Developing Optical Sensor Constellation Architectures for Space Domain Awareness Through Model-Based Trade Studies

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ABSTRACT

Modern space surveillance technologies leverage the engineering of constellations, system-of-systems comprised of multiple individual nodes. These constellations can accomplish multiple complex missions that an organization might have. To accomplish cislunar Space Domain Awareness (SDA), the Steward Observatory team at the University of Arizona has developed a novel optical space telescope concept to serve as the basis for surveillance constellation. An optimized constellation of these sensor systems, which feature an innovative continuous scanning system, can provide the necessary sensitivity and search rate performances that conventional "step-stare" surveillance approaches cannot achieve for observing objects near the moon. Trade studies assessing key performance parameters for optical systems provide evidence for decision-makers that specific design configurations best accomplish mission goals. Model-Based Systems Engineering (MBSE) provides an alternative to traditional document-based methods that is best suited for handling complexity in systems architecture design.

As opposed to a functions-rooted approach in modeling an SDA constellation, we have chosen a requirements-based approach to tackle the missions of cislunar synoptic space surveillance and lunar surface reconnaissance. Our team leverages system development lifecycle methodologies and MBSE to manage hierarchical requirements that form the design space and ensure correct system performance. While several methodologies exist for managing requirements, the systems modeling language SysML and its associated Object-Oriented Systems Engineering Methodology (OOSEM) provide a means by which to digitally connect those requirements to modeled representations of the constellation structure and mission elements. Furthermore, the NASA Jet Propulsion Laboratory Executable Systems Engineering Methodology (ESEM) for SysML provides a formal methodology by which to automate the systems engineering requirements verification process to ensure that specific mission configurations meet all requirements, down through the subsystem and component hierarchical levels.

Our team extends these methodologies using digital thread software bridges to integrate the SysML representation of the system and with data from external digital engineering tools. Additional software like Systems Toolkit (STK) and optical design data from Zemax OpticStudio can connect directly to parameters in our SysML model. Through integrating model data elements across different software, our group includes detailed physics-based data in instances of our constellation's logical architecture and maintains a compendium of acceptable designs within Cameo Systems Modeler. In this way, our requirements-based approach informs decision makers if a design alternative is acceptable without manually performing verification for every requirement. Our holistic approach permits modeling and simulation at a higher fidelity than traditionally possible through OOSEM and ESEM.

Herein we present SysML models built in 3DS Cameo Systems Modeler to automate mission and systems-level technical and stakeholder requirement verification for constellations of space-based telescopes designed to accomplish cislunar SDA. This paper reports on the preliminary results of our modeling endeavor, including details on our system's time delayed integration (TDI) continuous scanning concept. We also include details on formalizing the satisfaction of both mission and system-level requirements for holistic and detailed trade study results. With SysML's ability to both model and simulate the requirements, structure, behavior, and constraints hierarchically in a system-of-systems, program managers can rapidly evaluate design alternatives using visual programming techniques that raise the layer of abstract from line-by-line programming in one digital environment that enables renewable artifact generation of traditional documentation for stakeholders unfamiliar with MBSE.

1. INTRODUCTION

In 2022, the United States Office of Science and Technology Policy (OSTP) published a National Cislunar Science and Technology (S&T) Strategy towards ensuring responsible, peaceful, and sustainable cislunar space exploration and use [1]. As part of this strategy, OSTP specifies four key S&T objectives; the latter two are technical objectives: “extend U.S. space situational awareness capabilities into cislunar space”, and “implement Cislunar communications and positioning, navigation, and timing (PNT) capabilities with scalable and interoperable approaches” [1]. In alignment, Steward Observatory at the University of Arizona has investigated establishing space situational awareness in the cislunar domain—cislunar space domain awareness (SDA)—through synoptic surveillance constellations. Our developing methodologies and capabilities enable constellation optimization across performance and cost in the context of cislunar communications and PNT requirements.

Both optical and radar systems can accomplish SDA, and from several locales: in space, terrestrially, or on the Moon’s surface. Although terrestrial-based radars routinely provide precision range and rate astrometrics on geosynchronous objects, extending the reach of ground-based radars to cislunar SDA requires a substantial increase in their detection sensitivity. Even without this sensitivity gap, radars have little capacity to conduct uncued searches for new objects; they receive direction from synoptic optical systems. While modern Earth-based optical sensing systems can deliver the sensitivity to detect cislunar objects at ranges of 150-400 million meters (Mm), they fail to provide adequate search rates to discover new objects. One possibility to mitigate range-based sensitivity loss could be lunar surface basing for SDA systems. However, even from the moon, cislunar Lagrange Points L1 and L2 are quite distant, with ranges approximately twice Earth-GEO distances (Table 1). A lunar-based optical system offers no advantages over a space-based platform; lunar-based radars have significant environmental and power challenges imposed by the long lunar night. Additionally, cislunar SDA practitioners must site a significant fixed installation with associated infrastructure on the moon and design these systems to survive a soft landing on the lunar surface.

Table 1. Comparison of distances in cislunar space. ‘Topo’ refers to distances from the topocentric observer, located on the Earth’s surface in a typical geometry. All other distances are geocentric/selenocentric as appropriate.

			Sensitivity vs. Range			
			Optics (r^{-2})		Radar (r^{-4})	
	km	Earth radii	area (m^2)	V mag	area (m^2)	dBsm
Earth Radius	6371	1.00				
Moon Radius	1737	0.27				
Topo-LEO	1500	0.24	1.75×10^{-3}	-6.9	3×10^{-6}	-55
Topo-GEO	35829	5.62	1	0.0	1	0
Earth-L1	326200	51.2	83	4.8	6900	38
Earth-Moon	384300	60.3	115	5.2	13000	41
Earth-L2	449000	70.5	157	5.5	25000	44
Earth-L3	384700	60.4	115	5.2	13000	41
Earth-L4/L5	384300	60.3	115	5.2	13000	41
Moon-L1	58200	9.14	2.6	1.1	7.0	8.4
Moon-L2	64700	10.16	3.3	1.3	11	10

The most challenging aspect of establishing cislunar SDA is the large angular search volume that must be surveilled. The traditional “step-stare” approach for synoptic surveillance limits conventional space-based optical space systems: slow gimbal or spacecraft pointing hampers effective search rates. When searching wide fields of regard, step-stare systems spend a sizable portion of time moving and settling before finally surveilling within the search volume. To compensate for this performance limitation, conventional architectures require the deployment of large constellations of sensors to effectively search cislunar space, ballooning the overall SDA mission cost. Although engineers could use a smaller number of very wide field-of-view (FOV) small telescopes to cover the field of regard, this would yield low sensitivity and poor metric accuracy. The limitations in these approaches drive a technology gap between current capabilities and those described by the OSTP National Cislunar S&T strategy.

Our team’s novel system concept overcomes these limitations by equipping a satellite with a continuous scanning system comprised of the combination of two elements: a sequential time delayed integration (TDI) enabled Charge-Coupled Device (CCD) mosaic camera, and a low distortion, wide FOV three-mirror off-axis telescope design using free-form surfaces. TDI combines the serial operations of integration, camera readout and step/settle into a blended, simultaneous, and continuous operation. We have optimized this free-form three-mirror telescope design to control distortion, thereby not only using TDI across a wide sweep width, but also over a long TDI interval. This method of continuous scanning substantially increases the realizable search rate at the necessary detection sensitivities.

The sequential mosaic of three CCDs in this design provides a three-observation track per scan, and the bi-directional Hamamatsu imagers comprising the mosaic camera allow scanning in either direction, further enhancing search performance and operational flexibility. This all allows for better detection of objects against the dark lunar sky, and, by coincidence, lunar surface reconnaissance, which has similar requirements for sensitivity and scan rates to those of synoptic surveillance for cislunar SDA. Thus, our design considers both missions as prospective use cases. Figure 1 shows results from our team's TDI system electro-optical (EO) performance model that demonstrate clear benefits to the step-stare approach in search rate over a range of sensitivities for a given signal-to-noise ratio (SNR). The dramatic increase in synoptic search performance of a TDI-based sensor system vs. a conventional step-stare equivalent is a consequence of the high efficiency of the sequential TDI focal plane.

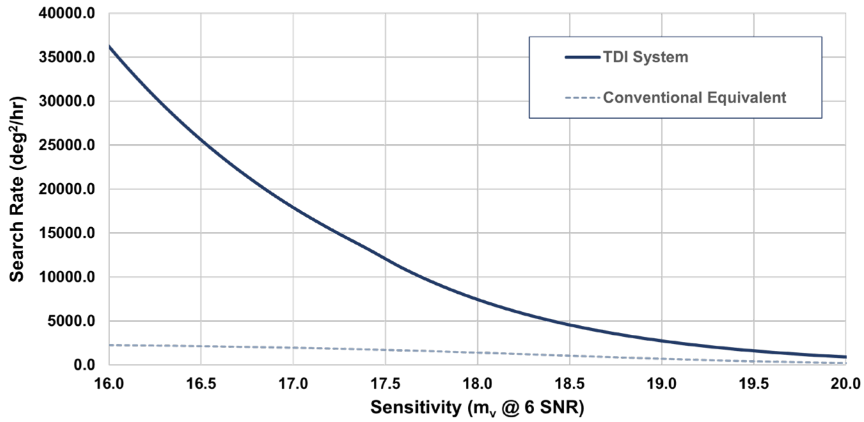

Fig. 1. Performance of cislunar space TDI surveillance systems vs. a similar-size conventional step-stare system.

The scanning rate in the scan direction across each imager's 128 pixels determines the system's effective integration time. Using satellite relative motion combined with TDI imaging, this concept can achieve a long effective integration time and thus high sensitivity while continuously scanning the field of regard in cislunar space instead of suffering the long moving and settling times of the step-stare approach. With our novel TDI-based system (summarized in Figure 2), the ability to trade sensitivity for higher search rate becomes limited only by slew rate and processing time requirements. We can tailor the operation of this system for deployment to different cislunar orbital constellations, including distant retrograde orbit (DRO) and halo orbits at L1 and L2. This system will serve as the basis for our design and modeling of optimal cislunar constellations for SDA. Cislunar constellations are complex system-of-systems with differing requirements from their terrestrial counterparts: just as surveilling the dark region surrounding the Moon is challenging, so is developing a formal trade study to ensure requirement verification at the system level with sufficient fidelity for a digital proof-of-concept.

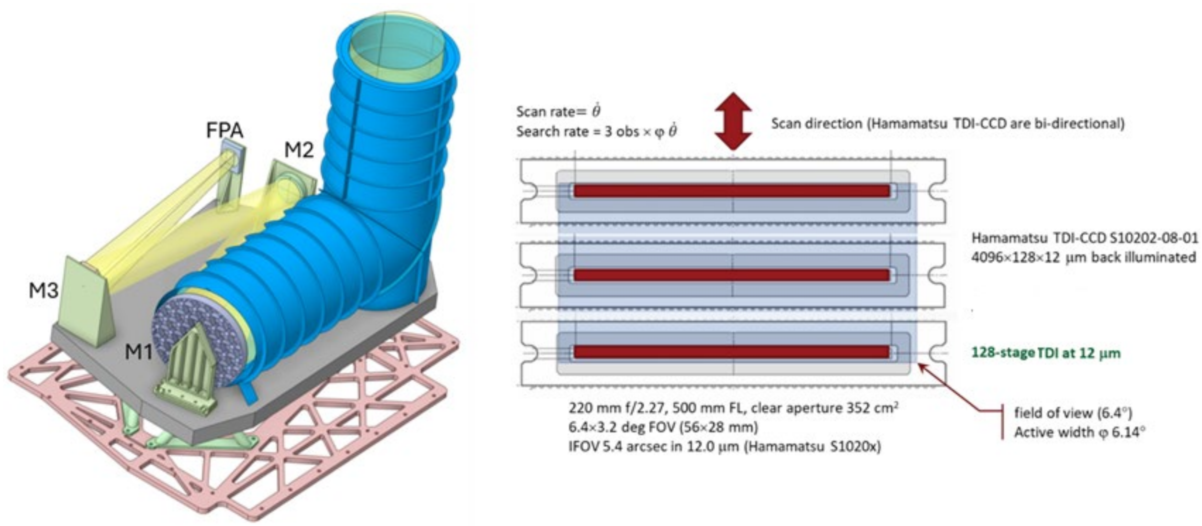

Fig. 2. The three-mirror off-axis telescope and sequential TDI focal plane detector array. A fold mirror (M0) optimizes the optomechanical mounting to the satellite bus that provides motion for the continuous scanning.

Trade studies are defined as decision supporting analyses that involve selecting one configuration from many, winnowing the number of possible solutions to a manageable group of validated design alternatives [2]. In this mission, we expect the trade space to be primarily designing a constellation of a to-be-determined number of satellites that simultaneously provides line of sight diversity for efficient initial orbit determination (IOD), phase angle diversity to maintain custody, and minimize costs by effective utilization of innovate PNT solutions such as the LiAISON mutual self-navigation techniques [3]. Mutual self-navigation eliminates the reliance of the system on GPS navigation, which is problematic in cislunar space due to large range and line-of-sight to the current GPS constellation. To formalize the engineering approach to studying these system trade-offs, our group has chosen to leverage Model-Based Systems Engineering for configuration management.

To accomplish Model-Based Systems Engineering, one needs a modeling language, a model authoring tool, and a methodology. Cameo Systems Modeler with Systems Modeling Language SysML and its corresponding Object-Oriented Systems Engineering Methodology, or OOSEM, enables visual programming through cross-cutting diagrams that provide both human and machine readable descriptions of complex systems-of-systems [4]. NASA JPL has extended OOSEM with the Executable Systems Engineering Methodology (ESEM), creating a means for automated requirement verification to facilitate comparison of design alternatives in a trade study [5]. Our team extends this methodology using digital thread technology to connect domain-specific engineering simulation software results to Cameo Systems Modeler and its Simulation Toolkit plugin, which provides a code interpreter to execute line-by-line code such that SysML models are executable and produce simulation results.

2. SENSOR PERFORMANCE CONSIDERATIONS

Because there is no pre-existing cislunar resident space object catalog, cislunar sensing systems must provide a synoptic capability to both discover and track new cislunar objects. Providing synoptic surveillance of the cislunar environment poses significant technical hurdles that conventional space-based space surveillance sensors cannot overcome. As opposed to synopsizing a specific hotspot orbit like Earth's geostationary (GEO) belt, in the cislunar domain, there are no analogous orbital "highways" to limit the field of regard we must surveil. As such, cislunar SDA requires sensors that rapidly search wide fields of regard while also attaining a relevant range of detection sensitivity to adequately identify regional resident space objects (RSOs). Otherwise stated, cislunar constraints drive a fundamental need for surveillance systems that simultaneously deliver high sensitivity and high search rates, beyond the available technology; yet there is an inherent engineering trade-off between sensitivity and search rate.

2.1 History of Space-Based Optical Telescopes

Space-based space surveillance was first demonstrated with the MIT Lincoln Laboratory (MIT/LL) Space-Based Visible (SBV) system and later operationalized with the Space-Based Space Surveillance (SBSS) system [6], [7]. Both SBV and SBSS used off-axis three-mirror-anastigmat (TMA) telescopes based on concepts developed by L.G. Cook in the late 1970s [8]. These designs provided wide FOV and good off-axis light rejection without advanced freeform optical surfaces, though designers struggled to reach diffraction limited performance across the entire FOV. Ground based systems with high search rates and performance like GEODSS and SST use large-aperture, wide-FOV telescopes, high-speed focal plane cameras and agile gimbals for comprehensive surveillance; in space, however, we are severely limited by much slower gimbal slew rates (i.e., SBSS), or spacecraft reorientation and settling times. The next generation space-based surveillance system was the MIT/LL developed SensorSAT system, later renamed ORS-5 and launched in August 2017 [9]. ORS-5 replaced the traditional TMA telescope with a 10-element f/2.3 modified-Petzval refractive telescope.

ORS-5 leveraged the unique equatorial LEO-GEO geometry and relative motion combined with TDI to achieve an effective integration time of 7.5 s. This significantly increased sensitivity and enabled GEO surveillance with a small 10 cm aperture telescope. The ORS-5 surveillance satellite used the unique equatorial LEO-GEO geometry and relative motion combined with TDI to achieve a long effective integration time and continuous scanning of the GEO belt. However, ORS-5 was limited to this specific geometry, orbital regime, and scheduling. The TDI technique enables an alternative approach that increases search efficiency by orders of magnitude. Using TDI, a sensor can scan continuously, increasing efficiency of area search by tens to hundreds of times over a conventional step-stare system. Zenith staring sensors using TDI are often used for Earth and planetary imaging. Systems like ESA's PROBA-V, NASA HiRISE, or the recent ASU ShadowCam are excellent examples [10], [11], [12].

The astronomical community has used TDI-based systems for survey work with projects such as SLOAN, Spacewatch, and the Carlsberg Meridian Telescope [13], [14], [15]. In the SDA application, Lincoln Laboratory successfully demonstrated TDI at the Experimental Test System (ETS) site in southern New Mexico in 1980 [16]. In all these systems, short effective integration times and narrow field of view caused by geometric distortion limited TDI capabilities. This distortion smears images across the TDI columns as the sensor moves, degrading the system's point spread function (PSF) and overall performance. A second and important consideration involves the fabrication of the telescope optics and the design and assembly of the corresponding optomechanical structure. This process involves a series of trades and programmatic decisions concerning the precision of optical polishing and fabrication, assembly and alignment that invariably requires compromise to meet cost or schedule requirements.

At a high level, these fabrication compromises generally decrease the image quality, as measured by the size of the telescope PSF of the final assembled telescope, and hence decrease the sensitivity performance of the system. The lower curve in Figure 3 demonstrates this concept of PSF degradation impacting TDI search rate at sensitivity ranges for a given SNR. Our team's EO model considers the PSF as a factor for performance calculations, and thus we must consider all possible sources of PSF degradation. Fabrication trades can be very difficult to manage during program execution, often because the overall system and constellation performance considerations cannot be quickly assessed to inform program management. Our tools strive to integrate the mechanical model of the telescope with the EO performance model and constellation performance model to inform program management in real-time.

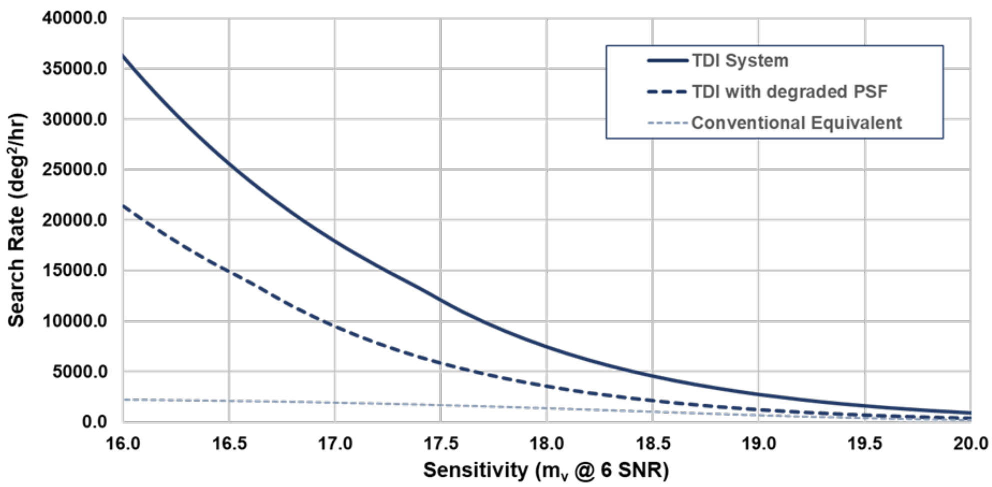

Fig. 3. Degraded tracking reduces PSF quality and decreases sensitivity at a given search rate.

2.2 Cislunar Orbits for Synoptic Surveillance

In cislunar space, the gravitational effects of the earth and moon are equally dominant. Of the diverse orbit classes in cislunar space, halo orbits around the metastable earth-moon Lagrange points L1 and L2 have received the greatest interest in research literature. Such orbits are centered around a set of equilibrium points in the earth-moon system named L1-L5 and were first identified in the late 1700s [17], [18]. Other orbits, such as the distant retrograde orbit (DRO) share many of the attributes of the LPOs but are geocentric orbits carefully designed to circumnavigate the moon in a reference frame which is co-rotating with the moon. Distant retrograde orbits were originally studied by Michel Henon [19].

When in DRO, a satellite is in an orbit about the earth with a similar period as the moon, but with a non-zero eccentricity. From the perspective of an earth-bound observer, the satellite appears to orbit the moon in a retrograde direction. While DROs are dynamically distinct from L1/L2 halo orbits, the observability of objects from DRO is similar. Objects orbiting in DRO linger near the moon within an angular extent like the L1/L2 LPOs, share similar illumination conditions as the moon, and appear to transit the sky to the earth-bound observer at a near-synodic rate. The maximum radius of stable LPOs around L1 and L2 limits the size of these volumes to radii of approximately 60,000-80,000 km. Stable DRO orbits occupy a similar volume of space, spanning the range from 20,000 to 80,000 km [20]. Furthermore, DROs having radii ranging from 36,000 to 67,000 km relative to the moon are stable of timescales of thousands of years [21].

Figure 4 shows a family of DROs our team generated in ANSYS STK using its Cislunar Orbit Designer (CODE) as seen in the Earth-Moon corotating frame. For a cislunar surveillance constellation architecture, the DRO's provide many obvious opportunities. The orbits are stable for long periods of time and the occasional eclipses can be managed by mission planning and small maneuvers. Second, a distribution of sensors in DRO can simultaneously establish both line-of-sight and phase angle diversity. Finally, DRO orbits provide the opportunity to "fly-through" the L1 and L2 halo regions once per orbital period (of order 10-20 days). For all these reasons, we have chosen DRO as the orbit type for our constellation mission to provide cislunar SDA through synoptic surveillance.

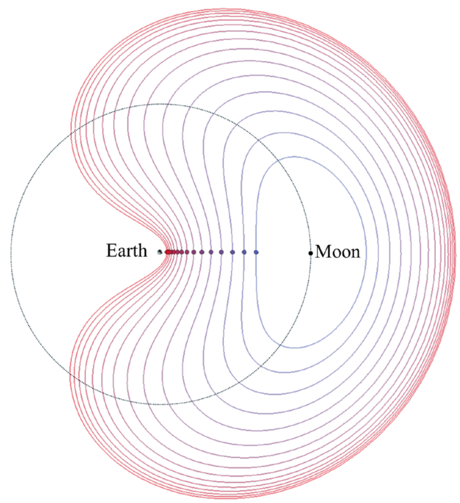

Fig. 4. Earth-Moon DRO family generated using STK CODE's Circular Restricted Three Body Problem Propagator.

2.3 Model-Based Systems Engineering for Space System Requirements Engineering

It is only in the 21st century that MBSE approaches have become commonplace within system development lifecycles methodologies. NASA Jet Propulsion Laboratory (JPL) has applied MBSE famously in its Europa Clipper project [22]. In this and other projects, JPL has used MBSE to: explore more comprehensive options for space systems, perform validation of system designs with a reduction in paper management for the design engineers, and improve quality of communications between system and subsystem engineers [23]. Meanwhile, the European Southern Observatory's (ESO) Extremely Large Telescope (E-ELT) has also used MBSE for a wide range of activities, successfully covering their following project need areas: requirements specification, system perspective diversity, analysis, document generation, configuration control, collaboration, reusability, and model organization. Other projects using MBSE include the Giant Magellan Telescope and the Square Kilometer Array telescope [24].

Notably, for the Thirty Meter Telescope (TMT), JPL researchers automated the verification methodology for their telescope's Alignment and Phasing Subsystem (APS) interface requirements using their SysML system architectural model. Accomplishing this task with traditional document-based systems engineering requires manual requirement verification, costing additional person-hours, extending schedule, and introducing error risk. Thus, JPL extended OOSEM develop the Executable Systems Engineering Methodology (ESEM) [4], [25]. ESEM formalizes the process of automating requirement verification in SysML to determine whether the model configuration satisfies both technical and stakeholder requirements for a given subsystem.

In Systems Engineering, requirements are the driving factor constraining system design. Requirements ensure that an intended system shall come to be, and the process of verification proves that has become so. Our team's approach extends ESEM hierarchically for holistic mission verification using digital thread: a means of using interoperability software to tie together common model elements across different files and formats. In previous publications we have demonstrated one method of accomplishing SysML digital thread to STK for the purposes of Mars mission planning using a software plugin no longer compatible with the modern version of Cameo Systems Modeler [26]. Because several methods for accomplishing SysML digital thread exist, our team considers multiple model integration approaches, including using ANSYS ModelCenter software for full automation, or simply enacting design heuristics to minimize human involvement in verification without fully removing that human-system interaction.

3. METHODOLOGIES

Compared to textual specifications, models developed using data-linked diagrams can offer an improvement in creating, managing, and verifying engineering trade study data. Implicit to the creation of modern models is Model-Based Systems Engineering, defined by the International Council of Systems Engineers (INCOSE) as “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [27]. A field related to MBSE, Digital Engineering (DE), has been defined by the United States Department of Defense (DoD) Defense Acquisition University (DAU) as “an integrated digital approach that uses authoritative sources of systems’ data and models as a continuum across disciplines to support lifecycle activities from concept through disposal" [28]. Lifecycle activities from concept through disposal for DE encompass all the phases mentioned in the INCOSE definition for MBSE. We combine MBSE and DE for enriched requirement modeling.

3.1 Model-Based System Development Lifecycle Methodology

While many MBSE software exist and may have different methods to capture requirements, to best enable collaboration between different engineering specialties—and enable the combination of multiple complex models for an overall system—systems engineers should choose software tools featuring interoperability. The data products from MBSE language SysML are reusable: researchers could conduct similar studies to the one described in this paper for other types of cislunar missions by modifying the encoded semantics developed for our SDA mission. This would include methods for interoperability between SysML and external software data. Furthermore, SysML can consolidate the results of multiple simulations and generate reports in traditional document format for human readability, facilitating adoption. In addition to software interoperability, SysML supports hierarchical requirements modeling. Engineers can generate requirements from past missions and physical constraints, then further derive requirements for lower-level hierarchical system design parameters. These requirements serve as the beginning for the system development lifecycle “V-model” [29]. To develop our novel cislunar SDA system as a basis for a constellation, our team has chosen the V-model for its system development lifecycle (SDLC) methodology.

The V-model approach is an established practice in the defense industry, often to guide modeling and simulation-based activities in acquisition [30]. As per our Figure 5 adaptation, first we develop well-formed requirements based on the natural constraints of cislunar SDA. These constraints drive our innovative FPA solution and choice of commercial-off-the-shelf (COTS) sensors to specify the architectural design. The architectural design comprises of our team’s electro-optical (EO) Performance model, formalized using SysML and OOSEM. The EO model simulates the performance of the chosen design configuration and has created the results in Figures 1 and 3; we shall discuss the EO model in greater detail in a forthcoming section. The requirements, specifications, and architectural design all flow down to the detailed design and inform the specialty engineering disciplines: electro-optics (Zemax OpticStudio and Synopsys CodeV), optomechanics (ANSYS Thermal Desktop), and astrodynamics (STK).

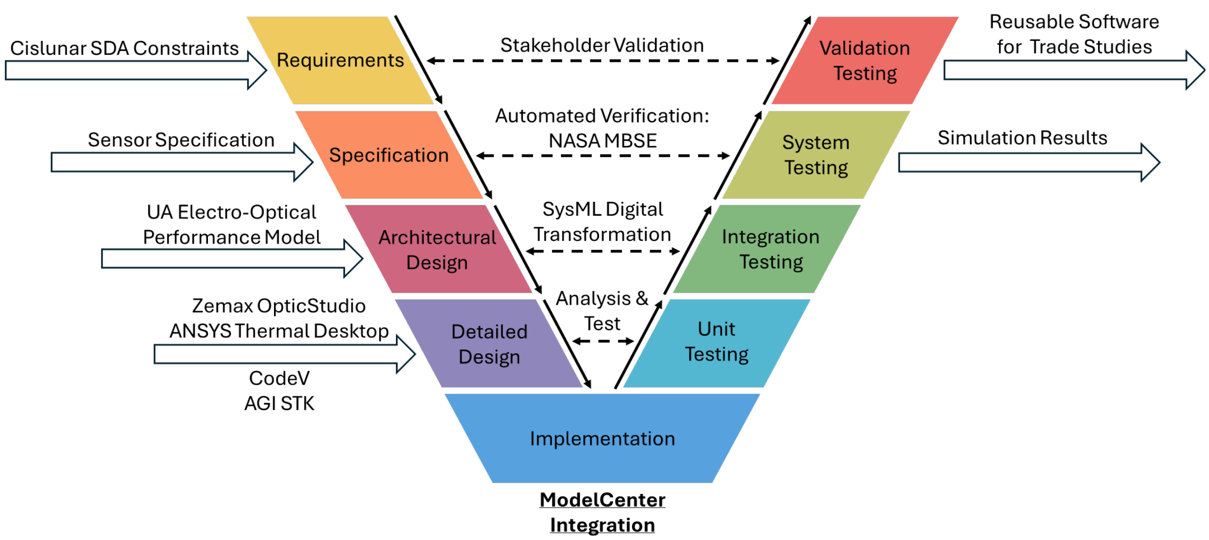

Fig. 5. The system development lifecycle V-model methodology, modified for our digital MBSE approach.

In Figure 5, the Detailed Design phase has the fully defined solution space, allowing us to create verifiable design alternatives for trade study analysis. In the implementation phase, we integrate disparate models (thermal, optical, vibrational, architectural) in a manner that combines all digital data products into one so-called authoritative-source-of-truth. We can accomplish this manually or with digital integration software ANSYS ModelCenter. On the right-side of the V-model begins the testing phases, starting at the lowest hierarchical level, and progressing through unit, integration, system, and overall mission validation testing. The rungs bisecting the V at each rung indicate verification and validation of each portion of the design through demonstration, analysis, test, or inspection [4]. Because of our formalized ESEM approach with digital thread that links ANSYS products to our digitally transformed SysML EO model, we can automate verification to our formalized requirements.

3.2 Requirements-Based Digital Thread Methodology

A digital thread is a systems technology concept that identifies execution paths for virtual elements through a digital system while meeting enterprise objectives and demonstrating executable architecture [31], [32], [23]. For our project, the virtual elements must satisfy our cislunar SDA SysML requirements. Figure 6 highlights a subsection of our requirements that encapsulates design benchmarks and dictates which analysis software we must use to prove our digital surrogate has sufficient fidelity for realistic feasibility. As per OOSEM heuristics, our requirements hierarchy starts with a "Mission Statement" parent requirement, signifying our team's alignment with the OSTP Cislunar S&T strategy by expanding cislunar SDA capabilities through optical space telescope constellations. Aside from general requirements for our constellation and its nodes, such as defining mission life and mandating standards use, our key derived requirements at the second hierarchical level refer to tracking accuracy, detectability, and number of observations to effectively search cislunar space, as previously discussed.

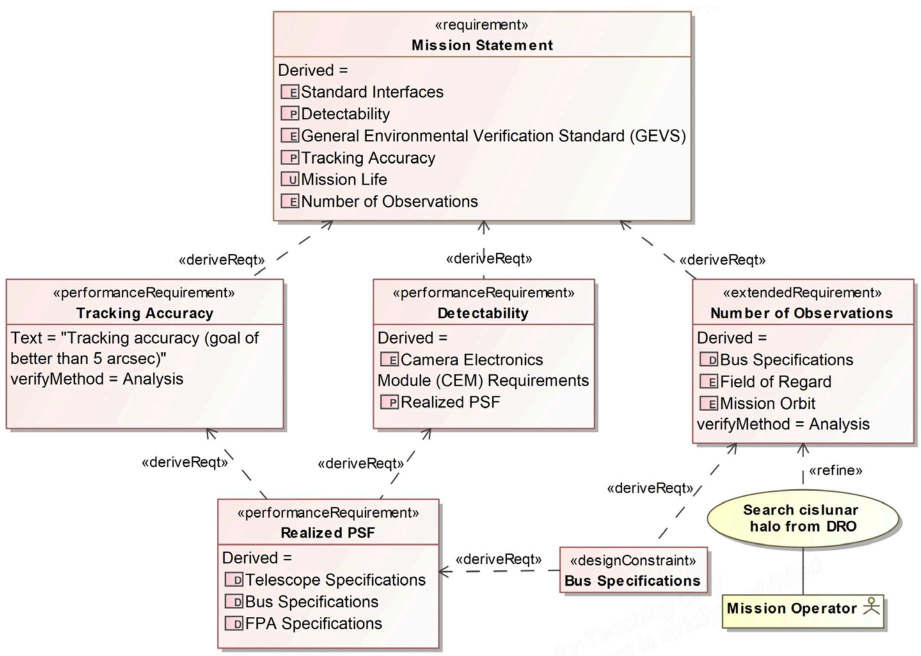

Fig. 6. A SysML diagram depicting our formalized hierarchical requirements that drive design in the V-model. The yellow blocks are a SysML Use Case and Actor, representing a mission operator searching cislunar halo orbit from DRO. The "refine" relationship indicates that this use case provides information on how the requirement can be met.

In Figure 6, the arrow direction signifies each requirement's "parent". Focusing on the example of tracking accuracy, our need for an accuracy of better than five arcseconds derives from our mission need statement. Similarly, the requirement for Realized PSF derives from both the tracking accuracy and detectability requirements; PSF impacts both sensitivity and accuracy. Similarly, the requirements constraining the satellite bus solution space derive from both our PSF and search rate goals. Because calculating accurate PSF is the limiting factor in feasibility trade studies for this system, the coordinated acts of modeling the physical telescope structure with host satellite bus interfaces, assessing that integrated thermal and vibrational response in its standard operations, and considering the impacts of manufacturing defects on overall performance, necessitate high-fidelity simulation software.

To combine these analyses captured in disparate software can digitally trace to SysML requirements, our team has considered the use of ANSYS ModelCenter, MATLAB, as well as manual data entry for facilitated trade study design alternative management at all hierarchical levels of our analysis context. Regardless of implementation methodology, it follows that our digital thread must combine results from the following software: Thermal Desktop, MATLAB, STK, and both ANSYS Zemax OpticStudio and Synopsys CodeV for optics optimization. We use both Zemax and CodeV because these two programs feature unique optimizers and expand the possible solution space in our trade study. Both software report the design fabrication and alignment tolerances for each mirror that degrades the theoretical system PSF, allowing for computational assessment of defect impacts.

Generally, each design configuration of our optical space telescope has a unique optical transfer function (OTF) calculated through Zemax and CodeV. Each solution has its own characteristic PSF, as calculated through an inverse Fourier transform of the OTF. Because DRO is thermally stable between certain ranges with rare periods of eclipsing, after ensuring that our optomechanical structure 3D modeled in ANSYS withstands the full thermal range in Thermal Desktop, we neglect any impact on the realized PSF that drives mission performance. Vibrational noise of the structural design does impact the PSF and requires analysis through MATLAB algorithms. For the number of observations requirement, ANSYS STK provides simulation capabilities capable for monitoring digital system SDA performance in simulated cislunar space, and automatically verifying requirement satisfaction through digital thread.

To reach a path to technology infusion or a space demonstration, we will use SysML as a means by which to link formalized requirements directly to cislunar satellite constellation simulation elements, enabling automated verification throughout a digital development lifecycle. Using interoperability software within an MBSE context, we perform the modeling, simulation, and verification of a cislunar small satellite constellation that will fulfill specific cislunar SDA requirements, such as sensitivity and custody. Derived Functional Outcome Measures (FOMs) and Key Performance Indicators (KPIs) for the constellation, calculated within STK or other SysML compliant systems, will be passed on to Cameo Systems Modeler software and verified to digitally satisfy MBSE requirements. In this way, MBSE will generate value as a decision-support tool for design optimization.

4. RESULTS AND DISCUSSION

Leveraging SysML simulation capabilities, our team has begun the task of developing an SDA design “calculator” that integrates all relevant digital design components for a unified demonstration of system validation. As we develop a litany of acceptable electro-optical design alternatives for cislunar SDA, we develop infrastructure to digitally thread full electro-optical-mechanical-thermal models into STK to simulate relevant operating scenarios such as the one portrayed in Figure 7 with physics-based orbit representations in 3D.This section presents and discusses the underlying SysML logical architecture that would collect data from these simulations and then store that data as contextualized by models in a centralized location. These results later form the basis of our decision-making trade study as a response surface representing cislunar SDA effectiveness metrics against constellation cost.

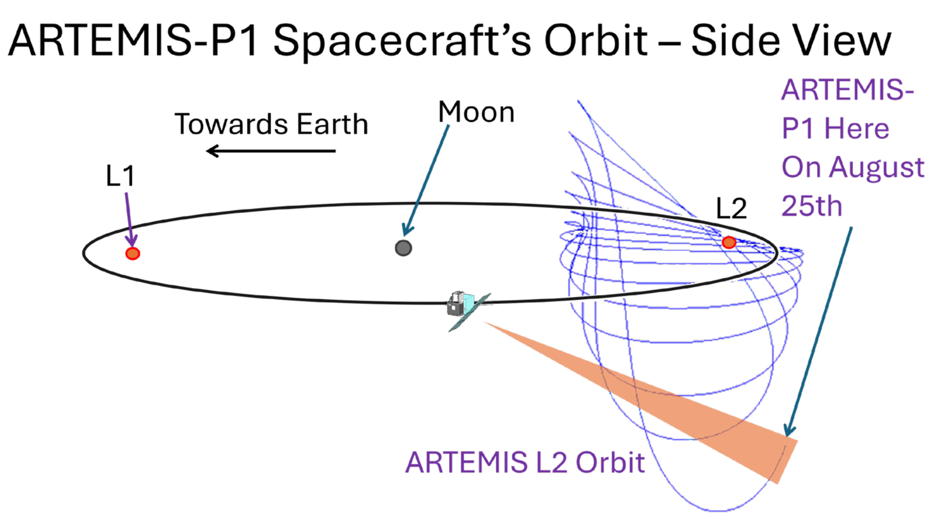

Fig. 7. Heritage NASA ARETEMIS-P1 Mission as surveilled by a sensor in a distant retrograde orbit (DRO).

4.1 Executable Systems Engineering Methodology Implementation

Based on the NASA JPL's ESEM work for the Thirty Meter Telescope, we have refined our requirements with Blocks containing value properties that convert requirement text into numerical variables in the model via a manual process depicted in Figure 8. The ESEM Block representing the original requirement composes an analysis context for realized PSF which also considers specifically the "realizedPSF" value property of our system-of-interest, calculated in another portion of the model. The Analysis Context block contains the parametric diagram performing the automated verification and is shown in Figure 9; upon execution, this diagram reports to the Cameo Systems Modeler console if the Boolean constraint between the system and requirement returns a false value. Our SysML model performs ESEM requirement conversion on all our requirements for hierarchical automated verification; for the sake of graphical simplicity, we only present the Realized PSF requirement for Figures 8 and 9.

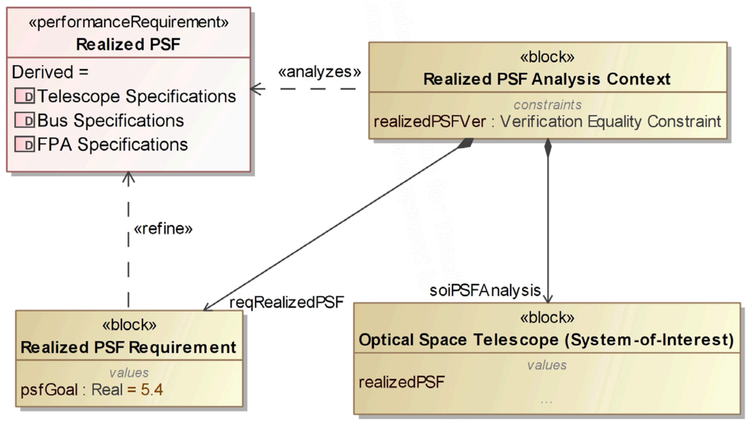

Fig. 8. SysML diagram of a text-based requirement ESEM conversion for PSF automated verification analysis.

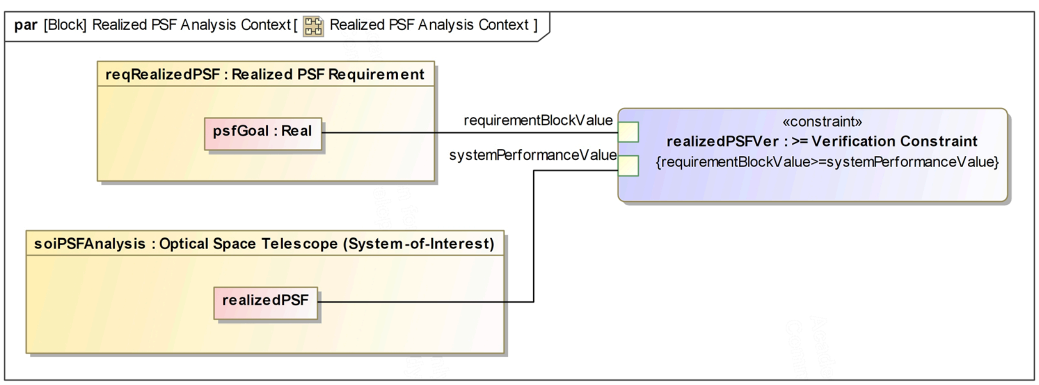

Fig. 9. SysML parametric diagram evaluating requirement verification. Yellow blocks represent part properties of the block represented by the diagram's frame. Pink blocks are value properties. The purple block is a constraint property typed by a constraint block with a Boolean expression, ensuring system performance meets requirements.

4.2 Requirement-Driven Model Specification

Our reference electro-optical system has been designed around the Hamamatsu TDI-CCDs, which are one of the only suitable TDI-CCDs available commercially. Coincidentally, the Hamamatsu format (4096x128) and pixel size (12 microns) are well suited for a focal plane of a small space surveillance system. Hence, the component-level requirements are more like specifications: only one COTS part can fit our system needs. Rather than create multiple locations within our system architecture to input parameters that configure our system, we have chosen a truly requirements-driven method utilizing ESEM to set those parameters directly from the requirements. Figure 10 demonstrates how we use a SysML Block Definition Diagram (BDD) to code this logic. A requirement-driven specification context for ESEM converted requirement blocks sets values within our system-of-interest. This is the same approach as Figure 9, but with a different constraint block typing the property and setting the equation. The parametric diagram made to complete this operation is too large to include in this document-based report.

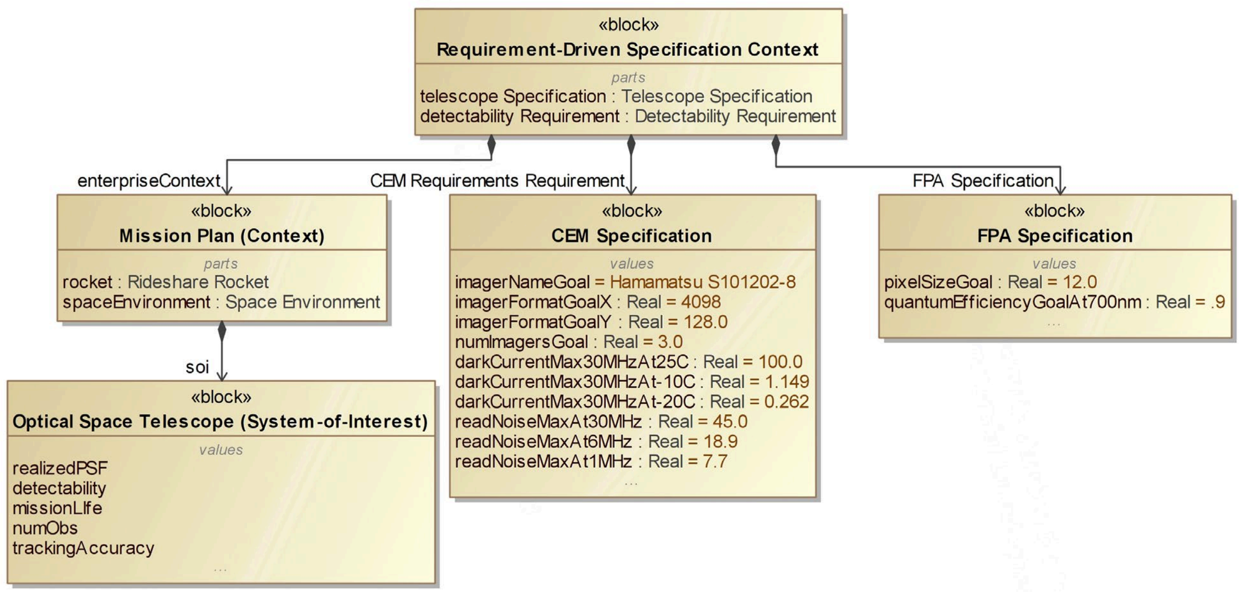

Fig. 10. SysML BDD of our system-of-interest's context within our mission plan, which is in an analytical context that sets system design parameters from ESEM requirement values at model execution and simulation runtime.

Notably in Figure 10 is the Optical Space Telescope system-of-interest block: also present in Figure 8, but now with additional values from the model visible. The arrowheads names in a BDD indicate part properties; in other words, the Mission Plan (or system context) block in Figure 10 has the cislunar SDA telescope as a part, just like the rocket and space environment. In Figure 8, the system-of-interest is a part property for the Realized PSF Analysis context with a distinct name "soiPSFAnalysis". We connect specifically the system-of-interest block to the analysis context, because when specialized engineering discipline analyses yield results for impact to PSF, these are aggregated as a whole and attributed to the overall system-level as opposed to a subsystem like the mirror assembly. Figure 11 shows through a SysML traceability matrix that the system-of-interest block's value properties formally satisfy the Figure 6 requirements. Because we connected the value properties and blocks to requirements with the "Satisfy" relationship, upon model execution, if there is a numerical inequality in the more simply stated requirements like Number of Observations, the Cameo Systems Modeler console alerts the user of requirement verification failure.

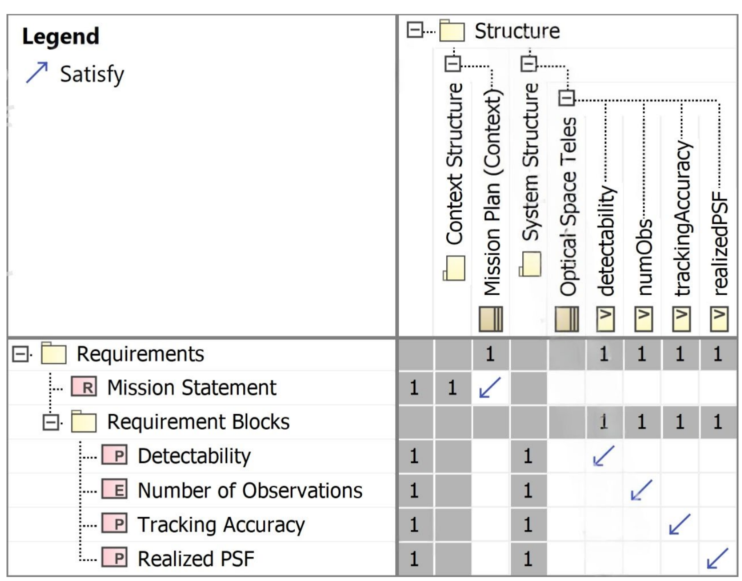

Fig. 11. SysML traceability matrix showing system-level roll-up value properties satisfying key requirements. Rows and columns are organized through model's file structure in the Cameo Systems Modeler containment tree.

4.3 Electro-Optical Performance Model Digital Transformation

Aside from our requirements, the core of our analysis is our EO performance model. This model, informed by those requirements, assumes illumination of a "grey" target with the AM0 solar spectrum. Its inputs include both design and environmental factors. Design inputs include clear aperture, 1/f, focal length, the throughput of each mirror and the CCD window, the sensor's quantum efficiency, pixel size, sensor dimensions, read noise, dark current, and a goal SNR. Illumination, telescope throughput, and quantum efficiency are all treated as frequency dependent values over the responsivity of the sensor. Environmental inputs determine values for sky background noise for the given SNR. For space-based sensors this background is dominated by the zodiacal light and is approximately solar in color. The model outputs include search rates at a given visual magnitude, as well as parameters constraining the choice of COTS satellite buses that can operate this novel SDA system. We have fully integrated this model into SysML, using Parametric Diagrams, Constraint Blocks, and Constraint Properties to capture the underlying mathematics that calculate system performance. A SysML Block representing the EO Model contains these parametric diagrams; the EO model SysML block, contextualized by the overall mission as a category, also houses simulation elements that create plots akin to Figures 1 and 3.

To maintain modularity and interoperability with future use cases and design changes, the SysML EO model block acts as a plug-and-play part property for our system-of-interest, as shown in the SysML Block Definition Diagram (BDD) in Figure 12. BDD are not a flow diagram; the arrows with black diamond sources represent structural composition in an architectural hierarchy. In this diagrammatic viewpoint, we show greater details about the content of several blocks, including the space environment, the mirror assembly (with a representation of the lefthand side of Figure 2), the focal plane assembly, and the focal plane array. The top-level requirement-driven specification context sets the system and subsystem values as previously described; through the power of SysML model querying, one can create a generic table which lists all input values and allows for quick configuration changes for trade study design alternative feasibility assessment. In the EO model block, we include a list of constraint properties that calculate system performance values like search rate as a function of magnitude. For modularity, we set values in the EO model from the system parameter values, many of which were set by requirements: this causes the enormous size of the parametric diagram for our requirements-based specification that limits publishable figures.

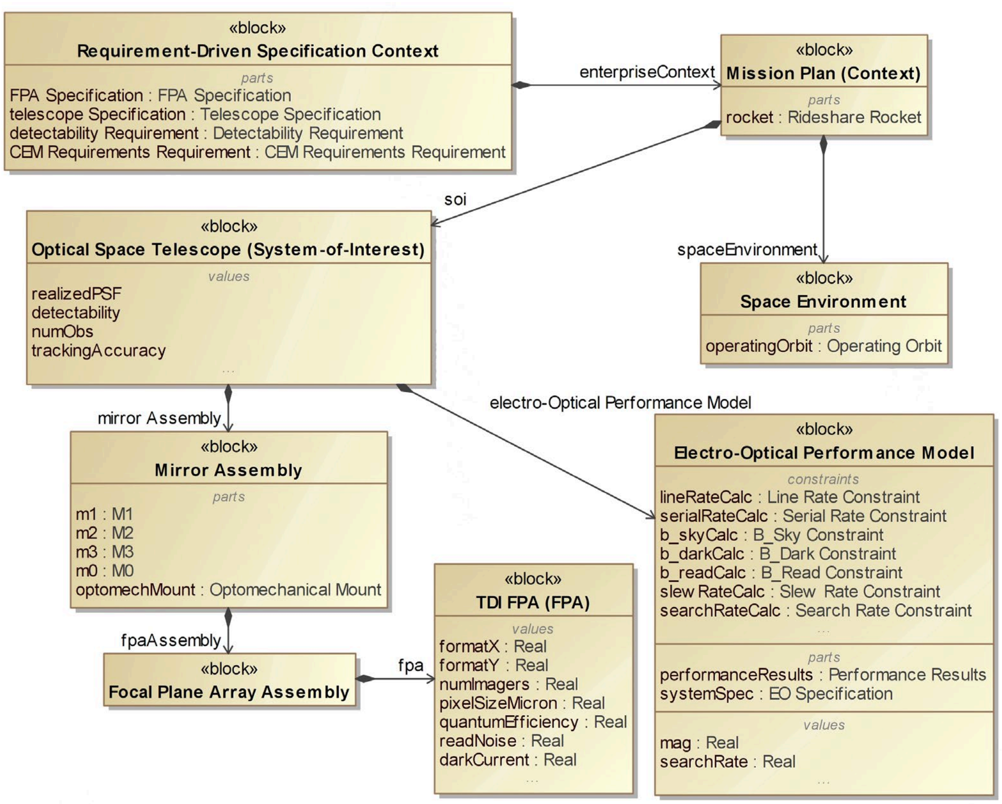

Fig. 13. Our structural SysML model shown in greater detail and connected to the digitally transformed EO model.

In SysML BDDs, Blocks represent a black-box view of a concept: a list of parameters, without details of inner workings. In SysML internal block diagrams (IBDs), engineers can create a white-box view of that block, codifying the interfaces between its part properties. While many of the detailed design elements are better suited for external Digital Engineering software, when connecting our telescope to a suitable satellite bus, ensuring verification of all standard interface requirements becomes tantamount to developing a successful system. Our team has begun developing infrastructure towards this end as shown in Figure 14, an IBD of the Focal Plane Array assembly.

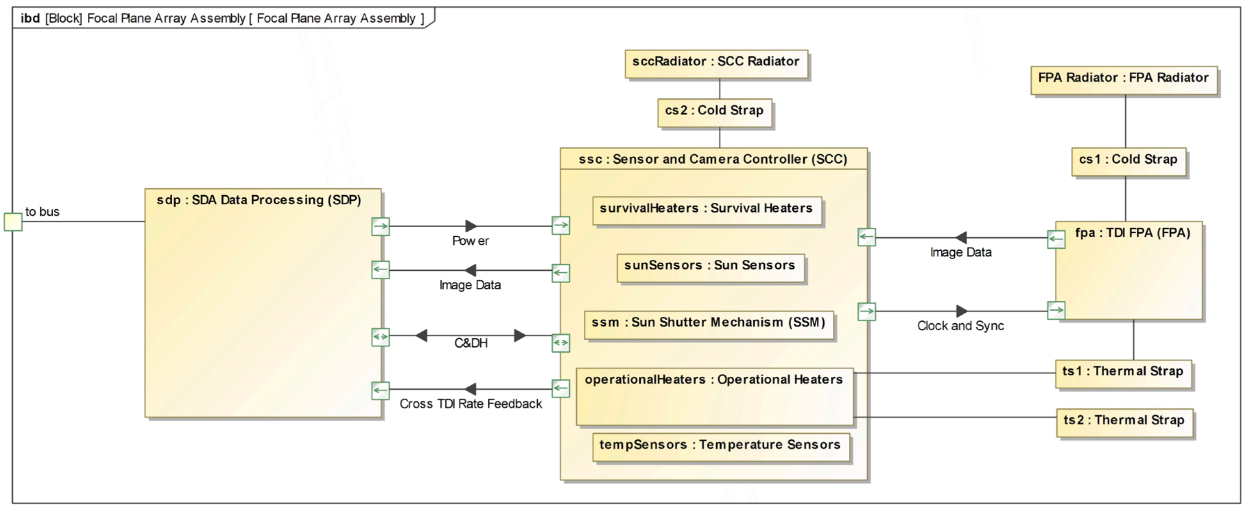

Fig. 15. An IBD of our TDI FPA's supporting assembly. The frame represents the TDI FPA block in Figure 13.

The part property "fpa: TDI FPA (FPA)" houses values in the Requirements-Driven Specification parametric diagram that connects to the EO model for simulation. Using SysML's internal visualization capabilities, we demonstrate the full connection and operation of our digitally transformed model in Figure 16. By linking values for desired magnitude to simulation time, we generate this time series plot within SysML to recreate the results from our original mode, shown in Figures 1 and 3. Behind-the-scenes SysML activity and state machine diagrams allow for this type of design trade-space exploration through visualization. With all this MBSE and DE infrastructure in place, our model is ready to seamlessly integrate data from external software for the V-model implementation phase.

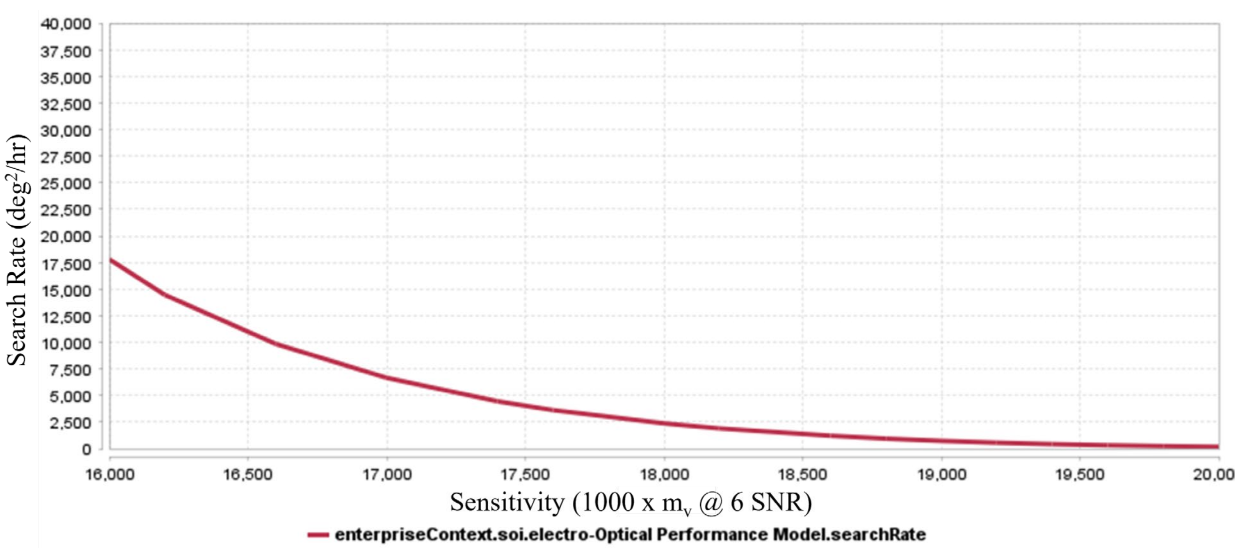

Fig. 16. A SysML Time Series Plot output representing search rate vs. sensitivity at a given SNR. Our code produces plots ostensibly identical to our original model confirming our model's successful digital transformation.

5. CONCLUSIONS AND FUTURE WORK

This paper has reviewed the need for extending cislunar SDA capabilities, the historical obstacles towards doing so, and has presented a valid solution to meet US national needs, with a formalized method to do so. In traditional optical space telescopes, geometrical distortion, or unwanted image warping limits TDI to small fields of view and short integration intervals. In our new system, we combine TDI with a free-form, linear astigmatism free three-mirror telescope to control geometrical distortions and enable smear-free TDI over long integration intervals and wide sweeps. This combination enables TDI-based systems to simultaneously have high search efficiency and sensitivity and overcome the limitations of conventional cislunar SDA systems. Through the V-model SDLC, MBSE, ESEM, and digital engineering, we have created a SysML model that evaluates the electro-optical performance of our system in the context of its operating scenarios, and furthermore automates requirement verification. This effective cislunar SDA surveillance system calculator enables rapid modifications of initial conditions to determine whether design alternatives meet the requirements for image quality degradation.

As our team generates PSF results from specialty engineering disciplines to include in our EO-model, we prepare to enact the digital thread between ANSYS products and our SysML value properties. While directly transferring system parameter values manually into a SysML generic table that acts the numerical input "dashboard" (Table 2), there is chance for human error. To minimize this and make full use of digital thread technology, our team has acquired access to ANSYS ModelCenter, which contains user-friendly visual programming capabilities to connect our value properties to numerical results exported from Zemax, CodeV, Thermal Desktop, and MATLAB. An added benefit to our MBSE approach is the reusability of our data products, allowing us to generalize and extend the logical architecture used for our trade study towards other applications. While for now our constellation architecture for cislunar SDA utilizes an off-axis three mirror design and considers free-form optics for generating design alternatives managed by SysML, the modeling of the mission context surrounding our space-borne payload can be reused to evaluate other systems-of-interest in similar environments.

Table 2. SysML Generic Table "dashboard" that allows rapid changing of default values during trade studies.

#	Name	Default Value
69	⊟ ESEM Blocks [Requirements]	
73	⊟ Tracking Accuracy Requirement	
74	trackingAccuracyMin	5
79	⊟ FPA Specification	
80	pixelSizeGoal	12
83	⊟ CEM Specification	
84	imagerFormatGoalX	4098
85	imagerFormatGoalY	128
86	numImagersGoal	3

Figure 17 presents a screenshot from ANSYS ModelCenter, where we have begun creating a data model with digital threads to our SysML files. Our specific installation configuration links ANSYS ModelCenter directly to our local Cameo Systems Modeler installation, so that either software can call upon the other to conduct analyses. Of note in Figure 17 is the listing for the Behavior Execution Engine: a plug-in we custom installed to base ModelCenter configuration. This engine is a part of STK and connects SysML state machine diagrams that describe system behavior directly into STK [26]. SysML State Machines further detail SysML Use Cases, like for example the goal to "search cislunar halo from DRO" in Figure 6. The implication of this is that we can define our optical telescope's actions in SysML using STK semantics and then automatically simulate those behaviors in STK while returning key performance values like number of observations back to the SysML model for trade studies. Unfortunately, at the time of writing, STK licenses have an error which prevents ModelCenter from accessing BEE capabilities. Because ModelCenter has yet to create a digital thread connector for ANSYS Zemax OpticStudio, and since CodeV parent company Synopsys has only recently purchased ANSYS, MBSE and DE technology is limited in that transporting certain optical design parameters into SysML would require coding complex Java-based delegates to connect value properties. Manual data transfer can be acceptable when full digital threads and not necessary. MATLAB can provide an alternative method to automating optical data transfer directly into SysML, with or without ModelCenter.

Name	Version	Author	Description	HelpURL	Keywords
ANSYS Mechanical	24.1.0	ANSYS, Inc.	Plug-in for File Input/Output Programs	www.phoenix-int.com	
Behavior Execution Engine	24.1.8732.24642	ANSYS, Inc.			
Catia	24.1.8739.40022	ANSYS Inc.	Plug-In for CATIA	https://www.ansys.c...	
Converger	24.1.8740.27490	ANSYS, Inc.	Converger component iteratively converges circular dependencies	www.ansys.com/sup...	Converger
Digital Thread	24.1.8712.31463	ANSYS, Inc.	Plug-in to store the state of all (non-file) variables in a file variable	www.ansys.com/sup...	digital, thread
DOE Tool	24.1.0	ANSYS, Inc.	DOE Tool Plug-In	www.ansys.com/sup...	doe, algorithm, trade ...
Excel	24.1.0.0	Ansys Inc.	Plug-In for Microsoft Excel	http://www.phoenix-...	
Export To Minerva	24.1.8713.17467	ANSYS, Inc.	Plug-in for exporting file variables to a Minerva server	www.ansys.com/sup...	Minerva, Export
Import From Minerva	24.1.8713.17467	ANSYS, Inc.	Plug-in for importing file contents from a Minerva server to file variables	www.ansys.com/sup...	Minerva, Import
Loop	24.1.0.4020	ANSYS, Inc.	Loop - RepeatUntil, While, For, ForEach	www.ansys.com/sup...	Loop, While, Repeat...
Matlab	24.1.8739.38417	ANSYS Inc.	Plug-In for Matlab	http://www.phoenix-...	
optiSLang	24.1.8740.17147	ANSYS Inc.	Plug-In for optiSLang	http://www.phoenix-...	
RSMToolkit	24.1.0.4047	ANSYS, Inc.	Toolkit for creation of Response Surface Models	www.ansys.com/sup...	RSM
SolidWorks	24.1.8739.40038	ANSYS Inc.	Plug-In for SolidWorks	https://www.ansys.c...	
STK	unknown	unknown	unknown		
STKDotNet	unknown	unknown	unknown		
User Task	24.1.0.4020	ANSYS, Inc.	Display a message to a user or change a variable value	www.ansys.com/sup...	User Task

Fig. 17. Screenshot from our team's ANSYS ModelCenter installation showing many software platforms available for digital thread integration. While no native connectors for Zemax or CodeV exist, MATLAB can bridge the gap.

5.1 Future Work

Our team has several plans to expand on this work to support OSTP's National Cislunar S&T Strategy. Most immediately, we will continue developing interoperability solutions to integrate external Digital Engineering software simulation results into our system design alternative compendium as they become available. This shall lead to a more holistic and higher fidelity overall model that will help decision-makers decide if our constellation system suits their enterprise's needs. To enhance the functionality of the presented space telescope design, we will extend our model to include PNT solutions for mutual self-navigation and communication architectures. In this way we can create a hierarchical trade study: one that both assesses the main goal of surveilling cislunar space, as well as the interoperability of our PNT implementation. Other planned extensions to our model include automated assessments for economic feasibility, environmental sustainability, and system cybersecurity. Our team's goal with this is to achieve eventual space flight to bring our digital proof-of-concept to a reality.

6. ACKNOWLEDGMENTS

This work is funded by the University of Arizona Office of Research, Innovation, and Impact. The authors thank LSAS-Tec for access to STK Cislunar Orbit Designer (CODE) software, and ANSYS for providing ModelCenter licenses for researching interoperability features between SysML, STK, and other ANSYS products.

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