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Preliminary Design of the DarkNESS Observatory for Fermi National Accelerator Laboratory

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ABSTRACT

The "Dark matter as a sterile NEutrino Search Satellite" (DarkNESS) is a collaboration between Fermi National Accelerator Laboratory (Fermilab), University of Illinois Department of Aerospace Engineering's Laboratory for Advanced Space Systems at Illinois (LASSI), and CU Aerospace. Fermilab's project seeks to clarify the X-ray emission spotted by the European Space Agency in galaxy clusters, hypothesized to result from the decay of sterile neutrinos that may be associated with dark matter. Limited by atmospheric interference, ground telescopes cannot discern the weak X-ray signal. A small satellite deployed in low Earth orbit (LEO) outfitted with an advanced Skipper X-ray detector has been proposed to observe the galactic center, potentially detecting the signal. DarkNESS is a challenging mission involving multiple operational constraints. This paper presents the results of the feasibility assessment undertaken for the Preliminary Design Review (PDR) that revealed the thermal, power, and pointing constraints imposed by orbital mechanics on the mission concept of operations, along with their resolutions. The DarkNESS mission's next milestone is the Critical Design Review scheduled for early 2024.

SCIENCE BACKGROUND

The Chandra X-Ray Observatory (CXO), deployed in 1999, uses a highly sensitive X-ray telescope to detect and image X-ray sources such as black holes, quasars, and high temperature gases. A significant contribution made by CXO was the low-resolution confirmation of an X-ray emission also detected by the European Space Agency's Multi-Mirror X-Ray Newton observatory (XMM-Newton).[2] Similar in design and purpose to CXO, XMM-Newton performed narrow and broad-range spectroscopy observations of X-ray emitting sources. Analysis of XMM-Newton stacked spectra from 73 groups of galaxy clusters revealed an emission line at 3.55-3.57 keV, which CXO also detected when observing the Perseus Cluster. Although the signal is distinguishable over the background radiation environment, it is at the limit of current X-ray observatories' instrument resolution. The source of the emission is not known.

One theory suggests that dark matter may be associated with sterile neutrinos if they exist. Energetic galactic black holes may be involved in their origin. As sterile neutrinos decay into standard neutrinos, photons are emitted at the 3.5 keV signal as shown in **Figure 1.**[2,4]

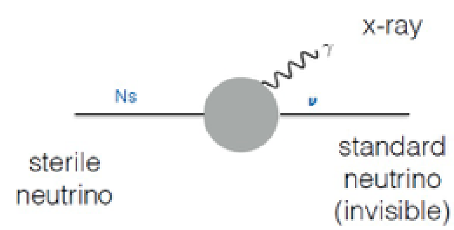

Figure 1: The decay of a sterile neutrino (Ns) into a standard neutrino (v), emitting an X-ray photon.[5]

To resolve the weak X-ray signal, observations must be of long duration, have unobstructed views of the galactic center, have the proper energy resolution on the focal plane, and have a wide field of view to gather a weak signal. Fermilab's proposed Skipper detectors for DarkNESS features two customized wide field-of-view (FOV) charged coupled devices (CCDs) with high-energy resolution in the 3.5 keV region. The CCDs have heritage from previous observatory science programs and are capable of higher resolution than current X-ray telescopes.[1,3]

The relatively small size of the CCDs, approximately 10 cm^2, make them ideal for deployment onboard a

CubeSat. However, the CCDs' thermal operating requirements present significant design challenges for this type of platform.

MISSION OVERVIEW

The DarkNESS Concept of Operations drives the formulation of the functional and performance requirements for the mission (**Figure 2**). The satellite is launched and deployed into LEO (**Figure 2.1**). Along with its associated instrument payload, the satellite is calibrated and readied for its seasonal observations (**Figure 2.2-2.3**). Observations are taken (**Figure 2.4**) and downlinked periodically to the ground (**Figure 2.5**). At the end of its mission, the satellite is turned off and is de-orbited by atmospheric drag (**Figure 2.6**)

One of the unknowns facing mission designers was the expected final orbit of the satellite. If deployed from the International Space Station (ISS) at an inclination of 51.6 deg, the satellite will experience different operating conditions than it would from a deployment into a polar or sun synchronous orbit. As such, the designers had to accommodate all operational scenarios during the early phases of mission design.

OBSTRUCTION ANALYSIS

DarkNESS will take images of Sagittarius A* (Sag A*), the supermassive black hole at the center of the Milky Way galaxy. Given the Earth, Sun, and target geometry shown **in Figure 3**, Sag A* can only be seen from the March to September period of Earth's orbit. At all other times, the satellite's field of view is obscured by the Sun. Additionally, for a portion of its orbit around Earth, the Earth itself obscures the sensor field of view.

To map out the timing and duration of these obscurations, an astrodynamics software tool, a. i. Solutions' FreeFlyer, was used. **Figure 4** provides an example of a "molar" plot illustrating when the satellite has Sag A* in its field of view. The darker blue areas of the plot indicate that the field of view is also partially obscured by the Earth itself as the satellite enters the eclipsed portion of its orbit.

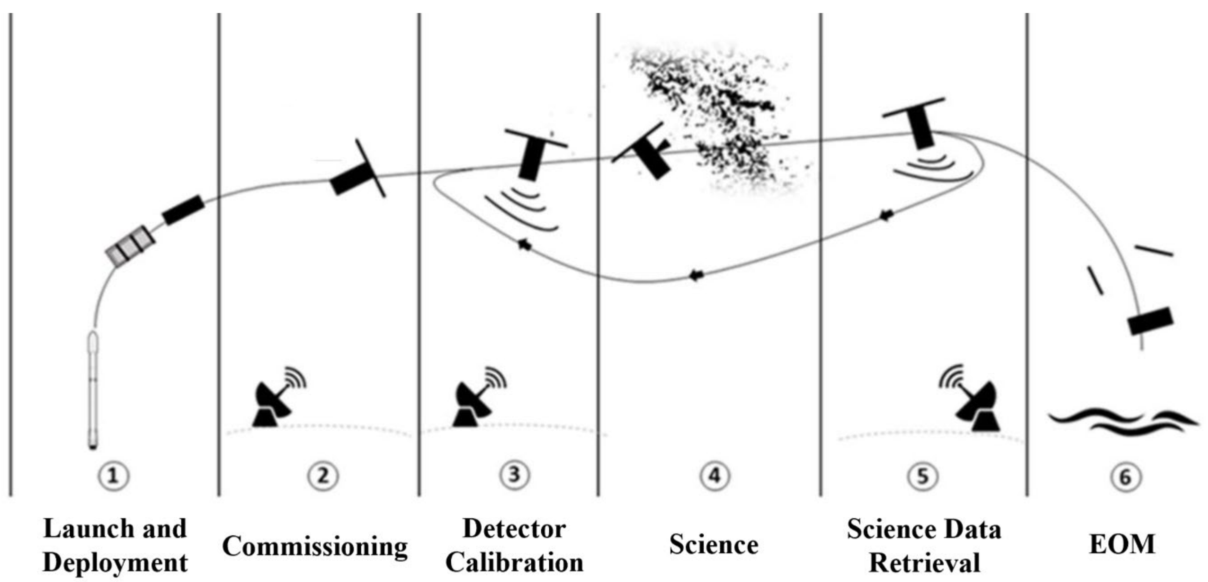

Figure 2: DarkNESS Mission Concept of Operations. The observatory collects X-ray images of the galactic center and relays them to the ground.

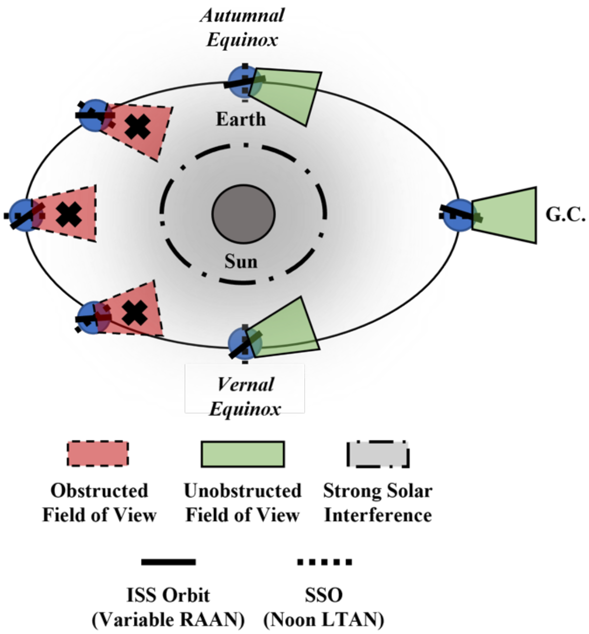

Figure 3: DarkNESS Seasonal Visibility. Obstruction caused by the Sun limits science data collection to about half a year. The Earth may also obscure celestial targets depending on the selected Observatory orbit.

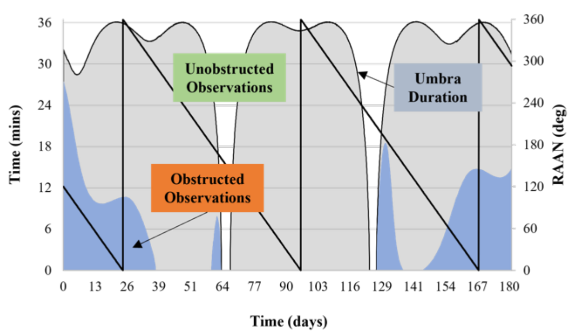

Figure 4: The detector field-of-view becomes obstructed by Earth at various times throughout the season (blue region). At all other times inside the light grey region observations are possible.

RADIATOR VIEW FACTOR ANALYSIS

Minimizing the satellite's radiator-Earth view factor and direct exposure to the Sun reduces heating from the ambient environment, improving radiator performance. Radiator exposure to Earth albedo is a function of instrument pointing configuration and orbit. Active alignment of the radiator panels minimizes the view factor to Earth during solar charging and science pointing regulation. By modeling view factors as the fraction of radiator surface area that is exposed to the Earth, profiles for four configurations were tracked using geometric calculations in FreeFlyer. The radiator surfaces of the front-pointing sensor configuration perform better than side-pointing sensor configurations during the science season as shown in **Table 1**. The front-pointing configuration was found to be better-suited for managing radiator exposure and was selected for further analysis.

Table 1: Configuration Performance Summary. Radiator view factors favor a front-pointing satellite configuration.

Configuration/Orbit	Maximum View Factor
Front-pointing/ISS	~0.40
Side-pointing/ISS	>0.50
Front-pointing/SSO	~0.35
Side-pointing/SSO	~0.40

THERMAL ANALYSIS

The most challenging engineering issue for DarkNESS is to be able to maintain the temperature of the Skipper-CCD detector at 170 K for the duration of the observation season.[6] A thermal model of the satellite, instrument, cryocooler, and major thermal loads was constructed and implemented using Siemen's NX Space Systems Thermal modeling tool.

Key features and assumptions used in the model included:

- A tetrahedral 3D mesh applied to individual parts.
- Materials assigned to each part included beryllium, silicon, invar, copper, etc.
- Assigned perfect surface-to-surface contacts between conductive surfaces.
- Orbital heating included as a simulation object with 12 calculation positions per orbit.
- Internal radiation is neglected.
- Reduced mesh resolution used to reduce computation time resulting in an average temperature representative of steady state conditions.

External radiation and internal heat loads were modeled by mechanically interfacing them to the satellite's aluminum structural frame. While the instrument also mechanically interfaces to the frame, the detector assembly is thermally isolated on stand-offs to reduce heat transfer into it from other satellite components. **Figure 5** shows the instrument integrated into the satellite bus with the cryocooler and copper thermal straps carrying heat from the cryocooler to the radiator panels. Satellite bus generated thermal loads were summed and distributed into the structure at defined contact points.

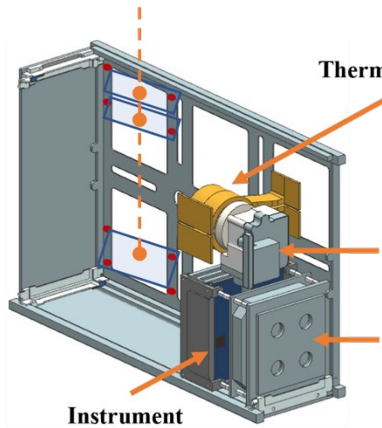

Figure 5: Instrument and internal satellite subsystem heat loads. The thermal analysis assessed the feasibility of the preliminary system design.

Internal heat loads applied to the thermal model are listed in **Table 2**. Total loads were distributed across mounting points on the structure that the actual equipment would eventually be fastened to.

Table 2: Thermal model internal heat loads.

Internal Heat Loads Applied	Value [W]
Cryocooler cylinder	9
Payload boards	15
Avionics boards	4
Reaction wheels	3
Communications	1

The meshed model was propagated for several orbits to include Sun-exposed and eclipsed environments. In the model, the cryocooler was able to maintain the detector assembly temperature at 170K +/- 5K.

POWER ANALYSIS

DarkNESS is a solar powered satellite that uses batteries to store power for use in eclipse. FreeFlyer was used to evaluate projected duty cycles for all powered satellite components. A sun pointing attitude control law was incorporated into the simulation to maximize solar charging on the daylit side of the orbit. A double deployable solar panel configuration incorporating a total of 72 cells was found to meet the worst-case power demand. Using a 25% depth of discharge limit to safeguard battery life for a two-year mission duration, eight 11.5 WHr batteries power DarkNESS during eclipse.

DATA AND COMMUNICATIONS ANALYSIS

DarkNESS will regularly downlink instrument science data and satellite health and status to a ground station. The instrument generates data in two formats: a 32 MB raw image produced during 15-minute detector exposures and a 2.5 KB binned histogram containing condensed information about each raw image. Each orbit's observation histogram data is downlinked as soon as possible following capture. Specific larger raw images can later be requested for downlink to the Fermilab science team, if needed, after review of an observation's histogram. **Table 3** provides the data downlink requirements.

Table 3: DarkNESS Data Budget. Satellite telemetry and Instrument data drive the communications requirements.

Data	Total Bytes per pass
Satellite telemetry	~5 KB
Image histogram	~2.5 KB
Overhead	25%
Total bytes per pass	**~9.4 KB**
Raw image	32 MB

Link budgets for UHF, S-band, and X-band communication systems were evaluated. The 32 MB raw image was the limiting factor in the analysis. A UHF radio requires approximately 70 passes to complete a raw image download. An S-band radio can complete the same every two days while an X-band radio can downlink the image in one pass. Based on the expected low frequency of full image downlinks, reduced power and mass requirements, and associated capital costs, the S-band radio was considered sufficient for DarkNESS.

PDR CONFIGURATION

Figure 6 illustrates the internal side view of the DarkNESS PDR configuration. Components associated with the science objective include the detector assembly, cryocooler, cold-finger-coldplate connector instrument board assembly, and thermal straps. **Figure 7** shows the external configuration that satisfies all functional and performance requirements.

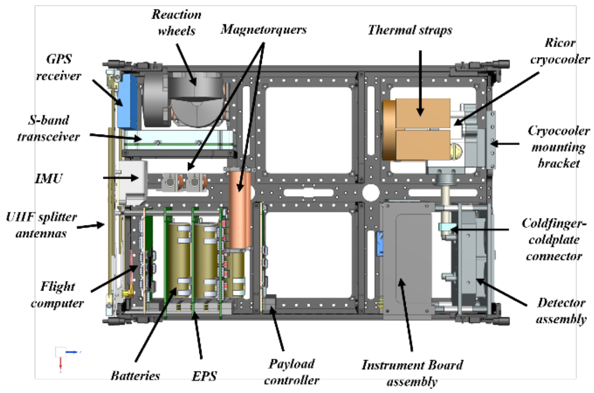

Figure 6: Interior configuration of DarkNESS Subsystem components.

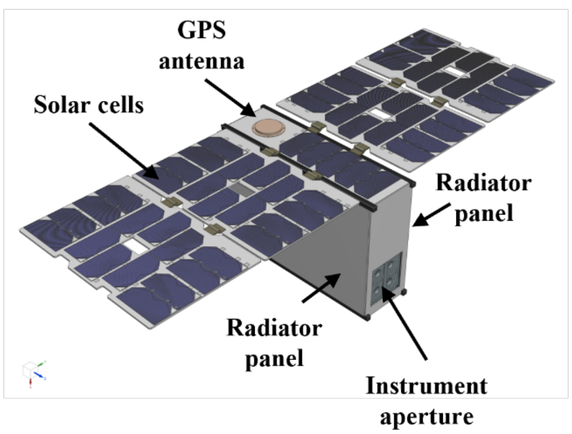

Figure 7: Preliminary design for DarkNESS.

CONCLUSIONS

The DarkNESS PDR provided a technically sound operational concept with a flow down of verifiable requirements that are complete and traceable to the mission goals and objectives. The definition of the technical interfaces was found to be consistent with the overall technical maturity and provided a manageable level of risk.

The temperature constraint on the detector's CCD coupled with the integration of a compact cryocooler drove the satellite internal and external design. Mission and thermal analysis revealed a 6U CubeSat with subsystem sizing meets technical performance evaluation margins.

Between now and the Critical Design Review (CDR) later this year, several development tasks will be performed to further reduce technical risk, particularly in the thermal control system. Some of the anticipated activities include:

- Further maturation of the design of a prototype thermal control system
- Testing of the prototype system in vacuum and verification of the thermal model
- Evaluation of satellite attitude control performance

Acknowledgments

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