

VISORS Mission Design and Spacecraft Layout

Abhraneel Dutta

The Virtual Super-resolution Optics with Reconfigurable Swarms (VISORS) mission aims to image the solar corona using distributed spacecraft optics. The Preliminary Design Review (PDR) held by the bus contractor (Blue Canyon Technologies, BCT) in the summer of 2021 resulted in the spacecraft covered in this report.

This document aims to:

1. Introduce the mission to someone unfamiliar with the project
2. Explain why the spacecraft is laid out in its current configuration
3. Detail important work left to be done before the Critical Design Review (CDR)
4. List of important points of contact

Mission Introduction

Onboarding onto this project is a separate issue and not covered in this document – however, there are a few important sources of information. The BCT PDR slides are maintained in two separate versions – one with redacted information for non-ITAR members, and full PDR slides for US persons. This should be one of the first documents reviewed by a new member to get caught up, along with the VISORS mission slides. The slides cover the following topics:

1. Mission Overview
2. Systems Overview: spacecraft and mission block diagrams
3. Mechanical: physical layout, assembly, etc.
4. Thermal: example thermal analysis slides from a similar spacecraft
5. Command and Data Handling: pinouts and interfaces
6. Electrical Power system: Power interface and block diagrams
7. Power analysis: sizing, extreme case analyses
8. RF system: requirements and analysis for ground communications
9. GNC: requirements, sensors and actuators details, analysis
10. Flight Software: interfaces, architecture, functionality
11. Assembly, I&T: Test examples and facilities
12. Mission Assurance: quality assurance, radiation effects, documentation

Overview

The VISORS mission is looking for structures in the solar corona at the scale of $\sim 100\text{km}$, which translates to an angular resolution of 0.15 arcseconds. The structures will be imaged in the extreme ultraviolet (EUV) spectrum. At this scale, mirror-based optics are infeasible, so the mission will use photon-sieve technology. The focal scale for this sieve and wavelength is 40 meters. Hence, the imager and the photon sieve are on two different spacecraft which work together to align with the sun at the moment of imaging. These are called the Detector Spacecraft and Optics Spacecraft (DSC, OSC) respectively, shown in formation below.



Figure 1. VISORS formation. DSC (left) and OSC (right)

There are 6 primary subsystems on the DSC and OSC:

- the Bus
- Science payload
- the Intersatellite Link (called ISL or XLINK more commonly)
- Propulsion
- Payload Avionics
- GNC

The spacecraft Bus provides the power, ground communications, attitude control, and other base functionalities. In steady operating condition, they act in a chief-deputy architecture. The OSC and DSC communicate with each other through the XLINK system, and the deputy performs thrusting maneuvers to fly into or out of a proper relative orbit to take images. The Payload Avionics acts as an interface between different subsystems. The GNC software calculates maneuvers, and is hosted software on the BCT Avionics Bus. The XLINK, GNC, and Propulsion systems on both spacecraft are identical, which allows for the two vehicles to exchange chief/deputy roles with each other and lengthen the usable life of the mission.

Concept of Operations

Figure 2a shows the event sequence when the spacecraft are operating in Science mode. Fig. 2b details the preliminary state diagram for the mission. There are several phases to this mission – first, after the spacecraft are deployed from the launch vehicle, the two vehicles enter a commissioning phase. The commissioning phase has two sections. The first portion is performed by BCT to deploy and checkout the bus itself. This involves deploying panels and the antenna, performing functionality checks for the attitude control system, etc. BCT then hands off the spacecraft to the VISORS team, and the payload checkouts and commissioning begins.

Payload commissioning involves putting each system through functionality checks, and communicating the results of these checks to the ground station – for example, executing thrust commands and checking spacecraft response, taking example images, etc. A protective door on the Detector must also be released.

Once the individual spacecraft have been checked out, they are commanded from the ground station to propulsively move into closer proximity (the formation acquisition maneuver). A XLINK checkout is performed when the two spacecraft are within range. Once these preliminary operations are performed, the mission has started its steady state operation, and the spacecraft are in the Standby Configuration. Here, the spacecraft have significant passive safety from colliding into one another, have the ability to communicate with the ground when needed, and are primarily gathering power.

Once the science team has identified a potential imaging time and location, the details are conveyed to the GNC Team. That team uploads parameters, and the spacecraft autonomously calculate transition maneuvers. These act to bring the OSC and DSC into much closer proximity. Transition from Standby to Science configuration may take up to ~3 orbits, depending on how the GNC team decides to distribute propellant usage. In the Science configuration, the relative orbits are designed such that, when the three spacecraft are aligned with the sun, the separation between spacecraft is exactly the focal length of the EUV optics, 40 meters.

Once the spacecraft have commands to perform an imaging campaign, a new orientation constraint becomes active: the GPS antenna must stay within 30° of vertical to maintain accurate navigation knowledge. Maneuvers are calculated as needed every 10 minutes to maintain a precise formation due to strict position and rate requirements at the time of imaging (see the requirements document). The GNC software outputs station-keeping maneuvers in a format shown below:

[time(s), dV in R(m/s), dV in T(m/s), dV in N(m/s)]

In other words, a total delta-V at a certain time in the future, expressed in an LVLH (local vertical, local horizontal) frame. These are recalculated and modified as needed, but are not expected to change often. Once the target time is reached, the spacecraft must produce a delta-V in the correct time, direction, and of the correct magnitude. The ADCS team must convert this inertial dV vector to one in the body frame, and then decide which of the propulsion valves to actuate to achieve the calculated body vector. Since our thrusters are not throttle-able, each valve may need to be held open for unique durations. In general, for any given maneuver, multiple thrusters will need to be actuated – this is because no nozzle has both 1) alignment with a primary axis and 2) a line of action passing through the spacecraft CG. It is currently unknown what the spacecraft bus' response is to a unit step increase in torque – most likely, thrusters for a given maneuver cannot all be switched on simultaneously, as this will torque the spacecraft. Once thruster will need to be activated and shut off, the attitude will need to be corrected, and a recalculation may need to be performed in case the thrust performed disturbed the spacecraft orientation significantly. The thruster numbering system was determined by the GT Propulsion team and the NMSU ADCS team.

Just before an image set is taken, pointing switches to an inertial direction, and it held until after the pictures are taken (a 10 second window). This repeats for ~10 orbits, or for ~1 day, for a full imaging campaign.

Once the imaging campaign is concluded, or a command from the ground is given, the spacecraft perform maneuvers to again separate from the science configuration to the standby configuration. Here, sun-pointing for power generation again becomes the primary constraint, and data may be downloaded or new commands may be uploaded. Transitioning to and from the Science Configuration consumes significant amounts of propellant. One 10 second imaging window results in multiple exposures being taken by the “camera” sensor, and of these, perhaps only one image will be downloaded.

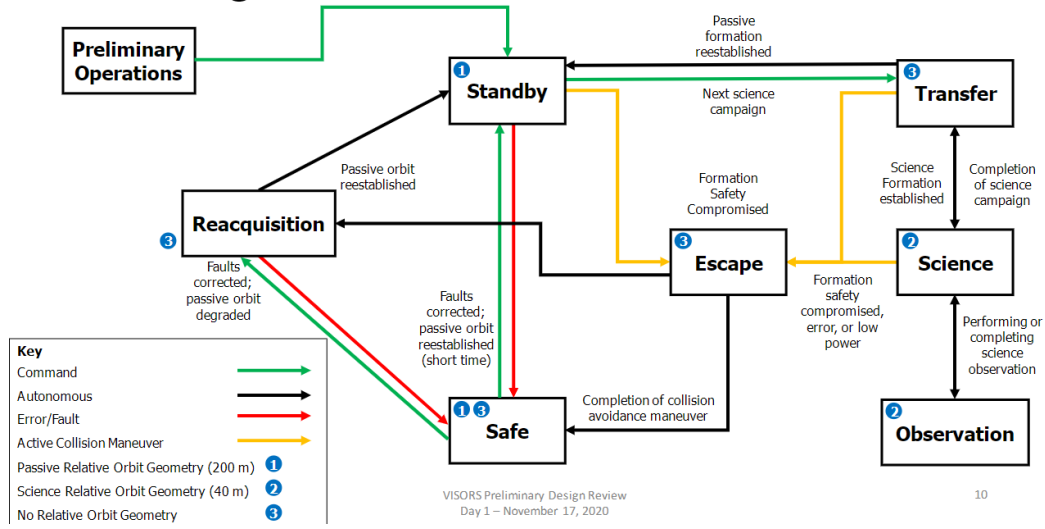
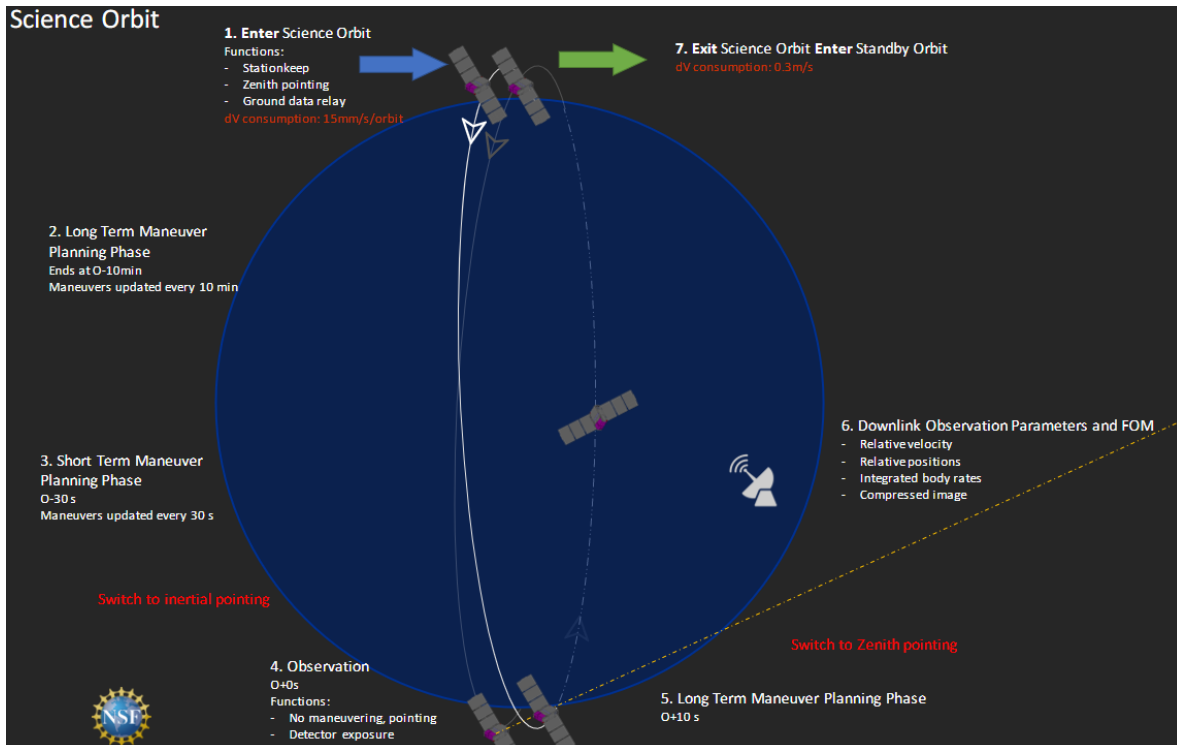


Figure 2a) Science Configuration operation. 2b) State Diagram for VISORS S/C from PDR.

The state of the spacecraft is driven by the GNC software, dictating what relative separation the spacecraft are attempting to maintain. The ADCS system state is also driven by this, but maintains different constraints in each of these conditions. The modes possible for the ADCS system to operate in are described in two contexts, the BCT ADCS modes and the Payload ADCS modes. BCT ADCS modes are an umbrella organization of modes:

- **Safe/Sun pointing Mode:** coarse, active pointing towards the sun to recharge batteries
- **Survival Mode:** Conserve power, all components turned off, no ADCS/GNC control

- **Fine Pointing Modes:** Commanding of ADCS handed over to payload to accurately point where the VISORS mission needs

The VISORS mission operates inside the Fine Pointing Mode. The mission further breaks this mode down into the following categories, with primary pointing vectors described:

- **Ground Communication:** Points UHF antenna for uplink/downlink with Ground Stations
- **Sun-pointing:** gathering solar power to maintain battery charge levels
- **Maneuvering:** GPS antenna kept within 30° of zenith to maintain quality navigation data
- **Inertial pointing:** observations require pointing both spacecraft at a static point in space

Spacecraft Overview

The OSC and DSC have identical propulsion modules, Avionics/XLINK systems, and functionally identical buses. The difference arises in the Science portion of the payload for these two spacecraft. The solar panels and boresights on the OSC and DSC Buses are also rotated 90° from each other. Below are views of the OSC and DSC, oriented relative to each other and with detailed views.

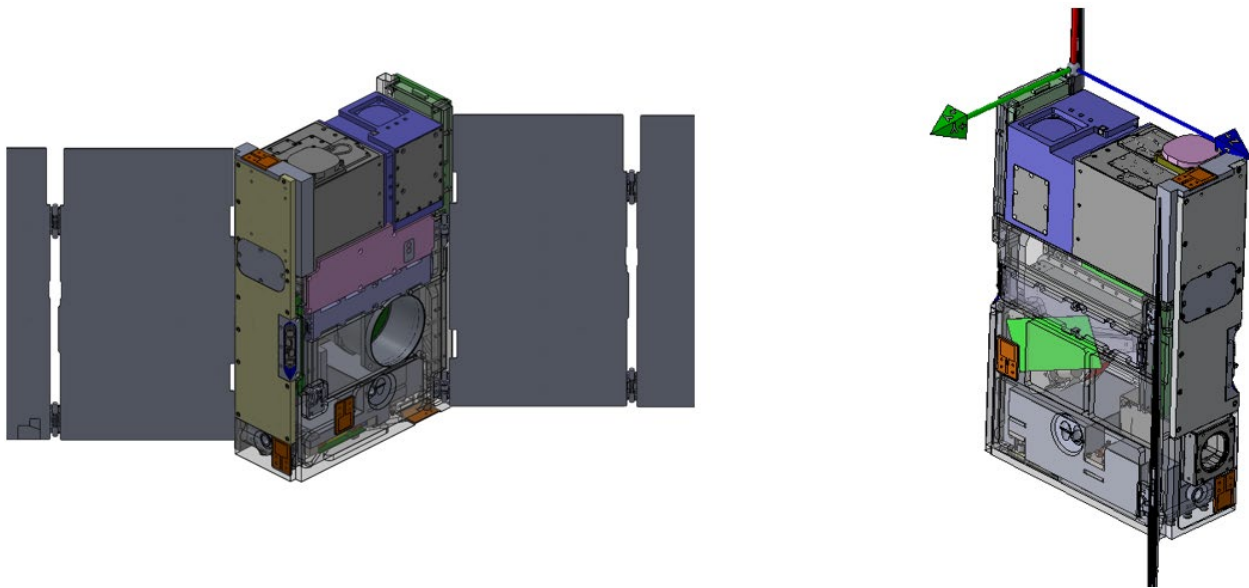


Figure 3. OSC (left) and DSC (right)

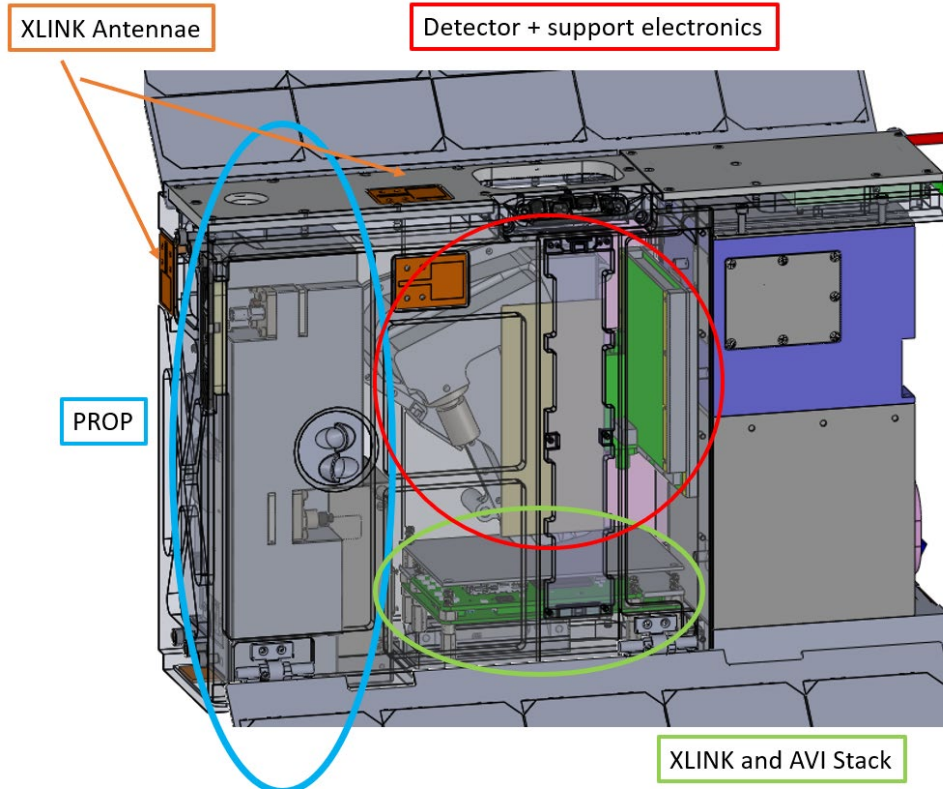


Figure 4. DSC Detailed view and Layout

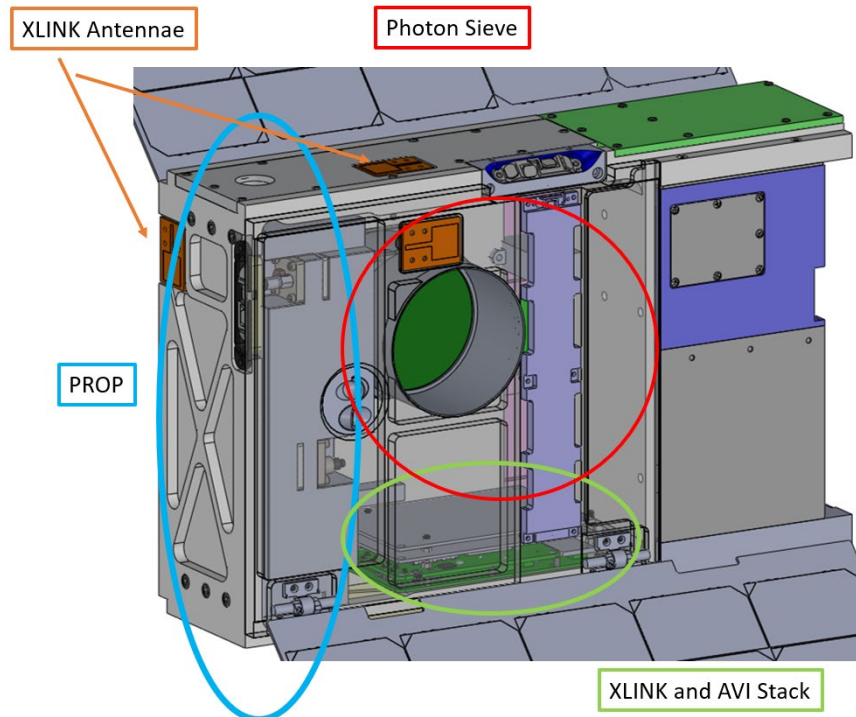


Figure 5. OSC Detailed view and Layout

Bus Design

The bus functionality is almost entirely contained inside the 1U X 3U volume near the top of the spacecraft. The chassis houses and mounts all payload components, as well as some other vendor-provided components, such as sun sensors, an extra Star Tracker for the DSC, panel release mechanisms, etc. The arrangement inside the chassis must also allow for harnessing and routing of electrical cables. The bus also hosts payload software applications, though this is not covered here.

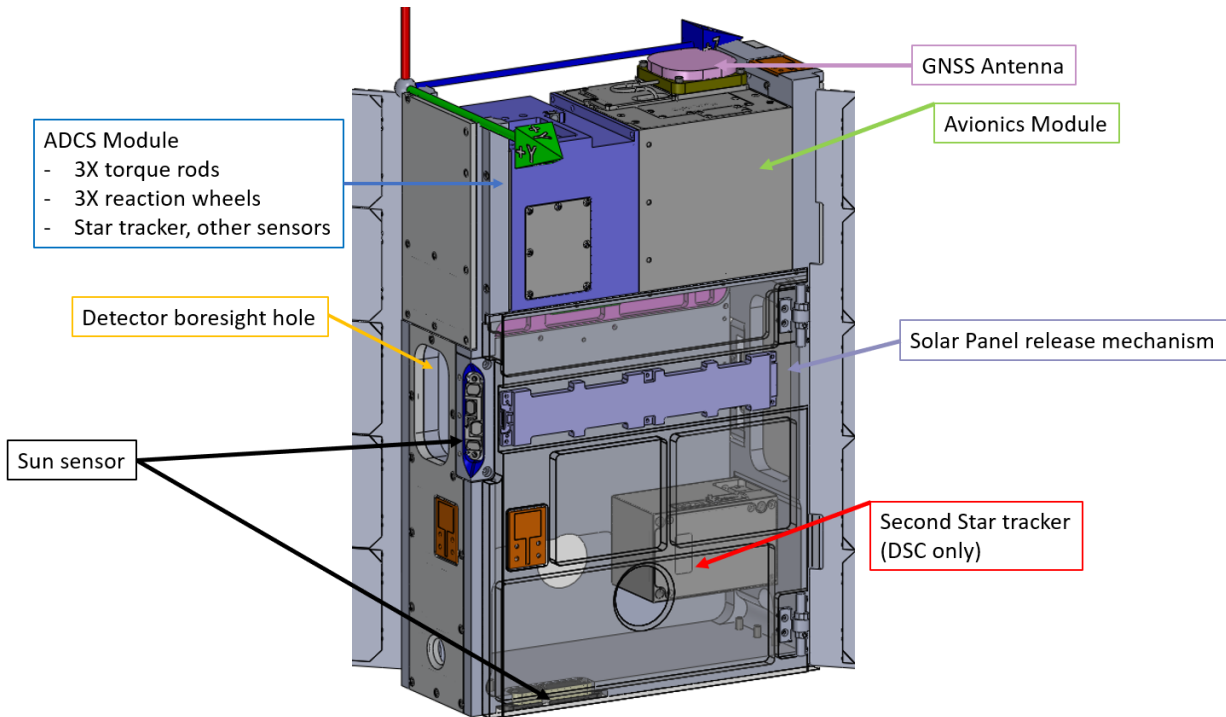


Figure 6. DSC Chassis

Solar panels have 3X fold out sections, but only two are populated with solar cells. These panels are stowed against the body of the spacecraft, requiring all components on these faces to remain flush or below the chassis upper surface. The release mechanism for these arrays are wired to the BCT Bus module for power and signal. The UHF Antenna is also housed here, with automatic release mechanism. The GPS antenna is an L1/L2 antenna, which must be placed on the zenith face. This pushes the BCT module volume into the payload volume by a few millimeters.

Mass is a significant constraint for this mission, so pockets and lightening holes are included in the primary structure. An access panel is included on both spacecraft to allow connectors to be attached to the Avionics board. A rail-based deployer has been baselined, as neither launch vehicle nor deployer have been confirmed yet. Currently, the bus is compatible with the following:

- **Tyvak (Option 1)**
- **Maverick-2**
- **ISIS 6U XL**
- **Nanoracks, rail configuration**

Propulsion Module

The propulsion on this spacecraft is a monopropellant cold-gas thruster. The structure is additively manufactured, and the propellant is stored as a liquid. The liquid is let into a plenum, where it turns into gas and is let into nozzles by thruster valves. The propulsion module has been placed at the “bottom” of the spacecraft to allow access to the maximum number of faces possible. Since BCT Avionics occupies an entire section of the spacecraft, Propulsion has access to only 5 faces of the spacecraft, so the 6 nozzles are angled such that the entire vector space is spanned. A combination of thrusters and durations can produce any delta-v vector.

Primary dimensions and an annotated diagram below gives an overview of the propulsion module. Figure 7 shows the mounting bolt patterns and the location of the quick-disconnect (QD) interface. The QD is a sleeve-based release, and will need an external interface for fueling. Nozzles are assumed to produce a 45° plume, which drives the keepout zone on the chassis. See the propulsion ICD Document for more details.

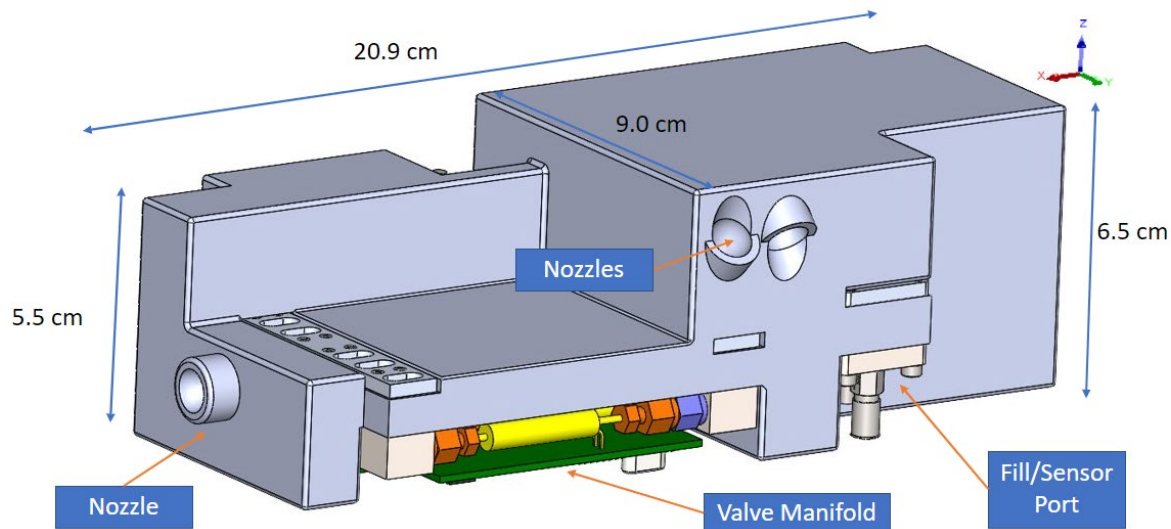


Figure 8. Propulsion Module overview

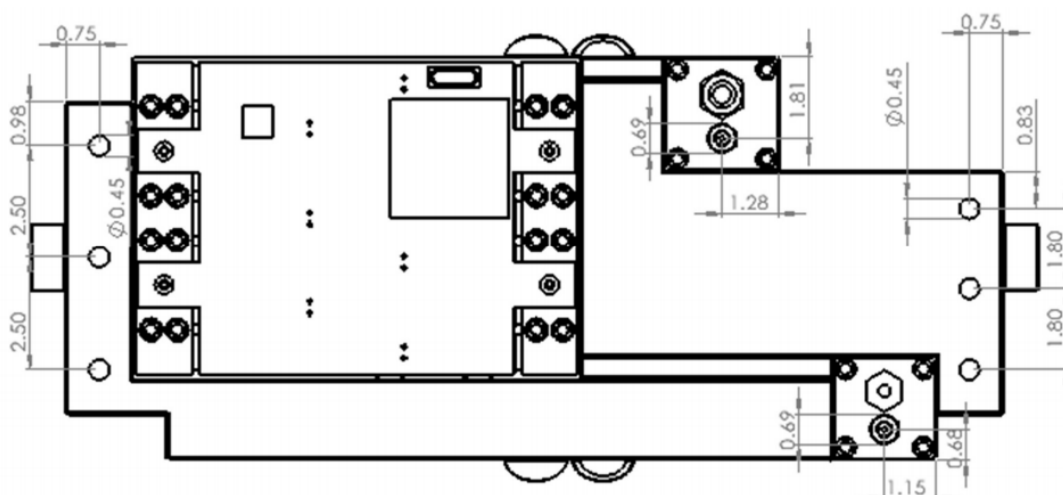


Figure 9. External interfaces of Propulsion Module

XLINK System

The XLINK system is composed of 3 distinct portions. First, a COTS components called the RF-SOM is the source of RF signals, sending and receiving into the XLINK system. These signals go to or come from the second part of the system: custom boards housed immediately above the RF SOM. There are two custom boards – the Amplifier board, and potentially two RF switching boards (baseline design calls for one only, which is the configuration shown below.). The last part of the system are the patch antennas. There are 6, one mounted on each face of the spacecraft, for near-full sky coverage. They are flush mounted into the chasis outer surface. The XLINK Stack and an example patch antenna is shown.

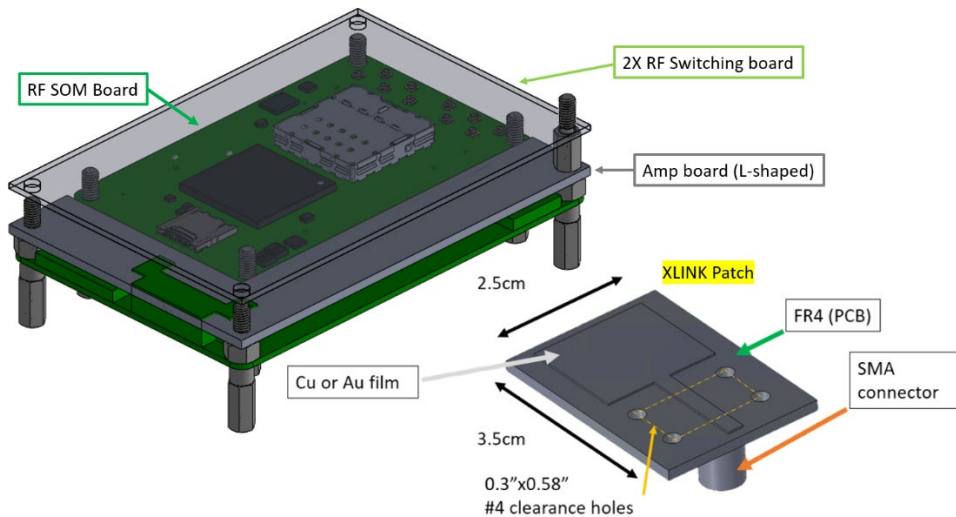


Figure 10. XLINK Hardware

The mounting pattern for this stack is in flux, but the current bolt pattern is shown below. This pattern is driven by a few factors: requiring enough material for the hole to be manufactured (including distance from other threaded holes), of the avionics boards, and avoiding other structural fasteners on the chasis. The patch locations were chosen by BCT, and are mounted using countersunk screws in a rectangular pattern. The XLINK's position inside the DSC/OSC is identical and shown in Fig. 5.

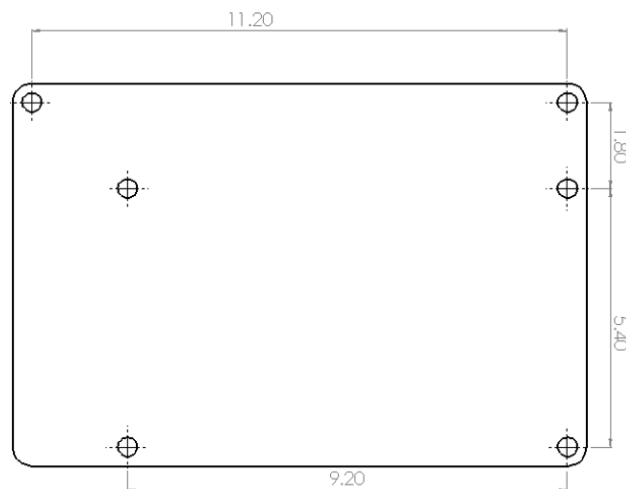


Figure 11. Electronics Stack bolt pattern (cm)

Science Instrument

The science instrument is made up of 4 major components – two on the OSC, two on the DSC. The OSC houses the Sieve and a Laser Rangefinder for accurate point-to-point distance measuring, and the DSC houses the Detector and the Coronal Imaging Science Electronics (CSIE) stack. The Detector (fondly called the Piano) houses a mirror and sensor chip. The EUV focused through the photon sieve on the OSC enters the DSC through a hole in the side of the spacecraft, is detected by the sensor. This then sends the data through an interface connector to the CSIE readout board. The alignment and positioning of the instrument is important. The sieve pattern is not about the center of the circular pattern, so the optical center of the sieve must be placed at the geometric center of the spacecraft. This results in a positioning as shown below:

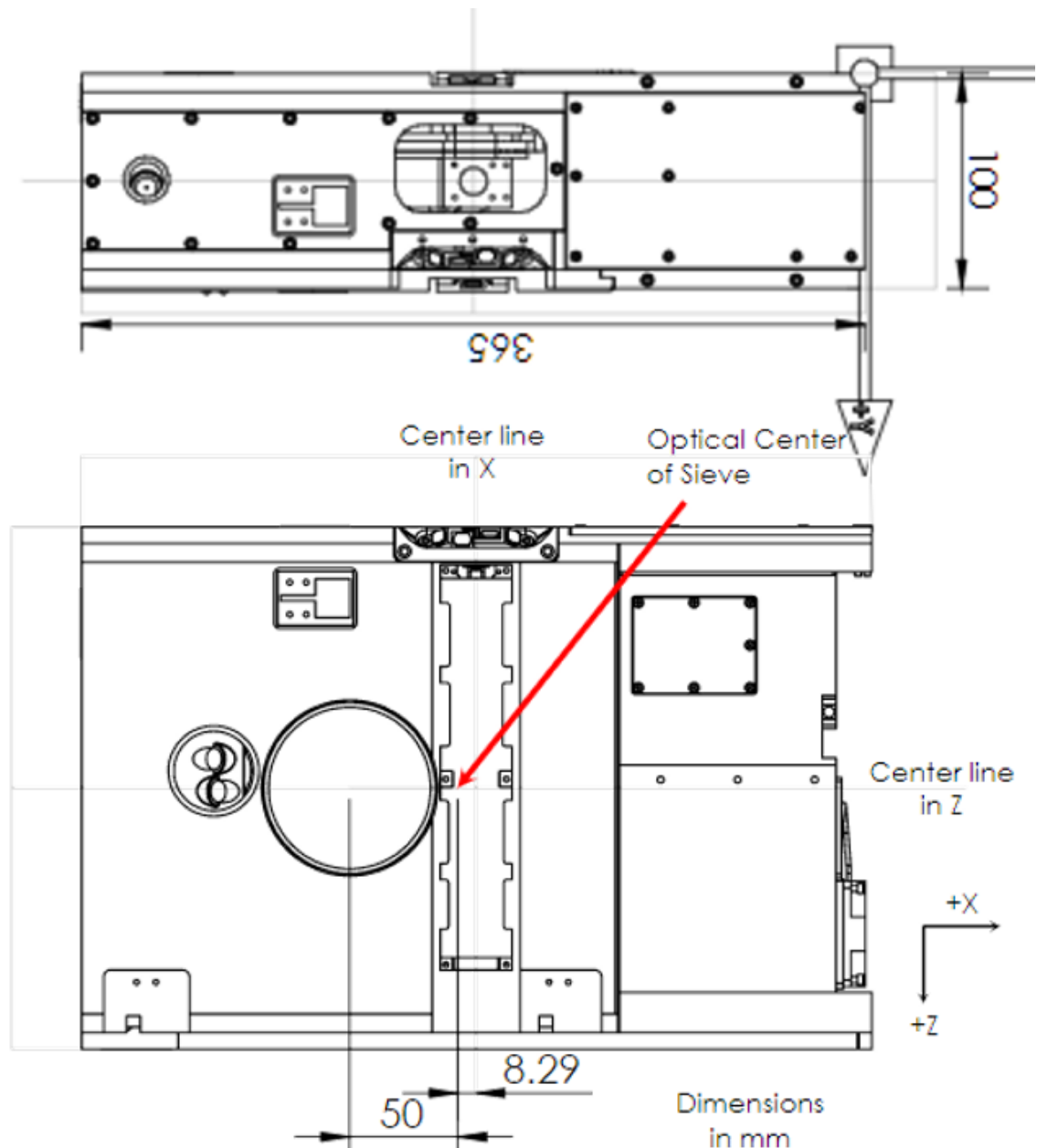


Figure 12. Detector and Sieve Alignment in spacecraft.

The focal center of the detector is outside of the physical body of the DSC. To ensure the least smearing or noise due to jitter during image exposures, it is required that the focal center is as near to the CG as possible. Since there are many unknowns at this point in the mission (launch vehicle, deployer, material properties of the bus, cabling and harnessing masses, etc.) it was decided that the geometric center of the spacecraft will be used instead. The Piano is offset from the sidewall by 0.5" to allow for the door to swing open, but this may change. It is mounted on the shaded face of the DSC, with ¼-20 fasteners. The female thread is placed on the Piano itself, with countersunk screws entering from the external face of the chassis. A similar setup is used for the Sieve on the OSC. The bolt pattern for the detector is shown below.

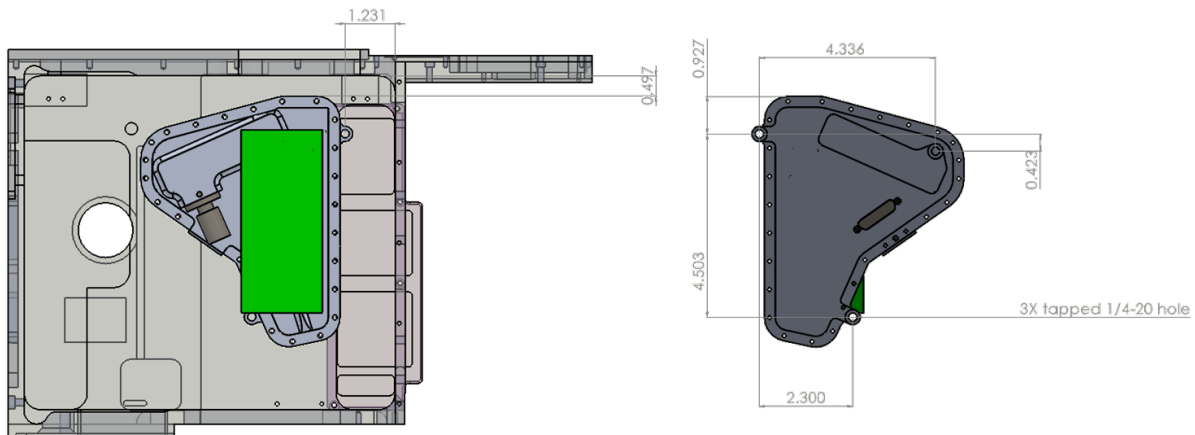


Figure 13. Piano mounting bolt pattern and location inside DSC

The CSIE board stack is mounted using large Aluminum blocks, to enable proper heat transfer out of the boards and into the chassis. They are mounted on the shared wall between the Payload and the Bus. The final location has not been agreed upon yet, and will depend on two things: ensuring no mechanical interference with BCT electrical or mechanical components; and clearance for the Detector Door release mechanism. An image of the CSIE stack is shown below, in context of the spacecraft.

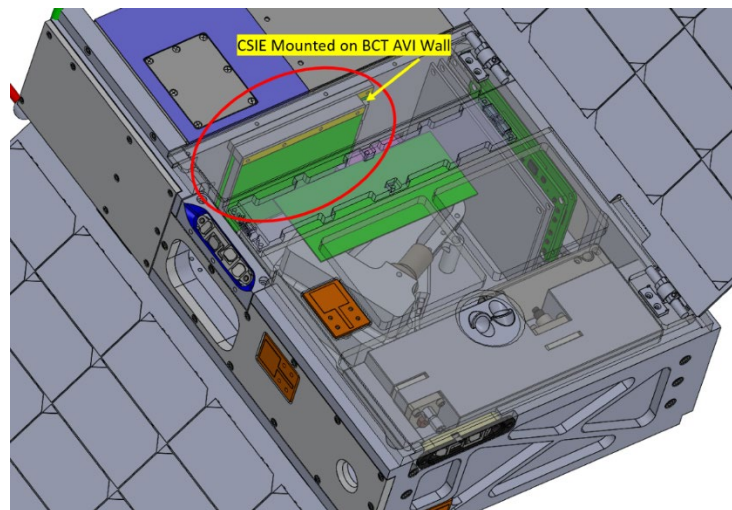


Figure 14. CSIE Mounting location inside DSC

The door release mechanism has not yet been finalized. It is currently in work, and notionally architected to be a hinge-based swinging door with a torsion spring incorporated. The door must seal against the opening into the detector, and the release has been baselined as a non-explosive actuator (NEA) that acts one time but is manually resettable. The seal is required to maintain cleanliness of optics and sensors inside the Piano – the detector will be purged with inert gas and sealed off before launch, then vented in space after the spacecraft are deployed. The sieve, on the other hand, will have no cover or protection from foreign object debris through final integration and delivery. Extra care must be taken to keep the Sieve clean.

Significant Remaining Work

This section aims to detail important tasks needed to be completed as soon as possible. This work will create a more granular design and understanding of how to operate this mission:

- Decide Figures of Merit for images taken
 - **Task Description:** Describe in detail what parameters, measured or calculated, can quickly, accurately, and autonomously give insight to the value of a picture taken. These values must be generated on-board the spacecraft by the payload, while in Science Configuration, and communicated to the ground in short groundpasses without reorienting the spacecraft towards the ground. This means these FoM must convey significant information while remaining short messages.
 - **Rationale for task and urgency:** There are multiple images (exposures) taken during one 10-second imaging opportunity. Approx. 10 such passes will be made in a nominal imaging campaign. These images represent significant volumes of data, and downloading one set of images may take up to 10 months – it is infeasible to download all images from even one imaging campaign. It is also unsafe to download even one image when in Science configuration – the GPS antenna must be kept zenith pointed to ensure the spacecraft do not have a collision. To make the problem worse, transitioning the spacecraft from Science configuration to Standby configuration requires a *significant* amount of delta-v. This combination of constraints: significant amount of data to download, significant dV cost, and a desire to minimize downlink time means that the spacecraft must be able to convey its best guess as to which image may be worth sending back to the ground station. Figures of Merit are key to getting useful data back for this mission and should be discussed *as soon as possible*.
 - **Project engineers to be involved:** Systems engineers, GNC engineers, Science instrument and process engineers, RF/link engineers.
 - **Current state of this task:** currently, the proposed FoM are relative body translational and angular position and rate data over the duration of the image, LRF ranging distance measurement, total pixel intensity of the image, and some value that indicates the total variation or contrast present in the image. These parameters have not been discussed or screened by the team or required project engineers. For image processing and

contrast calculations, there is not engineer assigned to this task and it has not yet been decided if this is the proper way to approach FoM for this type of image.

- Modes Diagrams for each subsystem
 - **Task Description:** Each team of the spacecraft must understand the flow of their subsystem through its operational modes. Once each subsystem mode diagram/state machine has been completed, they should be combined into a detailed, fleshed out modes diagram for the entire mission, with each spacecraft detailed.
 - **Rationale for task and urgency:** Currently, each system is still at a very high level of design. Granular understanding of every operational mode, and what causes the subsystem to enter or exit that mode is required before the spacecraft operational CONOPS can be understood in detail. Details in each subsystem can drive operation at the mission level, and the VISORS team must be aware at the earliest possible time these constraints arise.
 - **Project engineers to be involved:** Each operating system should create their own modes diagram, and discuss with the Systems Engineers. The systems engineers should then create a full spacecraft and a full mission modes diagram that details what each subsystem does, where it receives its commands from, and then build a master state machine that operates both spacecraft, considering the communication between the two.
 - **Current state of this task:** ADCS has performed a first pass at their modes diagram. It has been reviewed and feedback has been given. XLINK has identified functionalities, but has not produced a modes diagram. The Science team has not produced a modes diagram for the Detector. GNC has not produced a modes diagram. BCT has created a spacecraft level modes diagram and is included in the PDR slides. Propulsion has not created a VISORS-specific modes diagram, but has performed a similar task for a similar propulsion module.
- Conversion of GNC maneuver commands to propulsion valve commands
 - **Task Description:** GNC outputs maneuver commands minutes in advance of a required maneuver. This maneuver is expressed as a total dV required in an LVLH-equivalent frame at the time of the required maneuver (the LVLH frame in inertial space changes with time), but this doesn't mean anything to the spacecraft itself. The LVLH frame vector must be converted to a body frame vector at the time of the maneuver based on the spacecraft's attitude. This must then be mapped to the thruster valves that will create the given dV. These maneuver commands are output as (double check with GNC as this may change):

<time until maneuver (s), dV required in R (m/s), dV required in T (m/s), dV required in N (m/s)>

Sequencing of thrusters must also be considered – in the general case, not all thrusters will fire for the same amount of time. The thrusters are not aligned with the CG, so in general, any thruster or combination of thrusters will create a torque on the spacecraft. It is likely that thrusters will need to be staggered to make sure the spacecraft ADCS has time to rectify attitude discrepancies so that the calculated thrusters and durations result in the intended dV vector, instead of skewed due to a spacecraft rotation.

- **Rationale for task and urgency:** There is a disconnect between the GNC, BCT, ADCS, and PRP teams, and this task was not being tracked by any subteam until midsummer 2021. It has very recently been assigned to the ADCS team. As the task was not being tracked, it had not been allocated for at PDR in the hosted payload software applications within the BCT bus (as this is most likely where this code will be kept). Memory requirements, interfaces, information flow, and other aspects of this task must be figured out and communicated to the vendor to ensure any problems accommodating this functionality. It is also important that fuel inefficiency be considered – to achieve a random dV vector, multiple thrusters will have to fire to cancel out off-axis thrusts, given that thrusters are not aligned along primary axes and traveling through the spacecraft CG. The project must evaluate if this wastes enough fuel to warrant a change to the CONOPS.
- **Project engineers to be involved:** ADCS, GNC, PRP, Systems
- **Current state of this task:** ADCS has started the task of calculating which combination of thrusters results in any given dV vector direction. Defining the ADCS modes diagram was the first phase of determining if the thrusting will be inefficient. GNC has quoted approx. 30/60 split of along-track and cross-track thrusting (confirm with GNC).
- Assembly and Integration of systems into spacecraft, testing, and MGSE/EGSE/infrastructure considerations to I&T and mechanical design
 - **Task Description:** Assembly, integration, and test has not been considered in any significant or holistic way through the design of the bus, subsystems, or interfaces. A concerted effort should be made to plan the full I&T process, and walk the s/c through the I&T process making note of where, for example, MGSE interface bolt holes should be included.
 - **Rationale for task and urgency:** CDR will slip in a 1:1 relation with a delay in conveying the VISORS requirements on the spacecraft structure. Accessing the hardware, interacting with movable assemblies and electronics, and other I&T considerations may present significant, unknown, and *costly* changes to the design moving forward.
 - **Project engineers to be involved:** Systems, PRP, Science, XLINK, GNC, Thermal, RF, and all others
 - **Current state of this task:** Some high level tests have been identified, but no other work has been done for this task.

Points of Contact

System:

Glenn Lightsey: Systems Engineering lead. glenn.lightsey@gatech.edu

Farzad Kamalabadi: VISORS PI. farzadk@illinois.edu

Max Kolhof: Systems Engineer. mkolhof3@gatech.edu

GNC

Simone D'Amico: GNC PI. damicos@stanford.edu

Adam Koenig: Previous GNC POC. adamkoenig90@gmail.com

Tommaso Guffanti: Current GNC POC. tommaso@stanford.edu

Thermal

Petr Kazarin: Thermal PI. pkazarin@purdue.edu

Ben Greene: Thermal. green67@purdue.edu

Hasnain Daudi: Thermal. hdaudi@purdue.edu

Jillian Ross: Thermal. ross229@purdue.edu

ADCS

Hyeongjun Park: ADCS PI. hjpark@nmsu.edu

Micah Shuman: ADCS. mts@nmsu.edu

Science

Adrian Daw: Science Lead. adrian.daw@nasa.gov

Doug Rabin: Science Team + Laser Rangefinder. douglas.rabin@nasa.gov

Paul Mirrel: Science Instrument Mechanical Eng. paul.mirel-1@nasa.gov

Carl Himpfel: Detector Door designer (LASP). carl.himpfel@lasp.colorado.edu

Phil Chamberlain: Detector designer (LASP). phil.chamberlin@lasp.colorado.edu

BCT

Dave Baron: BCT VISORS lead. dbaron@bluecanyontech.com

Briand Monteiro: BCT Mechanical. bmonteiro@bluecanyontech.com

Jacob Payne: BCT VISORS POC. jpayne@bluecanyontech.com

XLINK

Subhanshu Gupta: XLINK PI. subhanshu.gupta@wsu.edu

Sai Teja: XLINK Software. manchala.4@buckeyemail.osu.edu

Gabe Adamson: XLINK. gabriel.adamson@wsu.edu

Vaibhav Nanha (Vibes): XLINK. v.nandha@wsu.edu

PRP

Sam Hart: Propulsion. samuelthart@gatech.edu

The team also uses Slack: <https://visors.slack.com/>