

Systems Architecture and Conceptual Design of a CubeSat Formation Serving as a Distributed Telescope

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The Virtual Super-Resolution Optics with Reconfigurable Swarms (VISORS) mission is a multi-CubeSat distributed telescope which will image the solar corona to investigate the existence of underlying energy release mechanisms. Such a task requires angular resolutions of less than 0.2 arc-seconds in extreme ultraviolet, which cannot be economically done with a conventional space telescope. Performing such a mission requires unprecedented relative navigation tolerances, a need for active collision avoidance, a development of inter-satellite communication, and a propulsion system that enables the relative navigation maneuvers. The mission was initially conceived as a three 3U satellite formation in the NSF CubeSat Innovations Ideas Lab to address NSF science goals with innovative technologies. Once beginning conceptual subsystem design, it was evident that significant constraints linked to the three 3U satellite formation configuration limit the likelihood of mission success and increase mission risk. A trade study was conducted to determine potential resolutions to the problems associated with the initial three 3U satellite formation configuration. The completion of the trade study resulted in a major design change to a two 6U satellite configuration that resolved the issues associated with the initial configuration, improved mission success while reducing risk, and intends to incorporate novel CubeSat technologies, all of which enable the mission to move forward. This paper discusses the path that led the team to conduct the trade study, the design alternatives considered, and the innovative subsystem technologies that were conceived as a result of updating the satellite formation configuration.

I. Introduction

A. Mission Overview

The solar corona exhibits highly dynamic behavior which results in its temperature rising to 1000 times hotter than the visible surface of the sun [1]. Prior investigations utilizing soft x-ray and extreme ultraviolet (EUV) imaging techniques detail potential causes for such heating; however, this severe temperature difference remains an open problem in space plasma physics. The primary hypothesis is that the coronal heating is confined to narrow current sheets on the order of 100 kilometers. This conjectured existence of thin heat-release sites is significant as it pertains to an encompassing “major outstanding science question” in the National Science Foundation (NSF) Geospace Section planning document: “How magnetic reconnection works and operates in the solar atmosphere, within the solar wind, at the dayside magnetopause, and in the magnetotail to initiate and facilitate energy transfer between the different regions of the space environment” [2]. The relative size of the hypothesized heating sheets poses a challenging remote sensing problem: the imaging resolution required to observe the heat-release regions from Earth orbit is on the scale of 150 milli-arcseconds. Such performance is beyond the capabilities of existing EUV coronal imagers, and scaling of the optics imposes infeasible design requirements on traditional, single-vehicle spacecraft, which explains why the science of coronal heating remains as a long-standing question.

The high imaging resolution required to observe the hypothesized heat-release sites in the solar corona entails that a proposed mission would require novel imaging technology supplemented with innovative spacecraft engineering to achieve the science objectives. A mission solution for the aforementioned coronal heating science problem was

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conceived at the NSF CubeSat Innovations Ideas Lab in 2019 and employs a cube satellite (CubeSat) formation. This formation aligns to form a sun-pointing “distributed telescope” in Low Earth Orbit and utilizes a diffractive-based imaging technology to collect coronal imagery at the required resolution for the heat-release sheets. The mission was appropriately named “Virtual Super-resolution Optics using Reconfigurable Swarms (VISORS)”, and its proposal was selected by NSF in 2019 to proceed with a flight demonstration.

B. Concept of Operations

Fig. 1 visualizes how the originally proposed three 3U satellite formation, when aligned, forms the distributed telescope to capture images of the solar corona. The optics spacecraft (OSC) is the satellite in closest proximity to the sun and houses a photon sieve, which is a diffractive optic technique built upon the canonical Fresnel zone plate [3]. The photon sieve is placed off-center in the OSC which allows the formation to rotate about the boresight vector to image various regions of the sun. The sunshade spacecraft (SSC) is behind the OSC and serves to prevent unwanted EUV radiation from entering the detector. The detector spacecraft (DSC) is the third spacecraft and stores the camera, corresponding sensors, and a processor to capture the instrument measurements. The coronal region this telescope can image is also highlighted inside the darkened circle in Fig. 1. The 40m separation is a natural consequence of the required focal length between the OSC and DSC, and the 20m separation of the SSC from the DSC is to ensure proper blockage while maintaining a minimum distance for passive collision avoidance.

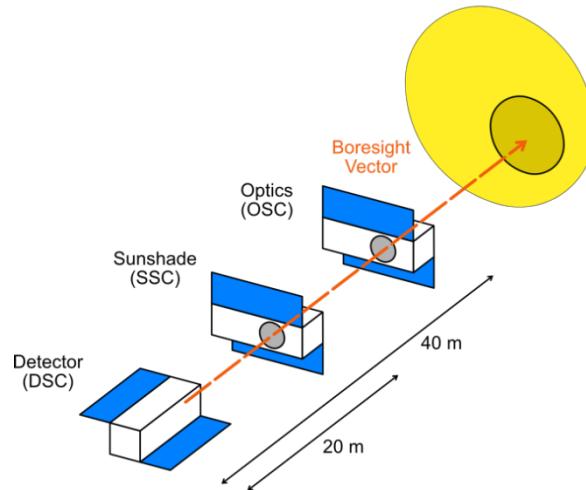


Fig. 1 VISORS Satellite formation when in alignment to collect coronal imagery.

Operationally, the VISORS mission can be stratified into two distinct modes. Upon release from the launch vehicle and startup, the spacecraft will assemble into a formation with a relative distance of approximately 100m. This standby mode will be used for routine operations such as battery recharging and downlinking to a ground station. Upon receipt of an uplinked command, the formation will enter science mode by performing a series of translational maneuvers to fly in the 20m-separated relative orbit. When in a favorable location along the Low-Earth orbit, the formation will drift into the alignment depicted in Fig. 1 to complete a measurement. The alignment shall be maintained for a minimum of 10s to obtain the required exposure for the detector. Several attempts to gather data will be executed before the formation exits the science mode relative orbit and returns to the standby formation. The spacecraft will downlink the collected images and perform its maintenance operations before another uplink command is delivered to collect observations. Fig. 2 summarizes the key operative modes for the VISORS mission.

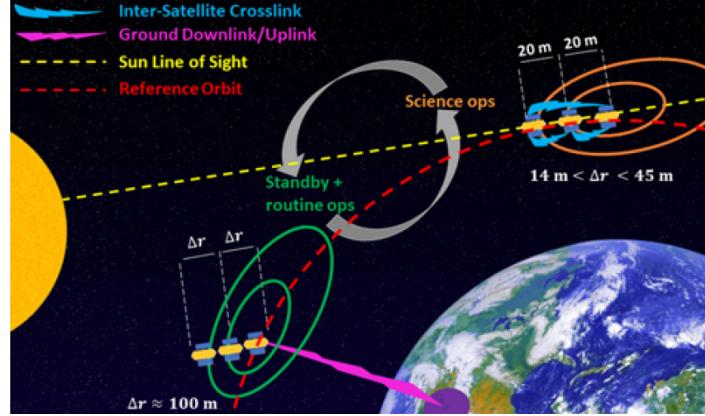


Fig. 2 Concept of operations for the VISORS mission.

The relative orbit is established with a technique named e/i vector separation as specified by D'Amico and Montenbruck [4]. This technique describes a relative orbit defined by the alignment of the relative eccentricity and inclination vectors and provides passive separation even in the presence of perturbations and uncertainty. Therefore, this approach provides multiple orbits of passive collision avoidance and degrades gradually as the relative vector alignment changes. When in science mode, the relative orbit still utilizes e/i vector separation but as depicted in Fig. 2, the relative distance between spacecraft is shortened from approximately 100m to 20m.

C. Key Mission Requirements

The telescope system distributed across the formation provides the required angular resolution to image the hypothesized sheet-like regions in the corona, but its sensitivity enforces strict requirements on the relative position and velocity errors when in alignment for data collection. The margins of error for key degrees of freedom when in this alignment are depicted in Fig. 3. The OSC lateral deviation from the DSC is restricted due to the boresight vector across the two vehicles that must be maintained, and the SSC lateral deviation from the DSC is restricted due to the vignetting that occurs if unwanted EUV radiation enters the DSC. The OSC cannot shift longitudinally during imaging in either direction past 13mm with respect to the DSC to maintain the nominal focal length. Furthermore, to prevent image blur no spacecraft can laterally drift at a rate greater than 200 $\mu\text{m/s}$. The margins of error portrayed in Fig. 3 highlight a significant design challenge; the VISORS mission team is not aware of any prior formation-flying mission that has established and maintained relative positions and velocities of this scale. Although each spacecraft shall be actively maneuvering to maintain its relative state, such close-proximity operations, when coupled with the notion that any onboard failure will severely impact performance, impose a risk of collision. Therefore, mission safety is a top-level mission requirement that flows down to active and passive safety considerations at the subsystem level.

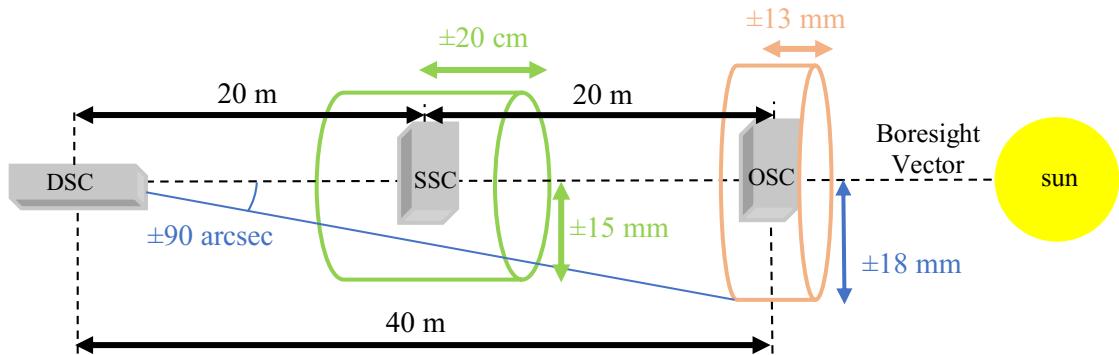


Fig. 3 Relative state requirements for the formation when aligned for collecting observations.

Meeting the relative state tolerances shown in Fig. 3 is not only driven by the science requirements but also is reinforced by the need to minimize uncertainty when computing the probability of collision. Since such probabilities are determined via state propagation, driving state uncertainties to the magnitude required for coronal observations will ensure that the formation can operate in the science mode relative orbit without frequently triggering a potential

collision avoidance maneuver. Standard GNSS solutions cannot provide the required relative state performance, so a spacecraft navigation system named DiGiTaL, or Distributed Timing and Localization, will be implemented on the spacecraft formation. Developed by Stanford University, an institution on the VISORS team, DiGiTaL employs carrier-phase observables between GNSS receivers on different spacecraft for millimeter-level accurate measurements of the vehicle relative states [5].

Since the DiGiTaL platform requires the GNSS raw measurements from each spacecraft to obtain the required estimation performance, a continual inter-satellite communication link (ISL) must be established between every satellite in the formation. Therefore, when in the science mode relative orbit, the ISL is a functional requirement that flows from the top-level science and mission safety requirements. To perform the relative translational maneuvers required to enter the science mode relative orbit and align for an observation, each satellite must also be equipped with a propulsion system. When preparing for an observation, the maneuver frequency will likely increase to once per minute so if any re-orientation of the thruster system is required, each spacecraft shall be required to slew and settle to the desired attitude within the current maneuver period. To minimize the attitude uncertainty to the tolerance required for an observation attempt, the star tracker must perform nominally as any degradation or occlusion can jeopardize the arcsecond-level pointing accuracy. Thus, the attitude determination and control system (ADCS) of each spacecraft has strict estimation and control performance requirements which flow from the operation and science requirements.

II. Design Constraints

The originally proposed three spacecraft formation created a number of driving requirements that made the mission more challenging. The design consequences created by this architecture choice are listed below.

A. 3U Volume Limitation

Since each spacecraft must fit within a 3U form factor, there is a significant limitation of volume available for the VISORS components. The mission intends to use Blue Canyon Technologies' (BCT) 3U bus, and through preliminary design it was determined that there is approximately 1.5U of available volume for all payload subsystems: propulsion, instrument, and ISL system. A ramification is that the functionality of these components is reduced due to the lack of volume availability. This can be most clearly seen with the propulsion and ISL systems. The overall payload volume constraints limit the propulsion system to only have one nozzle due to the physical design of the propulsion module. The ISL radio is limited to only side of the spacecraft, only allowing a communication link when that side is in the direction of another spacecraft in the formation. The antenna is shown notionally as the red rectangular prism above the blue propulsion system with its maximum surface area face parallel to the solar panels in Fig. 4.

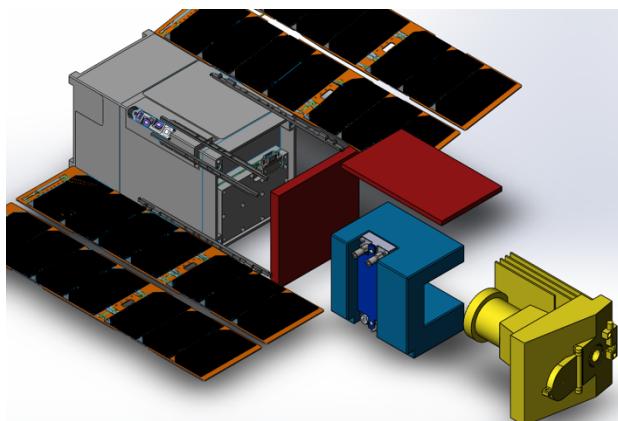


Fig. 4 Exploded view of 3U detector spacecraft payload section: propulsion (blue), detector (yellow), ISL (red).

The limitations of the available space in the 3U design naturally constrain mass and volume margins. Simply put, there is minimal margin for the physical growth of subsystems. This presents a concern as components are expected to increase in size as the design matures. Furthermore, the densely packed nature of each 3U bus imposes significant limitations on fastening, wiring, and harnessing and therefore will lead to additional complications in the integration and test phase of the mission.

The limited volume issue was also manifested in the decision of how the relative navigation software is executed. The DiGiTaL platform incorporates a distributed architecture where each spacecraft hosts the DiGiTaL software and thus will only compute its own maneuver plan; the only data transmitted between spacecraft are the raw GNSS measurements required to obtain an accurate relative position fix. This solution is robust to processor or computing failures on one vehicle; the two functional spacecraft can provide maneuver commands to the debilitated spacecraft and complete the mission objectives. However, each spacecraft must also store an additional processor to host the DiGiTaL software. Conceptual designs for the OSC and DSC have utilized all available volume due to the size of their respective science instruments and therefore an additional processor requires adjustments from other subsystems.

An alternative solution is the chief-deputy architecture where the SSC is the sole spacecraft to host DiGiTaL and is therefore denoted as the chief. The SSC must receive the raw measurements from the deputy vehicles, the OSC and DSC, and compute not only the relative states of all three spacecraft, but also the maneuver commands that the deputies must execute. The OSC and DSC will subsequently receive the maneuver commands and state estimates from the SSC. The consequence of having only one spacecraft host DiGiTaL is that no inherent robustness exists. Any failure on the SSC that hinders the usage of DiGiTaL will likely result in mission failure. Fig. 5 depicts the two potential GNC architectures. This GNC architecture trade study highlights the severity of the 1.5U payload volume constraint. While a possible solution exists, it increases operational complexity, reduces robustness, and therefore compounds to greater mission risk.

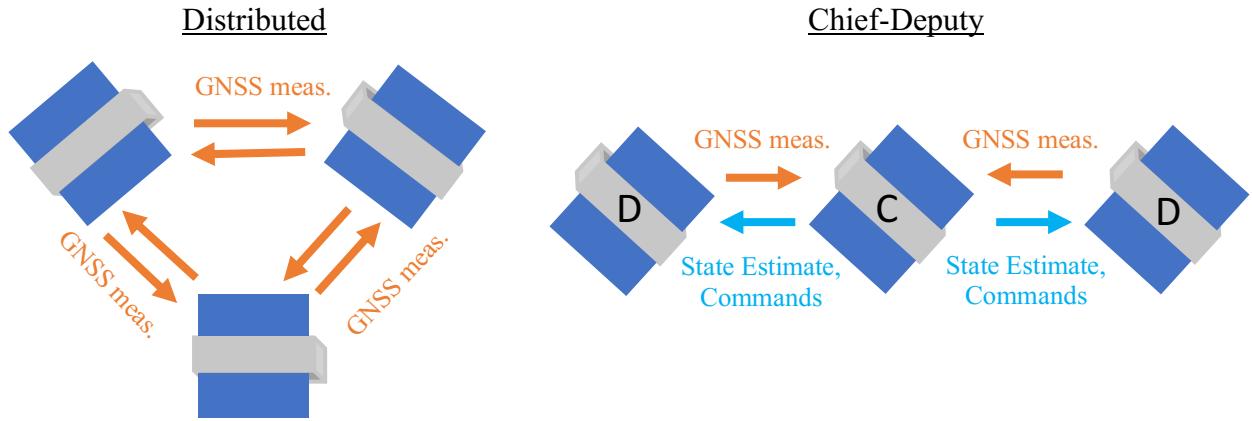


Fig. 5 Proposed GNC architectures for the VISORS formation.

B. Over-Constrained Pointing Requirements

In order to achieve the high-resolution coronal imagery with a three 3U CubeSat formation, the stringent translational and attitude requirements in Fig. 3 must be maintained for 10 seconds to achieve a successful science observation. To achieve such precise requirements, every subsystem must continually exhibit its expected performance. For each spacecraft to retain millimeter-level accuracy of their relative states, their GNSS receiver must be pointing near-zenith to obtain GNSS measurements and the ISL antennae must be pointing to those of the relative spacecraft. Since the ISL antennae do not provide full sky coverage, the ISL antennae impose a secondary pointing requirement. While e/i vector separation offers passive collision avoidance for multiple orbits, the degradation of these orbits introduces additional risk of collision if any spacecraft experiences extended GNSS or ISL blackouts which prevent precise maneuver planning and millimeter-level estimation uncertainties [4].

When collecting an observation, each spacecraft must maintain the proper alignment of their respective science instrument along the formation boresight vector. When also considering the star tracker pointing requirement, each spacecraft now must adhere to two additional attitude constraints along with the aforementioned GNSS and ISL pointing. Another requirement arises from the propulsion system; due to the single-nozzle design, the spacecraft will likely need to rotate to produce the desired thrust vector, which the maneuver planner may compute along any direction. Having each spacecraft rotate prior to each translational maneuver may be infeasible if the previously mentioned pointing requirements for science mode must be maintained.

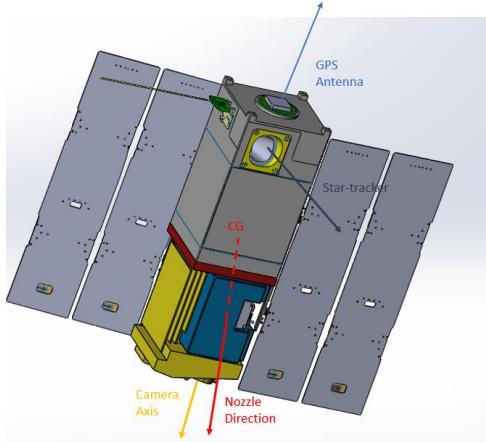


Fig. 6 Image of a 3U detector spacecraft with important pointing vectors labeled.

Fig. 6 highlights several of these pointing requirements on the initial design of the 3U detector spacecraft. When collecting an observation, the camera axis will be aligned with the formation boresight vector displayed in Fig. 1. A rotational degree of freedom exists along the camera axis which can be utilized to point the star tracker to guarantee its nominal performance. However, this attitude enforces the GNSS antenna to be anti-parallel to the boresight vector which, depending on the location along the orbit, may be nadir-pointed. Furthermore, since the face perpendicular to the boresight vector solely contains the detector, the other spacecraft are not in the ISL antenna field-of-view which reduces the probability of maintaining the ISL. This situational example highlights the inability of a 3U form factor to provide a closed design that meets the pointing requirements.

C. Impact to Mission Success

The 3U form factor and myriad pointing requirements severely impact operations in science mode. Specifically, the need to re-orient the spacecraft for thruster firing hinders the preparational steps prior to conducting an observation. In the few minutes before an observation attempt begins, translational maneuvers will be performed every minute to reduce the position and velocity errors to within the required tolerance. The translational maneuvers may be planned along any direction, including a worst-case scenario in which the nozzle is currently pointed anti-parallel to the desired impulse vector. Requiring each spacecraft to slew and settle to the required accuracy in time for a thruster firing every minute is a difficult requirement that the ADCS systems equipped on each spacecraft cannot continually meet. Thus, the single nozzle design requires frequent slewing in science mode that is not only infeasible during the high-frequency maneuver phase of the mission, but also may cause the spacecraft to violate its other pointing requirements that are imperative for a successful observation.

This operational challenge highlights that the stringent mission safety requirements, multitude of simultaneous pointing vectors, and physical limitations of a 3U spacecraft formulate into a design problem that is likely infeasible to solve. A feasible design with the current formation configuration requires a compromise on the quality of coronal imagery while increasing the risk of collision. While a degraded set of imagery may still yield insight into coronal heating regions, its coupling with a higher collision risk resulted in this being an unviable solution. Therefore, a trade study was conducted in the concept phase of the project life cycle to investigate other possible mission architectures to meet the science, mission, and safety objectives.

III. Mission Architecture Trade Study

A. Trade Space

Based on the design constraints and impacts to mission success associated with the original mission design, a trade study was conducted to consider potential solutions to these problems. A common root cause of the many design constraints stems from the limited available volume, so the trade study focused on alternative formation configurations and bus sizes. An additional dimension of the trade space is the modification to the mission and relaxation of science requirements. Since the mission is focused on proving and testing a novel science observation capability, the design team arrived at the conclusion to not pursue this option in the trade space.

In the formation trade space considered, there were two alternatives to the original three 3U configuration. One was a 3U DSC and a 6U OSC that performed the sunshade duties of the SSC as well. Another option was two 6U

satellites, where both the OSC and DSC utilize 6U buses. A three 6U configuration was not considered due to cost. The increased surface area of the solar panels and bus surface area of the DSC was determined to provide the functionality of a separate sunshade. A 6U SSC would have increased the spacecraft hardware cost while only providing marginal benefit to the mission.

B. Trade Space Analysis

With the trade space defined, an analysis of the alternatives was conducted to determine if they would resolve the original design constraints. The focus of the analysis was whether the over-constrained pointing problem and volume limitations could be resolved while simultaneously improving mission success likelihood.

The initial parameter to be varied was the number of satellites in the formation. By increasing the bus size, it was possible to reduce the total number of satellites required from three to two. Therefore, when considering alternative formation configurations in the design space, a consideration is the inclusion of a 6U bus, whether just for one spacecraft or both. Using the BCT 6U bus as a baseline, the volume available for the payload subsystems grows from 1.5U on the BCT 3U bus to 4U in the 6U bus. Not only does this change increase the mass and volume margins for the subsystems, but it also provides more spacing for mechanical and electrical interfaces between components. The increased surface area with a 6U bus is pivotal for enabling the propulsion system. Previous flight heritage propulsion systems provide 3 degree-of-freedom (3DOF) maneuverability that approximately occupy 1.5U and therefore fits in the provided 4U form factor [6]. This increase in nozzle placement greatly reduces the frequency of slewing required prior to performing a translational maneuver. This decoupling from the ADCS system ensures that when a collision avoidance maneuver is planned, no time is spent slewing the spacecraft as would be necessary with the original 3U design. The increased surface area allows for more ISL antennae on a greater number of spacecraft faces, resulting in increased sky coverage and reducing the risk of ISL blackout periods when in science mode. Since the 6U bus is also a common spacecraft bus form factor, commercial-off-the-shelf (COTS) designs exist that provide the ground communication, power generation, ADCS, and command & data handling needs of the VISORS mission.

A 6U bus resolves the volume constraints in the original design and relaxes several of the over-constrained pointing requirements. The increased payload volume results in greater flexibility with subsystem placement, thus allowing for pointing-constrained components to be situated in locations that meet the requirements. Furthermore, the pointing requirement for the ISL is more likely to be met without an added constraint as the field-of-view can be increased to near full sky coverage. Similarly, the addition of a more capable 3-DOF propulsion system removes the pointing constraint created by the original, single-nozzle design. In Fig. 7, a notional DSC 6U design is shown with the different pointing requirements overlaid during science mode. A Blue Canyon Technologies (BCT) 6U bus is used as the example bus in this conceptual mockup. It is evident that the pointing requirements of the instrument, GNSS antenna, and star tracker are all met simultaneously.

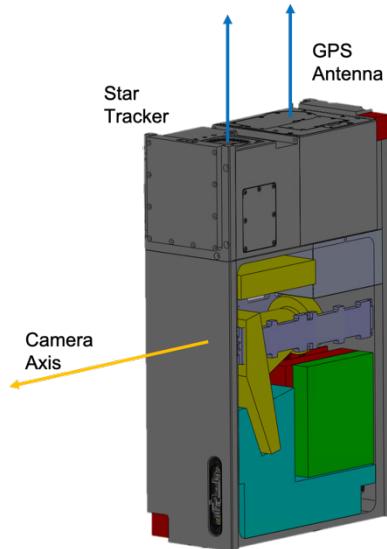


Fig. 7 During science observation, the star tracker and GPS antenna are zenith pointing while the camera axis is aligned with the sun vector.

Moving to any quantity of 6U buses has its associated disadvantages. The one major disadvantage is the need to redesign the payload subsystems, which were previously designed with a 3U bus in mind. A redesign of subsystems could potentially cause schedule slip, causing the margin built into the schedule to be used or delaying the launch window. Furthermore, 6U launchers are less common, so there may be a reduced number of launch opportunities and consequently a reduced opportunity to achieve the desired sun-synchronous orbit.

There are also ramifications from the alternative configurations reducing to two satellites instead of three. The major advantage is reduced mission complexity; the DiGiTaL software and ISL now only operate on two spacecraft. In the event of a high collision risk, the software can more easily determine a propulsive maneuver to separate the spacecraft to safety. An additional advantage is the capability to modify the target and chaser roles in the relative orbit. The target is the spacecraft which is relatively stationary while the chaser performs maneuvers to move around the target. When having two spacecraft, the roles can switch, providing the formation with more operational flexibility, if utilized, for maintaining the spacecraft's delta-velocity (ΔV) budget and adding redundancy in the event one propulsion system fails. A potential disadvantage with a reduction in spacecraft number is a loss of novelty that comes with the ability to demonstrate a larger formation configuration of CubeSats.

One major distinction between the two formation alternatives is the number of 6U spacecraft, which has ramifications to their capability of resolving the original constraints. The 3U and 6U configuration contains advantages associated with the larger OSC bus while keeping several disadvantages of the original three satellite configuration. One advantage is the OSC would incorporate all the benefits that come with the 6U bus. Having one nozzle on the 3U DSC is now a smaller issue since the DSC can always perform the target role in the relative orbit while the OSC is the chaser: the OSC performs maneuvers relative to the DSC. Nonetheless, having one nozzle on the DSC still induces risk if a collision is imminent and a propulsive maneuver is required for active collision avoidance. Furthermore, the different cross-sectional areas of the spacecraft lead to different drag profiles. The different drag profiles impact orbit decay and the ΔV cost of maintaining the relative science orbit. If this alternate configuration is chosen, the ΔV budget must be modified to account for a different set of maneuvers associated with non-identical drag profiles. A more prominent issue is the 3U DSC still faces the over-constrained pointing issues and the volume limitations associated with the original design. While mission success may be improved due to the inclusion of a 6U OSC, the team must account for the different capabilities of the different spacecraft, which could increase complexity of operations. However, one advantage is the payload subsystems do not need to be modified for the DSC, which could reduce the risk of schedule slip associated with redesigning payload subsystems.

The two 6U configuration, unlike the 3U and 6U configuration, equally provides the solutions to design constraints and added flexibility from the 6U bus to both spacecraft. One benefit is both spacecraft do not have the over-constrained pointing problem; this not only reduces operational complexity but also provides both spacecraft with a 3-DOF propulsion system for active collision avoidance, reducing operational risk. The increased ISL antennae coverage associated with more surface area is also shared between the spacecraft, eliminating the pointing requirement which still manifested in the 3U & 6U configuration. The main disadvantage is all subsystems must be redesigned for both spacecraft, but there is a simultaneous reduction in design complexity as both spacecraft can use identical subsystem designs. Additionally, the target and chaser roles may now be switched with the two 6U configuration. The roles could not be switched with the 3U and 6U configuration since the 3U would have a 1-DOF propulsion system. After collecting all the results of the trade study, the overarching capabilities of the different alternatives are shown in Table 1.

Table 1: Morphological matrix showing the differences between each alternative in the trade space.

Feature	3x3U	3U & 6U	2x6U
# of communication links	3	2	2
Total Volume Allocation	9U	9U	12U
ISL Directionality	Directional	Directional	Omnidirectional
Spacecraft Drag Profiles	Similar	Different	Similar
Propulsion DOF	1 on all spacecraft	1 on 3U, 3 on 6U	3 on all spacecraft
Target & Chaser Roles	Fixed	Fixed	Reconfigurable

C. Trade Study Decision

Based on the analysis of the design alternatives in the trade space the VISORS team selected the two 6U formation, hence why the corresponding column is highlighted green in Table 1. Employing a two 6U spacecraft formation for the VISORS mission expands the design space to include solutions that meet the original science, mission, and safety requirements. Expanding the available volume to 6U allows for 3-DOF propulsion and full sky coverage capability for the ISL releases two pointing constraints which were imposed on the original three 3U formation. Both technologies are also critical for mission safety: continual communication with the rapid ability for translational maneuvering is imperative for collision avoidance. Although no SSC spacecraft exists in this new formation, the 6U OSC spacecraft with its solar panels was deemed sufficient to provide the necessary sunlight coverage for the detector. While implementing a two 6U design requires redesigning of payload subsystems, the decision allows the VISORS mission to meet its original science objectives while maintaining a safer level of collision risk and minimizing operational complexity. The decision also does not modify mission and science operations originally outlined; rather, it enables them to be executed and thus increases the likelihood of mission success.

IV. Impact on Mission Operations

The original concept of operations can be readily adapted to a new satellite formation as this flexibility reinforced the decision to conduct the mission architecture trade study. The two 6U formation becomes a distributed telescope when in alignment for an observation attempt with the boresight vector passing through the science instruments of each respective spacecraft. This alignment, with the associated tolerances depicted in Fig. 9, shall be held for a minimum of 10s to collect coronal imagery. Since the larger solar panels on the OSC ensure sufficient blockage of unwanted solar radiation from entering the detector aperture, the focal length between the optics and detector remains at 40m. Fig. 8a depicts the new architecture when aligned to collect coronal imagery and is intentionally constructed to appear similar to Fig. 1.

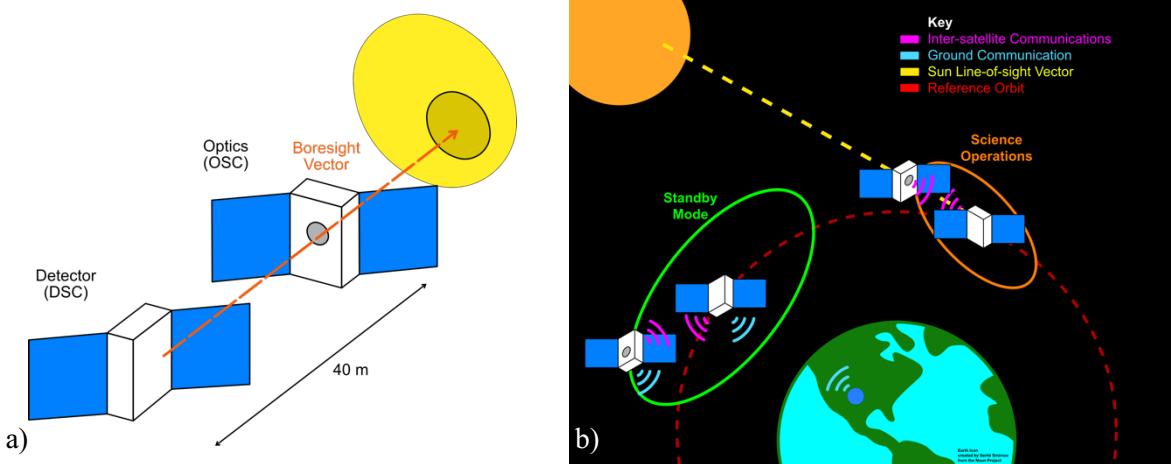


Fig. 8 a) Two 6U satellite formation when in alignment to collect coronal imagery b) Updated VISORS concept of operations.

In the science mode relative orbit, each spacecraft maintains a distance of at least 40m which is larger, and therefore passively safer, than the original 20m separation between spacecraft in the three 3U formation. The reduction to two spacecraft not only simplifies the data volume and transmission paths along the ISL, but also allows for configurable target and chaser roles: the chaser spacecraft will always maneuver relative to the target spacecraft, and the designation of target and chaser can be interchanged. This provides a contingency mode if a propulsion system on one spacecraft malfunctions since the chaser spacecraft will be the only spacecraft performing translational maneuvers in nominal operations. The formation still retains an approximately 200m separation in the standby mode relative orbit where maintenance operations are conducted. Similar to the three 3U relative orbits, the standby and science mode relative orbits with the two 6U formation will be constructed using e/i vector separation. Fig. 8b depicts the concept of operations for the two 6U design; the diagram closely resembles Fig. 2 which highlights how the new formation fits in the original mission architecture.

To meet the original science objectives, stringent relative state requirements on the formation when in an observation attempt continue to exist; the requirements and associated tolerances are depicted in Fig. 9. The lateral drift rate requirement being less than 200 $\mu\text{m/s}$ still applies to the new formation. Transitioning to the 6U buses enables design solutions that increase the likelihood of meeting the relative state requirements when compared to those of the original three 3U formation. The full sky coverage that the ISL now provides allows for a continual communication link that is independent of the attitude of each spacecraft. This enables DiGiTaL to consistently produce relative state estimates with the millimeter-level accuracy required to meet the tolerances in Fig. 9. Furthermore, the 3-DOF propulsion system ensures that the spacecraft can conduct a translational maneuver without rotating the vehicle; this enhancement enables the formation to more effectively prepare for an observation attempt. Thus, the strict relative state requirements, which flow down from the science objectives, are more likely to be met with the two 6U formation.

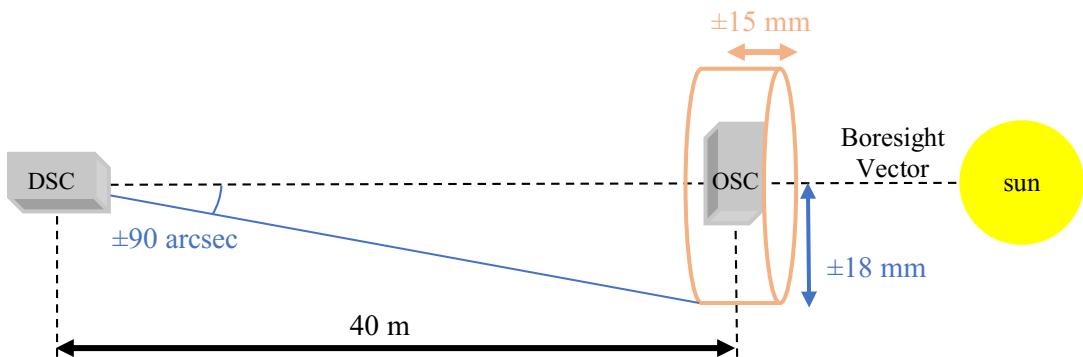


Fig. 9 Relative state requirements for the two 6U formation when aligned for an observation.

V. Enabling Technologies

A. Spacecraft Bus

The spacecraft bus is crucial in enabling mission success as it is responsible for completing all the secondary functions foundational to the mission, including attitude determination and control, power generation, command and data handling, and ground communication. In order to reduce risk, the VISORS mission team intends to employ a COTS bus which contains these secondary functions. The Blue Canyon Technologies (BCT) 6U bus was chosen for this mission. With a Technology Readiness Level-9 (TRL-9) from previous CubeSat missions, the spacecraft bus design has considerable flight heritage [7]. Furthermore, it includes the XACT-15 Attitude Determination & Control (ADC) module that provides the necessary attitude stability and pointing needs for the science mission. The bus includes a GPS receiver and antenna that can be modified to work with the DiGiTaL software. The BCT bus also meets the needs for other secondary functions such as providing ground communication, power generation, power distribution, and command & data handling for the spacecraft. By utilizing the BCT bus, the team can focus their efforts on developing the novel technologies for this mission. Utilizing a COTS bus also enables a unique public, private, and academic partnership as collaboration between NSF, NASA, BCT, and universities allow this mission to be possible.

The overall spacecraft system is shown in the Fig. 10 below, including the technologies being built in-house for this mission. The BCT 6U bus is the gray section shown in the figure and contains the ADC module, GPS receiver, power system, and flight computer for each spacecraft.

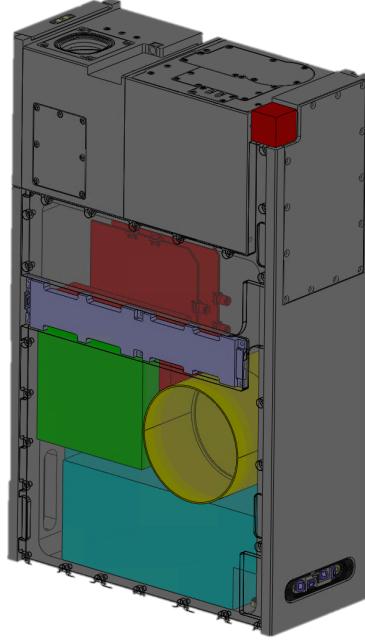


Fig. 10 Preliminary CAD model of OSC spacecraft: BCT 6U bus (grey), propulsion (blue-green), optics (yellow), Avionics board (green) and ISL components (red).

B. Inter-satellite Link (ISL)

From the key requirements discussed earlier, inter-satellite communication is a capability that is required in this mission. The ISL system's capabilities can now be fully realized with the 6U bus. The custom designed system incorporates two arrays of three patch antennas on opposite sides of the spacecraft. With these arrays, there exists a patch on six sides of the spacecraft, allowing for near full sky coverage. This entails that the ISL can be maintained regardless of how each spacecraft is oriented with respect to each other. Furthermore, the system is being designed to establish a link from a 1km range to ensure constant inter-satellite communication in science orbit. In order to utilize all these antennas at once, the system incorporates two separate radio boards, one for each array, and an FPGA board that performs the signal processing and management of the antennas. The increased payload volume enables the inclusion of these boards while the increased surface area allows access to all sides of the spacecraft for antenna placement. Fig. 10 shows conceptual placement of these components in the 6U bus. As the design matures, specifics

on the boards and antennas will be realized; the components in the figure are determined from notional designs and COTS components that exist for these technologies.

C. Propulsion

The propulsion system in VISORS is another fundamental technology required for the mission for several reasons. First, there is an operational need to transfer between the mission's two distinct modes: standby formation and science formation. This is only possible with the capability to perform propulsive maneuvers to modify the relative orbits. Furthermore, the capability to conduct an active collision avoidance maneuver when an anomaly occurs is critical to the safety of the spacecraft and feasibility of the mission; the propulsion system provides the satellites with the capability to achieve a safe distance between the spacecraft. Finally, the strict relative position and velocity requirements during science observation can only be met by performing propulsive maneuvers prior to the observation. As can be seen, the formation flying mission objectives could not be accomplished without a propulsion system.

The conceptual design of the propulsion system is based on the flight heritage of systems Georgia Tech, a VISORS team member, and by the spacecraft bus design itself. Georgia Tech's TRL-6 6U cold-gas propulsion system reduces the risks associated with developing technologies from scratch for this mission and allows the fulfillment of the 3-DOF maneuver capability is enabled by the additional available volume. Moreover, Georgia Tech's capability to 3D print their systems is an enabler of using space effectively in the spacecraft bus. The flexibility associated with a 3D printed system also allows the VISORS team to choose the nozzle placement in the propulsion system as the design matures. The 3-DOF system will be based on Georgia Tech's propulsion system previously designed for the BioSentinel CubeSat mission launching on the Artemis Exploration Mission 1 (EM-1) [6]. The propulsion module occupies approximately 1.5U of volume and is designed to fit on the 2U-by-1U side of a 6U bus. Fig. 11 highlights the propulsion system as installed on the BioSentinel spacecraft. A volume is shown in Fig. 10 for where it notionally might exist in the VISORS DSC; although, the placement has not been finalized when this paper goes to press.

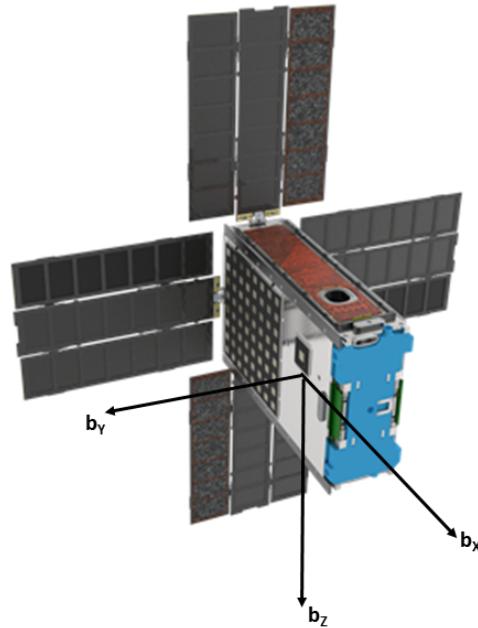


Fig. 11 Biosentinel CAD model with 3-DOF thruster shown in blue.

VI. Conclusion and Future Work

The satellite formation trade study was imperative as the two 6U formation results in a design space in which a design solution exists that meets the original set of requirements. The trade study was delivered to NSF for review, and the two 6U formation was approved as this architecture still collects compelling science data in the form of coronal imagery while incorporating novel subsystem technologies. Selecting a COTS 6U bus allows the VISORS team to focus on the unique propulsion, inter-satellite communication, and relative navigation subsystems. The omnidirectional ISL will provide an unprecedented connection between the formation while the 3-DOF propulsion unit

will steer each spacecraft into the desired relative orbits and maintain a safe separation throughout the mission. The top-level requirement to reduce the risk of collision was a key driver in the trade study and has manifested into subsystem and component level requirements that drive the design. The trade study did not impact the mission schedule and the Preliminary Design Review (PDR) is expected to occur on its original time frame of the 4th quarter in 2020.

As discussed in this paper, the VISORS team aims to develop, test, and integrate innovative technologies in the areas of propulsion, close-range communications, formation flying, relative navigation, and solar imaging. Such technologies are required to complete the intricate mission that VISORS will undertake, and the team has consequently adopted a systems engineering methodology to characterize, track and mitigate the myriad complexities that are inherent in the mission and system design. The developments from this mission will aid the creation of the next generation space missions that will utilize the capabilities and performance demonstrated by the VISORS satellite formation.

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Table 2: VISORS mission team.

Participant	Institution
Farzad Kamalabadi (PI), Endowed Professor	Univ. of Illinois, Electrical and Computer Eng.
Alina Alexeenko, Professor	Purdue Univ., Aeronautics & Astronautics
Philip Chamberlin, Research Scientist	Univ. of Colorado, LASP
Simone D'Amico, Assistant Professor	Stanford Univ., Aeronautics & Astronautics
Adrian Daw, Research Astrophysicist	NASA GSFC, Heliophysics Science Division
Kevin Denis, Electrical Engineer	NASA GSFC, Instrument Systems and Tech. Division
Eylem Ekici, Professor	Ohio State Univ., Electrical & Computer Eng.
Subhanshu Gupta, Assistant Professor	Washington State Univ., Electrical Eng.
John Hwang, Assistant Professor	Univ. of Calif. San Diego, Mechanical & Aerosp. Eng.
James Klimchuk, Research Astrophysicist	NASA GSFC, Heliophysics Science Division
Glenn Lightsey, Professor	Georgia Tech, Aerospace Eng.
Hyeongjun Park, Assistant Professor	New Mexico State Univ., Mechanical & Aerosp. Eng.
Douglas Rabin, Research Astrophysicist	NASA GSFC, Heliophysics Science Division
John Sample, Assistant Professor	Montana State Univ., Physics
Thomas Woods, Associate Director	Univ. of Colorado, LASP

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