reflectance peaks from the atmospheric gasses in particular ozone and nitrous oxide. The calibration will also identify if the atmospheric components can interfere with ozone and nitrous oxide. The measurements are intended to provide data to answer atmospheric chemistry questions, whether there is a distinct correlation between SPEs and ozone concentrations in the mesosphere. The testing apparatus has been designed and built in a calibration chamber that can hold the gasses in an airtight dark environment, see Figure 4. The testing chamber is installed with the gas input/output, fiber optic cable, and a light source. The collected data from the calibration experiment will help determine whether the instrument could function properly and is able to obtain absorbance and reflectance spectra in the wavelength zone of ozone and nitrous oxide. The research data are useful to support the VIA-SEEs project and other atmospheric research missions with CubeSats.

The AvaSpec-Mini2048CL has a mass of 175g, accounting for 14.89% of the total payload and just 5.11% of the total mass budget for the spacecraft. The integration of the VIA instrument will require sufficient thermal shielding, as well as careful laboratory calibration and testing. Typical maximum power budget for a 3U CubeSat range from 7-20 Watt-hours (Wh), and the Avaspec-Mini 2048CL has a power input with a default USB power at 1.25W. The total power budget for the spacecraft is approximately 15Wh which is within the range of maximum power budget 7-20Wh and the AvaSpec-Mini2048CL consumes approximately 4.73% of the total power budget.

Solar Energetic Event (SEE) Detector design

Several particle telescope design concepts have been developed and are utilizing the Monte Carlo-based GEANT 4 code. The first SEE detector design has been adapted, with modifications, to measure electrons and protons from the REPTile detectors .[12,14] Modifications considered for this concept included the use of Silicon Carbide detector materials with expected better performance in the high radiation environment expected during SEEs during, our most important science measurement activities. It also included the use of adaptive instrument logic in data acquisition. This feature implies that the SEE instrument can adapt to environmental conditions to provide better science readings. After a recent review the approach was considered for further development yet is to be replaced by a new concept using time of flight and energy loss to identify particles and quantify particle fluxes.

The new design concept of the SEE detector will significantly benefit from parallel and advanced developments for space radiation detection, the CubeSat Relativistic Electron and Proton separator (CREPES) mission. The CREPES mission is utilizing the Artemis 1U CubeSat Kit as the baseline for its CubeSat bus.[19] The primary mission of the CREPES satellite is to provide a cost-effective and compact satellite capable of monitoring high energy electrons and medium energy protons in low Earth orbit, compatible with VIA-SEEs research goals.

The CREPES detector concepts include the use of Gas Electron Multiplier (GEM) detectors developed by Fabio Sauli of the Conseil Européen pour la Recherche Nucléaire (CERN) Gas Detectors Development Group.[20] The detector array will utilize the position sensitivity of the GEM detectors and/or time of flight techniques to characterize relativistic electrons and protons emitted in solar energetic events.[21] VIA-SEEs adaptation of the CREPES concepts is underway with the preliminary design review scheduled for the start of the 2023 fall semester.

The Payload locations for the VIA and the SEE instrument are shown in Figure 5.

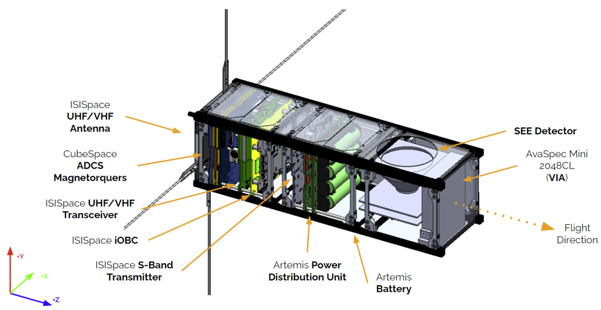

Figure 5: Payload Location for VIA and SEE

CONCLUSIONS

The VIA-SEEs mission will be minimally successful if the payload instruments collect datasets with high time resolution for at least one solar energetic event while passing through polar regions and transmitting them to Earth for processing. The mission will be successful if several similar datasets are collected for more than three SEEs and are transmitted to Earth for processing, allowing for detailed analyses of the solar energetic event-atmospheric effect mechanisms.

The mission payload is designed to provide data sets that may reveal new relations between particle flux timing and intensity and atmospheric effects on fine time scales. The mission launch window, a highly inclined orbit, and the planned lifetime of six months or more during solar maximum increase the probability of obtaining a minimum data set for a meaningful science outcome.

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