The Pandora SmallSat: Mission Overview

Jordan Karburn, Pete Supsinskas, Hilary Johnson, Maricris Schneider
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550; 925-422-6364
karburn1@llnl.gov

Elisa Quintana, Jessie Dotson, Knicole Colon, Tom Barclay, Christina Hedges
NASA Goddard Space Flight Center
8800 Greenbelt Road, Greenbelt, MD 20771; 301-286-0851
elisa.quintana@nasa.gov

Jessie Dotson
NASA Ames Research Center
MS 245-6 Moffett Field, CA 94035; 650-604-2041
jessie.dotson@nasa.gov

ABSTRACT

The NASA Pioneers Program is tasked with performing compelling astrophysics science at lower cost, with smaller hardware, compared to Explorers Program missions. The Pandora SmallSat was selected as an inaugural Pioneers mission. Pandora uses an aluminum, 45-cm, dual channel Cassegrain telescope as its scientific instrument. The instrument will obtain the first dataset of simultaneous, multiband, long-baseline observations of exoplanets and their host stars. The goal is to use these data to reliably characterize planetary atmospheres by disentangling star and planet signals in transmission spectra.

Early in project formulation, the Pandora team developed a suite of high-fidelity parametrized simulation and modeling tools to estimate the performance of both imaging channels. This enabled a unique bottoms-up approach to deriving system requirements. This approach, while unconventional for aerospace missions, enabled synergies between previously disparate existing technologies and capabilities throughout the mission. Pandora heavily leverages existing capabilities that required no to low amounts of engineering development, as well as firm-fixed-price contracts, to stay within the constraints of a Pioneers class mission. Pandora will disrupt the cost-schedule paradigm of half-meter class observatories. The team is preparing for its Critical Design Review in October 2023. Launch to sun-synchronous low earth orbit is anticipated in early 2025.

INTRODUCTION

The Pandora SmallSat, led by Dr. Elisa Quintana at NASA Goddard Space Flight Center, was selected as an inaugural NASA Pioneers mission. The NASA Astrophysics Pioneers Program is a new mission class, launched in 2020, tasked with performing compelling astrophysics science at lower cost and with smaller hardware than the Explorers Program missions[1].

Frank Calvelli, Assistant Secretary of the Air Force for Space Acquisitions and Integration, recently outlined a "… Simple Formula to Go Fast in Space Acquisition"[2]. In the memorandum, there were four ingredients identified to the formula: (1) build smaller systems (2) use existing technologies (3) drive shorter contract scope (4) use firm-fixed price (FFP) contracts.

Pandora embodies all four ingredients. Specifically, use of existing technologies and FFPs uniquely enable Pandora's ambitious goal to field a half-meter class dual channel imaging in a Pioneers-class mission. The goal of this paper is to provide a brief summary of the challenges facing space acquisition, to give an overview of Pandora's science mission, to summarize the Pandora Observatory, and to describe how Pandora leverages existing technology and FFP contracts to achieve success under the Pioneers Program.

SPACE ACQUISITION CHALLENGES

As we move into a new era in space exploration and military competition, the need for swift government procurement of space systems is increasingly apparent[5]. A shift away from historic tendencies, marked by colossal monolithic satellites, protracted development cycles, and cost-plus contracts, is critical for both scientific exploration and national security applications. The urgency for speed is compounded by the dramatic transformations wrought by international proliferation of small satellite systems[3].

The major obstacles to rapid space acquisition are the legacy practices endemic to the industry[3]. Traditionally, space assets, such as communication and observation platforms, were hulking behemoths driven by unique technical requirements, often taking a decade or more to design, manufacture, and deploy. Coupled with cost-plus contracts, budgets and schedules frequently are over run, leading to delivery delays[4]. Such sluggishness, characteristic of an older era, threatens to undermine the strategic and scientific objectives in contemporary space[5].

Small satellites revolutionized the space industry by enabling low-cost ride share opportunities, thus decreasing a historic barrier to entry in aerospace, initiating a compelling motivation for disruption[6]. With their advent, the long-held assumption that 'bigger is better' in space has been upended, inviting a novel approach to the sector[7]. Despite their diminutive size, these platforms have demonstrated their efficacy, often at a fraction of the cost and within reduced timelines. Small satellites offer a nimble, cost-effective alternative, opening avenues for swift procurement while enhancing both scientific understanding and national security.

Expeditious acquisition and procurement is pivotal to maintaining the American edge in an increasingly competitive space race[5]. For scientific purposes, swift development cycles allow for rapid maturity of technology readiness, ensuring technical capabilities evolve at the same pace as understanding of the cosmos. Meanwhile, from a security standpoint, the ability to deploy space assets rapidly can be the deciding factor in maintaining a robust defense against potential adversaries. The accelerating pace of technological advancements demands a development and acquisition strategy that can keep up.

The need for improved government procurement cycles in space has never been more pressing. By embracing the changes brought about by the small satellite revolution and implementing our proposed steps, we can pivot from historical norms and accelerate national space endeavors. Embracing the "go fast" approach is not just a luxury, but a necessity to remain at the forefront of the new space era.

SCIENCE MISSION OVERVIEW

Pandora is a SmallSat, selected in NASA's inaugural Astrophysics Pioneers program, designed to characterize exoplanets and their host stars with long-duration, multiwavelength observations. Transmission spectroscopy is a proven technique to probe the atmospheres of transiting exoplanets. During a transit, starlight filters through the planet's atmosphere and comparisons of spectra during and outside of transit are used to reveal the planet's atmospheric composition. Transmission spectroscopy works by assuming that the planet's host star—the light source illuminating the planet's atmosphere—can be treated as a uniform light source. In reality, many stars are magnetically active with dark, cool spots and bright, hot faculae that cause the emergent light to vary across the stellar disk. These changes in surface brightness vary with time as spots and faculae evolve or as a star rotates, and can lead to significant stellar spectral contamination that can mask or mimic features in a planet's true spectrum. Surface brightness variation is more likely to contaminate the spectrum of exoplanets around smaller, cooler stars since those stars are more likely to have substantial stellar activity. However, many recent and planned observations of exoplanet atmospheres with HST and JWST focus on smaller, cooler stars because the transit signal is larger for those systems. As a result, understanding the magnitude of stellar contamination on the measurement of exoplanet atmospheres is essential to fully understand data taken with these flagship missions. Pandora will provide a unique dataset of long-duration, simultaneous multiwavelength (visible and near-infrared) observations that will be used to disentangle star and planet signals in transmission spectra of at least 20 planet/star systems to reliably determine exoplanet atmosphere compositions.

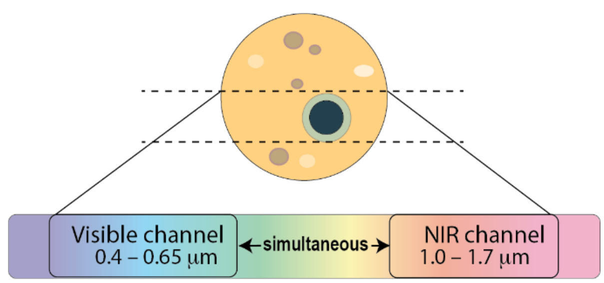

Figure 1: Pandora provides unique, continuous dual-band data to determine stellar photosphere properties and disentangle star and planetary signals in transmission spectroscopy.

Pandora's visible channel photometry is in a wavelength band where stellar variability (induced by star spots and faculae) has high contrast, thereby providing constraints on star spot and faculae brightness contrasts (Figure 1). The NIR channel measures spectra in a band where water is a strong molecular absorber, enabling the study of planet atmosphere compositions. Pandora's combined time-series photometry and spectra uniquely provides constraints on absolute star spot covering fractions as a function of time and stellar rotation. The stellar spectrum can then be decomposed into its constituent parts (spot, faculae, and quiescent photosphere) and with models and mitigation strategies, constraints on stellar contamination can be determined. With corrected spectra, Pandora will subsequently identify which planets have hydrogen- or water-dominated atmospheres, and robustly determine which planets are covered by clouds and hazes.

Pandora fills a key gap in NASA's astrophysics roadmap and is well-aligned with the National Academy of Sciences Astro2020 Decadal top priority “Worlds and Suns in Context”. There is a broad consensus in the exoplanet community about the importance of mitigating stellar contamination in exoplanet transmission spectra. For example, NASA’s Exoplanet Exploration Program (ExEP) launched a Study Analysis Group to specifically address the issue. Furthermore, stellar contamination is shown to prevent definitive exoplanet atmosphere detections from the Hubble Space Telescope (HST) and early James Webb Space Telescope (JWST) observations[8,9].

Pandora’s novel design (45cm all aluminum telescope) and innovative observing strategy (continuous and simultaneous multi-band observations) will enable the mission to address two major science objectives.

Objective 1: Spot Coverage

Pandora will observe in long baseline stares (10 visits of 24 hours per target), providing in-depth views of targets that are not possible from the ground. This will allow us to address Pandora’s first science objective: **What are typical spot coverages of low- mass exoplanet host stars, and how do they vary with time?** With 120 hours of observations per star, Pandora will measure spot and faculae covering fractions and quantify stellar contamination as a function of time and stellar rotation phase. Targets are carefully selected for Pandora to maximize star and planet diversity. This will enable Pandora to explore how stellar properties (size, mass, temperature) correlate with contamination, and how the impact of contamination changes with planet properties (size, mass, bulk density, orbital distance). Pandora's notional target list includes planets as small as Earth and as large as Jupiter, with host stars spanning mid-K to late-M. Pandora will identify trends with stellar contamination and planet/star properties that will be used as inputs to models that generate and interpret exoplanet transmission spectra.

Objective 2: Atmospheric Composition

Pandora's first objective will provide the necessary data to correct the observed spectra for stellar contamination, and ultimately enable robust measurements of atmospheric compositions. Building on the first objective, Pandora’s second objective will address: **How does the atmospheric composition of planets vary with planetary radius/mass/bulk density, orbital distance, and host star properties?** Pandora's selected planets have orbital periods of 1-20 days (corresponding to equilibrium temperatures of 400-1000 K). Pandora is sensitive to both lighter H2-dominated and heavier H2O-dominated atmospheres. Pandora also enables exploration of prior transmission spectroscopy observations to verify if they yield the same atmospheric results after correcting for stellar contamination. Pandora's target list includes planets previously observed by HST, including the sub-Neptunes GJ 436 b, GJ 3470 b, L98-59 c and d, and planets in the TRAPPIST-1 system[10]. Many planets in Pandora's notional target list are also JWST planned observations.

Pandora’s science objectives are well-suited for the Pioneers SmallSat platform, providing big science in a small form-factor. Pandora's legacy will be a unique catalog of long-baseline time-series photometry and simultaneous spectroscopy, and a catalog of at least 20 benchmark planets that will aid in target selection for HST, JWST, and future exoplanet missions. If funded, an extended mission could facilitate additional exoplanet science as well as a broad range of time domain astronomy studies. Pandora will rapidly make all data publicly available, maximizing the value of Pandora data to the science community.

INSTRUMENT OVERVIEW

The following sections provide a brief overview of Pandora’s key subsystems. Figure 2, below, oulines the Pandora mission-data flow.

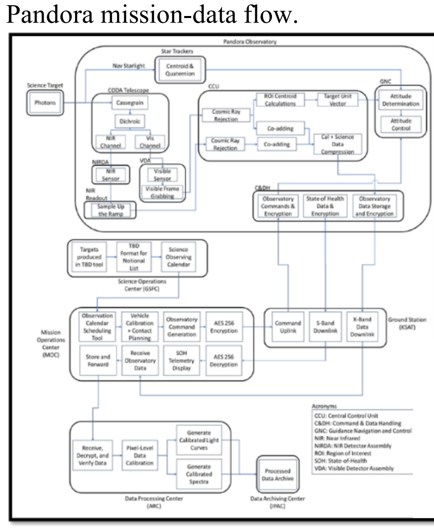

Figure 2: Pandora’s photons-to-science pipeline.

Spacecraft Bus

Pandora partnered with Blue Canyon Technologies (BCT) to provide the spacecraft bus. Pandora leverages BCT's ESPA-Grande "Saturn-class" bus, which is the same bus used in the DARPA Blackjack program. Pandora required no mechanical or electrical design modifications from the standard Saturn-class vehicle. In large part, the payload was designed around the capabilities of the standard Saturn bus. The bus provided more than enough SWAP (size, weight, and power) for Pandora's requirements.

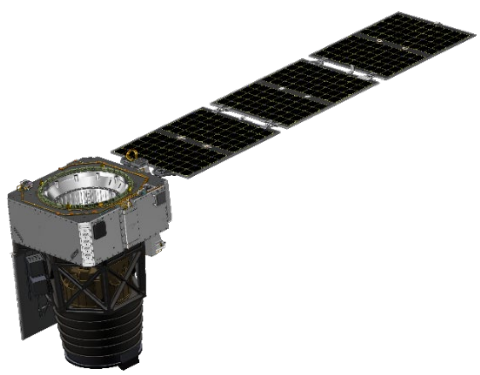

Figure 3: Rendering of BCT Saturn-class ESPA Grande vehicle with Pandora

Telescope

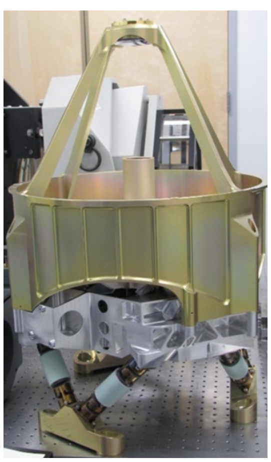

Figure 4: CODA 2.1 qualification unit prior to environmental testing

Pandora is based around a single optical telescope assembly, known as CODA 2.1. CODA is a design family of all-aluminum 45-cm relayed Cassegrain telescopes that have been in development at LLNL over the past six years, with partnership of Corning Specialty Materials in Keene, NH. The naming convention of CODA X.Y refers to the number of imaging channels (X) and the specific design variant (Y). Pandora's CODA 2.1 is a dual channel system that supports simultaneous observations, with 400-650 nm photometry and 1,000 – 1,750 nm spectroscopy.

Visible Detector Assembly (VDA)

The visible channel utilizes a low noise commercial off-the-shelf camera made by PCO. The camera, the pco.panda 4.2, uses a 16-bit sCMOS sensor, with 6.5 um pixels, and a USB 3.1 interface. The Pandora mechanical design team integrated the commercial camera into a ruggedized detector assembly to enable easier mechanical and thermal interfacing.

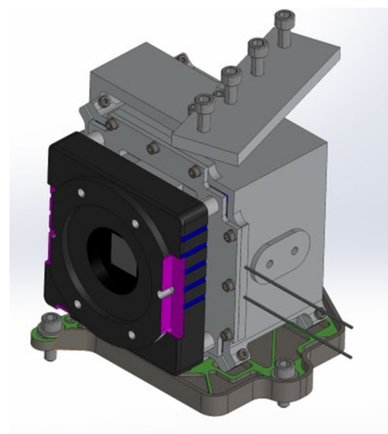

Figure 5: CAD rendering of the ruggedized pco.panda 4.2, with additional mitigation for heat disipation and precision optomechanical interfacing.

Figure 6: Integrated CAD rendering of the NIRDA, including the H2RG imaging sensor and SIDECAR ASIC.

Near-infrared Detector Assembly (NIRDA)

The near-infrared channel utilizes a Teledyne HAWAII-2RG, with 2.5 um cutoff, and a SIDECAR application specific integrated circuit (ASIC). These components were provided to Pandora as residual flight spares from the James Webb Space Telescope NIRCam team. LLNL has designed a detector assembly (NIRDA) to provide the necessary thermal isolation and mechanical interface. Pandora is utilizing the Multi-purpose ASIC Control & Interface Electronics (MACIE), designed by Markury Scientific, to provide the necessary power and signal condition for the SIDECAR ASIC. The MACIE is a lab-grade element that has undergone environmental qualification to prove its flight-worthiness for a 1 year mission in low-earth orbit.

To maintain optimal performance, the H2RG and SIDECAR must be cooled. Pandora utilizes a high-reliability commercially available cryocooler to achieve the desired operating temperature of 110 K and 200 K, respectively. Iris Technologies Corporation provides the cryocooler and thermal control electronics, heavily leveraging their TRL-9 Iris Control Electronics (ICE)-G2 platform. This subsystem maintains the NIRDA temperature stability to within +/- 0.01 K/60s.

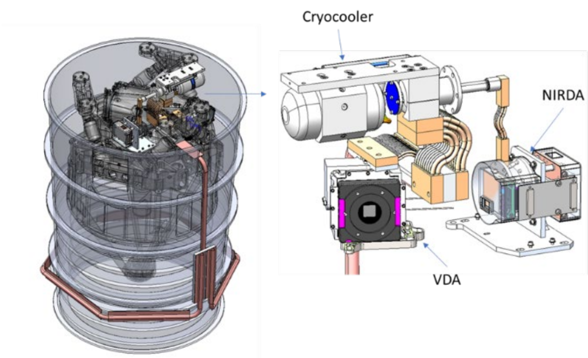

Figure 8: Cryocooler and thermal transport system for the NIRDA

Payload Electronics Module (PEM)

Pandora is leveraging the LLNL designed Payload Electronics Module (PEM) as the primary electrical power system (EPS) and avionics for the payload.

The PEM was developed inhouse at LLNL and uses a combination of commercial and aerospace-rated parts. The avionics is powered by an Nvidia Jetson TX2i and provides all necessary compute capabilities to execute Pandora's payload requirements.

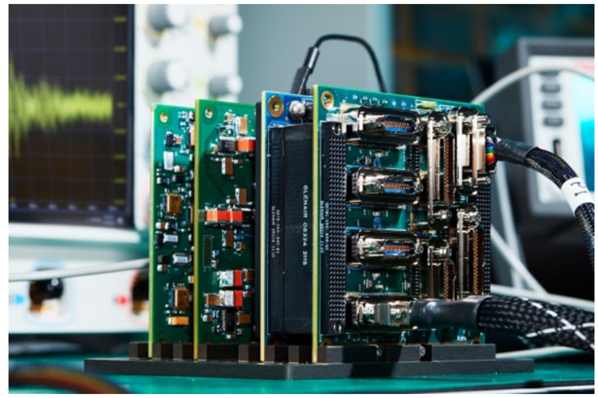

Figure 7: The Pandora PEM provides all power distribution, circuit protection, and central computing for the payload.

GOING FAST

Part of the appeal for small satellite missions is the capability to "go-fast" and avoid the burdens of large-scale missions, such as proportionally higher launch costs and system complexity. However, going fast while maintaining high performance in any aerospace application, regardless of the mission size, is never an easy feat. This section discusses two areas that Pandora employs to aid in its success: integrating existing high TRL technologies and firm-fixed-price contracts.

Existing Technologies

Pandora is fundamentally enabled by its reliance on mature, existing technologies. Many elements of the system architecture were principally constrained by previous designs. The leadership team views Pandora as a demonstration of the scale of mission capability that can be achieved with existing technologies. This can be seen throughout all systems and is exemplified by the two largest cost drivers of the program: the CODA telescope and the Saturn bus.

Shortly after selection by NASA for the Pioneer's mission, the Pandora team evaluated the capabilities of commercially available "off the shelf" spacecraft busses. At the time, the

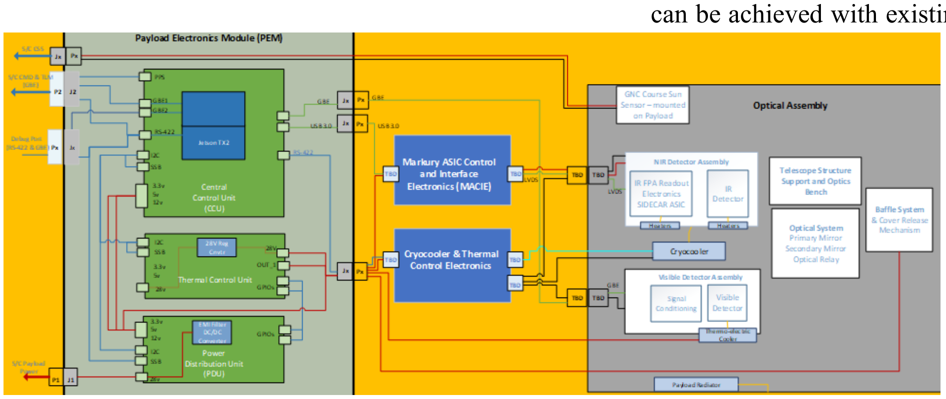

Figure 9: Block diagram for Pandora electronics interfaces

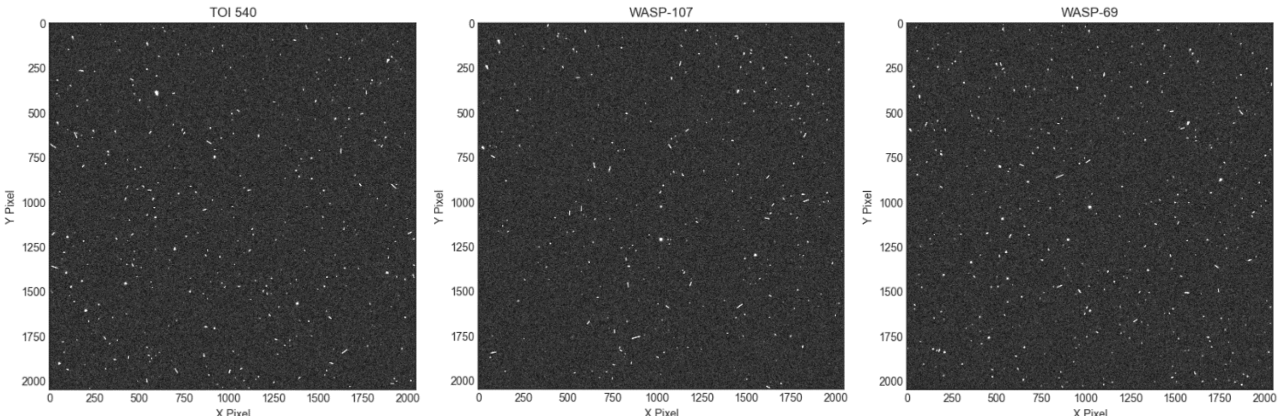

Figure 10: example simulated starfields from the Pandora visible channel. Simulation parameters included detector noise, spacecraft jitter, and optical wavefront performance.

BCT Saturn-class vehicle was the only vehicle that was both large enough to fit the CODA telescope and meet the boresight pointing stability requirements, all while requiring no design modifications. While there were several competing manufacturers that were able to design a system that would meet Pandora's needs, no other platform was available with no non-recurring-engineering (NRE). Pandora leverages BCT's economies of scale with the Saturn platform, helping stay within the cost constraints of the program. More than simply cost, leveraging a heritage bus with no design modifications significantly decreased schedule and technical risk.

The CODA project is a family of relayed Cassegrain telescopes. The modular design goal uses a common front-end Cassegrain (with supporting optomechanical interface) and a customizable relay. The relay is redesigned for mission specific applications, with constraints for volume and weight. The front-end telescope does not need to be requalified. Pandora successfully realized this design goal. Pandora's CODA 2.1 design uses a truly identical Cassegrain front-end, including mirrors, optomechanical interfaces, optical bench, and supporting spider, as the initial CODA 1.0 design. Pandora-specific designs are the relay assembly to support multiple imaging channels. By constraining the design space to the relay, Pandora leverages residual hardware, existing fixturing and metrology, and thousands of hours in process development for assembly, integration, and test. Without constraining the Pandora mission to the CODA front-end Cassegrain, it is unlikely that the instrument costs would have been within the limits of a Pioneers class mission.

Design and selection of the rest of the instrument follow a similar focus on minimizing NRE. No new electronics were designed for this system, and the mechanical packaging relied heavily on previous mission design. The majority of labor costs on the Pandora payload development are for system integration, rather than new-component design.

Understanding previous design constraints and how they roll into mission-level performance, was enabled by early electro-optical high-fidelity simulations of each imaging channel. The science and engineering teams iterated early and often on these simulations, ultimately enabling a bottoms-up approach for most system elements.

Unlike conventional top-down approaches to functional requirement development, where requirements are set a priori based on a broader system's demands or from a stakeholder's perspective, a bottoms-up requirements derivation encourages a more empirical approach[12]. This process begins at the grass-root level of the system's components and leverages high-fidelity simulations to define the key performance metrics which dictate the remaining instrument design. Parametrization of key technical performance measures constrains system-design by existing "off the shelf" technologies. Consequently, requirements are derived based on analysis and understanding of the detailed system behavior, which establishes a strong linkage between the requirements and their functional motivations.

Utilizing high-fidelity parametrized performance simulation as an analytical tool allows the examination of various facets of the system. Such simulations accurately represent the system's performance under different operating conditions and configurations, promoting a thorough exploration of the design space. Specifically, performance simulators for visible channel photometry (Figure 10, above) and near-infrared spectroscopy were parametrized with comprehensive instrument performance indicators, such as thermal stability, optical wavefront error-induced point spread functions (Figure 11), absolute temperature, detector

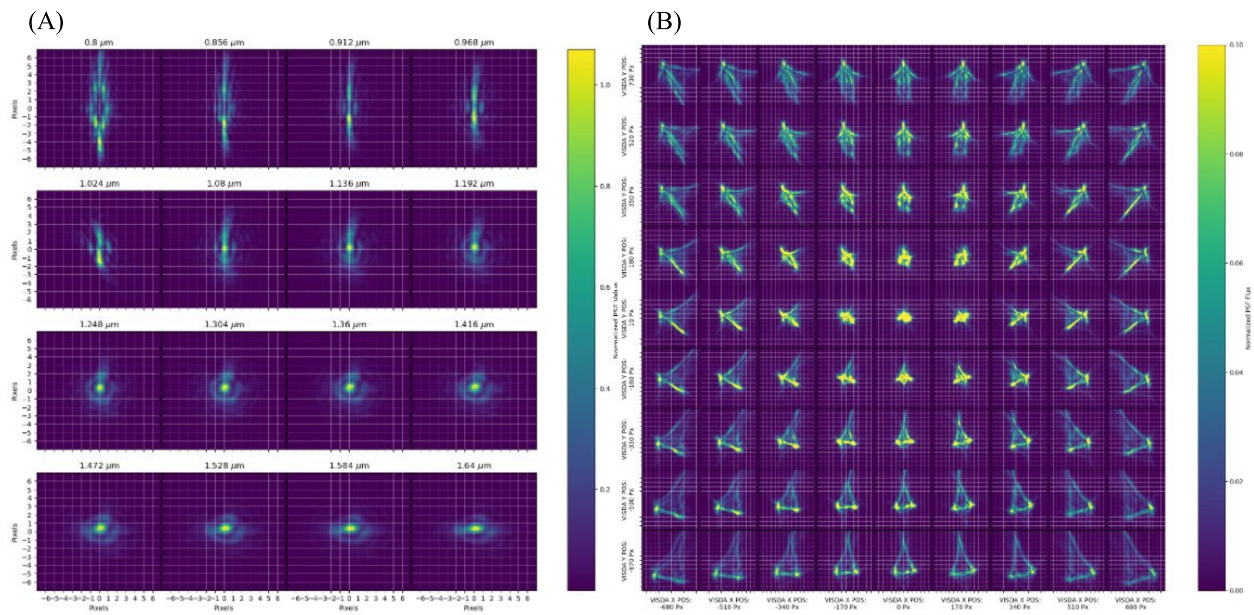

Figure 11: Simulated point-spread-functions from the integrated CODA 2.1 telescope, including historic actuals for as-built component surface wavefront figure. (A) NIR channel and (B) visible channel.

quantum efficiency, dark current, read noise, spacecraft pointing stability, jitter, and pointing accuracy.

These comprehensive parametrizations feed into the simulation, generating mission-level signal-to-noise ratios that are representative of the actual system performance. This meticulous analysis helped set well-defined, realistic performance targets that align with vendors' existing capabilities, therefore supporting efficient, streamlined procurement. Furthermore, by establishing a baseline for optimal system performance, these simulations enable an iterative optimization of design parameters, enhancing the robustness of the overall system design.

However, this bottom-up requirements derivation process is not without challenges. Achieving a high level of detail in the simulations demands a thorough understanding of the system's operational environment and component behavior. This requirement necessitates a comprehensive investment in preliminary research and design studies, which could potentially lengthen the initial phase of the project. However, Pandora was able to execute the necessary simulations during the concept development phase, successfully culminating in a system requirements review in the first program year of the mission.

While challenging under the constraints of a Pioneers budget, the front-loaded effort proved an extremely advantageous trade-off for the resulting system's optimal performance and reduced risk of failure due to ill-defined or unrealistic requirements.

Firm-Fixed Price Contracts

Contractual mechanisms such as cost-plus contracts (CPC) and time and materials (T&M) are often utilized in aerospace applications. With CPC, the contractor is reimbursed for allowable costs and receives a predetermined profit. This type of contract is especially beneficial during the research and development phase when risks and costs are difficult to predict accurately. Cost-reimbursement contracts may incentivize inefficiency, since costs exceeding initial estimates are typically absorbed by the customer. Time and materials (T&M) contracts can provide a middle-ground solution, giving some flexibility on costs while maintaining some controls, but require vigilant management to prevent misuse.

Pandora felt that neither CPC nor T&M aligned with the spirit of the Pioneers program. While Pioneers missions are encouraged to take technical risks, there is significantly lower program tolerance for cost-uncertainty. Throughout the selection process, the emphasis on minimal cost uncertainty for Pandora was made clear. As such, all procurements on Pandora were executed as firm-fixed-price contracts, including the bus and the CODA telescope. Assuming that Pandora could manage the execution of the contracts, this minimized cost uncertainty on the program. The Space Program at LLNL has had a long and successful history of strategic alignment with vendors to execute complex development under FFP contracts.

Firm fixed price (FFP) contracts do present challenges in aerospace development work, chiefly due to the high degree of uncertainty, complexity, and technological novelty inherent in such projects. However, FFP contracts do have substantial advantages in terms of budget predictability. As such, institutional relationships and technical alignment become paramount to ensuring success.

Under an FFP contract, the contractor bears the brunt of risk[13]. If the project encounters unforeseen technical hurdles, cost overruns, or schedule delays, the contractor is obligated to deliver the agreed-upon system within the initially estimated cost. This may result in a temptation to cut corners, potentially compromising quality and performance, to adhere to budgetary constraints. Pandora mitigated these concerns by owning technical integration risk at the payload and observatory level. Subcontractors, under FFP contracts, were largely obligated on delivering existing capabilities that they had experience manufacturing. While some of these subcontracts were low dollar amount and relatively straightforward (i.e. heat straps), others were several millions of dollars and highly complex (spacecraft bus). Regardless of their technical complexity, Pandora relied upon FFP for absolute cost certainty. To date, Pandora has obligated over 75% of its procurements and has not incurred cost overruns to agreed upon technical scope.

SUMMARY

Pandora is one of the inaugural NASA Astrophysics Pioneers Class missions. It will provide continuous, dual-band, simultaneous observations to determine photosphere properties and disentangle star and planetary signals in transmission spectroscopy. The primary instrument on Pandora is CODA 2.1, an all-aluminum relayed Cassegrain telescope that provides photometry in 400-650 nm and spectroscopy in 1000 – 1700 nm.

The use of existing technologies, as well as firm fixed price contracts, is critical to Pandora's success to date. Early development of parametrized high-fidelity system-level performance simulations was a critical step in enabling the Pandora team to define mission requirements around existing commercial capabilities, wherever possible.

Pandora is in the process of preparing for its critical design review (CDR), which is scheduled to be held in the last quarter of 2023. After successful completion of CDR, Pandora will undergo assembly, integration, and testing during 2024, with launch in early 2025. There will be a one-month commission period, followed by 12 months of science operation.

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