

AURORA: Advanced Underground Resource Observation

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Abstract

The Aurora Advanced Underground Resource Observation lunar surveyor is a mission concept designed to map lunar resources in three dimensions, enabling the development of infrastructure critical to NASA's Moon-to-Mars initiative. As NASA's Artemis program advances toward crewed lunar landings beginning with Artemis IV, the need for reliable In-Situ Resource Utilization (ISRU) data becomes essential for sustainable surface operations. Current lunar missions lack a dedicated resource-mapping capability at the resolution and spatial coverage required for infrastructure planning and ISRU-driven manufacturing. Aurora addresses this gap by generating high-fidelity 3D resource distribution models of the lunar surface, providing actionable data for mining architecture, manufacturing site selection, and long-term base development. These models will directly support Artemis mission planning and serve as a foundational dataset for both NASA programs and private commercial partners investing in the lunar economy.

Introduction

Humanity's return to the Moon hinges on a deceptively simple question: where are the resources? Subsurface water ice, confirmed present across the lunar surface, offers the raw material for ISRU-derived propellants that NASA studies project could reduce Earth-to-lunar-orbit payload requirements by up to 40% [1]. Helium-3, a rare isotope with applications in nuclear fusion, medical imaging, and neutron detection, commands a market value of approximately \$2,500 per liter, and a single fusion power plant could require up to 100 kg annually, representing a potential market exceeding \$1.4 billion per facility [2]. Yet despite these stakes, no surface mission has produced the direct, high-confidence resource measurements needed to turn these deposits from scientific curiosities into actionable infrastructure targets.

The Aurora (Advanced Underground Resource Observation) lunar surveyor is a mission concept developed to map the distribution of surface and subsurface lunar resources using both direct and indirect sensing methods. Aurora operates as a sensor payload mounted to a rover platform and deployed from Astrobotic's Griffin lander, traversing targeted regions of the lunar surface to collect multimodal geophysical data. Onboard sensing systems, including

UV/Vis/NIR spectroscopy, Ground Penetrating Radar (GPR), quadrupole mass spectrometry, and a magnetometer-integrated drilling system, characterize key resource indicators including Helium-3 (He-3) proxy signatures and subsurface water ice deposits. Collected data is downlinked from Aurora to the Griffin lander, which relays the information to a mission control center on Earth, where it is processed, sorted, and synthesized into a quantitative Probable Resource Model (PRM) of He-3 and H₂O distribution across the surveyed area.

The mission addresses a critical gap in current lunar exploration: while orbital and predictive models of resource distribution exist, no surface mission has yet produced direct, high-confidence measurements of He-3 and H₂O reserves at the resolution required to support infrastructure planning and ISRU operations [3, 4]. Aurora moves the industry standard from predictive to direct physical measurement, significantly increasing data reliability for future high-cost missions. By generating georeferenced, high-fidelity resource maps, Aurora provides the foundational prospecting dataset needed to support NASA's Artemis program, commercial partners such as Interlune, and the broader development of sustainable lunar infrastructure under NASA's Moon-to-Mars architecture.



Fig. 1: Aurora Auger concept, used for gathering various depths of He-3 for direct measurements.

Reserve Models

Probable Reserve Models (PRMs) are an industry-standard method of defining the availability and quantity of extractable assets to support the development of harvesting operations across a variety of resource modeling fields, including oil and gas, mineral extraction, and increasingly, space resource utilization. A probable reserve is defined as a resource deposit that has been sufficiently characterized — through direct measurement or high-confidence inference — to justify economic planning and infrastructure investment, though not yet to the certainty threshold of a proven reserve [5]. The distinction is consequential: probable reserves carry an estimated 50% or greater confidence of economic recoverability, making them the standard benchmark for pre-extraction feasibility studies and site selection decisions.

Translating this framework to the lunar context, Aurora's primary mission output is the generation of a Probable Resource Model of He-3 and H₂O distribution across the surveyed area. Existing lunar resource maps rely on orbital spectral data and predictive correlations derived from Apollo-era soil samples, which provide regional estimates but lack the spatial resolution and direct subsurface measurement necessary to meet PRM confidence thresholds [6, 7]. Aurora addresses this limitation by combining surface spectroscopy, ground penetrating radar, and direct regolith sampling through its auger-drilling system to produce ground-truth measurements that anchor the resource model in physical data rather than correlation-based inference. The resulting PRM will provide the first surface-validated, georeferenced

resource dataset of sufficient confidence to support commercial mining feasibility studies and NASA ISRU infrastructure planning on the lunar surface.

Mission Context

Long term human occupation of the lunar surface will require in-situ resource exploitation. Chief among these resources are water and solar wind implanted volatile elements such as carbon, nitrogen, helium-3 and others. Water in particular is an important component of life support systems and source of in-situ hydrogen-oxygen propellant. Solar wind implanted volatiles have various uses as life support, or in the case of helium-3 as fusion fuel.

Water is present in two forms on the lunar surface, as concentrated deposits in permanently shadowed regions, and in smaller endogenous concentrations throughout the lunar surface. The larger deposits are of particular interest to NASA's plans for Artemis and long-term infrastructure. These deposits remain largely uncharacterized in morphology and trace composition and may be shallow surface or possibly more substantial deposits. This uncertainty is reflected in the opposing views in the literature [8]. Trace elemental contamination may also be present in these deposits as well. The characteristics of these deposits will determine the level of infrastructure development possible in any locality and if any purification is needed.

Solar wind implanted volatiles such as carbon, nitrogen, and helium-3 are mostly present in surface exposed regolith. Many factors affect the concentrations of these elements in the regolith, principally time exposed to the solar wind, composition, and bulk grain fineness.

Measurements of solar wind exposure time, composition, and bulk grain fineness can and have been determined on the surface from orbit. It is important to note though that this is not necessarily representative of the properties of the regolith stratigraphically. The lunar regolith is mostly the cumulative buildup of debris from meteoroid impacts. Consequently, the properties of the lunar regolith cannot generally be determined at depth. This is illustrated by measurements of helium-3 concentrations in the Apollo coring samples [9].

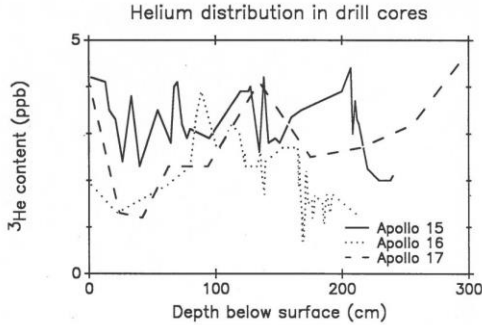


Fig. 2: Apollo Core Sample Stratigraphic He-3 Concentrations [9].

Solar wind exposure time and bulk grain fineness are representative of regolith maturity. Generally, more mature regolith has been exposed to solar wind longer and has a finer bulk grain size. Solar wind exposure time can be directly correlated with the concentration of nanophase iron, generated by cosmic rays, in regolith [9]. Grain fineness correlates to longer surface exposure time and surface area, determining the available surface to be implanted by solar wind. Consequently, regolith with higher concentrations of nanophase iron and lower bulk grain sizes have higher concentrations of solar implanted elements.

For the solar wind volatile helium-3, there is also a strong correlation between concentration and %wt of the mineral ilmenite in the regolith [9]. The regions of highest ilmenite content on the lunar surface are in the mare at and near the lunar equator, the highest of all being in Mare Tranquillitatis and Oceanus Procellarum [1].

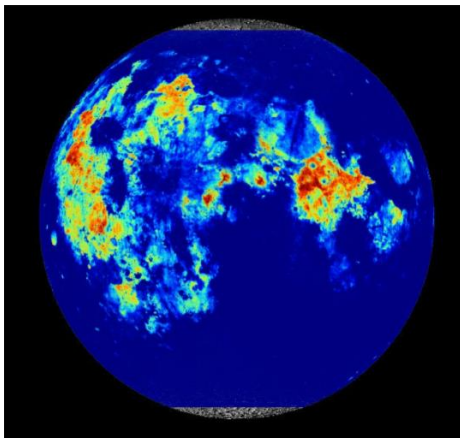


Fig. 3: TiO₂ wt% on the Lunar Nearside [7].

Despite these correlations being well established from orbit, the stratigraphic variability illustrated in Figure 2 underscores why surface-level orbital data alone is insufficient for PRM-quality resource characterization, and why direct, ground-truth measurement is the necessary next step.

Conceptual Design

Aurora's conceptual design is grounded in a single governing philosophy: build a modular, reusable platform that directly measures Water, and He-3 proxy indicators at the surface and subsurface levels, while remaining extensible enough to expand coverage area and depth in future mission iterations. Rather than optimizing for a single survey pass, Aurora is designed as the first deployment of a scalable lunar prospecting toolchain, one that supports NASA's Artemis program by generating the resource intelligence required for sustainable surface operations and long-term Moon-to-Mars infrastructure development [3, 4].

A. Alignment with Artemis Architecture

Aurora's mission concept is directly responsive to a critical gap identified within NASA's Moon-to-Mars architecture: the absence of ground-truth resource data at the resolution required for ISRU infrastructure planning [3]. Artemis missions beginning with Artemis IV will demand actionable site selection data for mining architecture and propellant production systems, yet current resource maps rely on orbital spectral correlations and Apollo-era sample extrapolations rather than direct surface measurement [3, 4]. Aurora addresses this by operating as a dedicated prospecting payload, generating a Probable Resource Model (PRM) of He-3 and H₂O distribution that is directly consumable by both NASA mission planners and commercial partners such as Interlune investing in lunar extraction infrastructure.

The modular design of Aurora's sensor suite further aligns with Artemis goals by establishing a reusable prospecting toolchain that can be integrated into future lunar rovers without redesign, reducing the cost and development timeline of subsequent missions. The suite — spanning surface elemental analysis via the Alpha Particle X-Ray Spectrometer, spatial TiO₂ mapping via the Multispectral Imaging Camera, subsurface characterization via the Lunar Penetrating Radar, and direct borehole measurement via the magnetometer-integrated Aurora Drilling Probe — is architected from the outset for modularity, with each instrument interfacing through a

standardized bus that permits substitution, upgrade, or expansion as mission requirements evolve.

B. Site Selection – Mare Tranquillitatis

Landing site selection for Aurora was driven by the requirement to maximize He-3 prospecting yield and PRM confidence within a single mission deployment, while remaining within the operational and thermal constraints of a five-year development timeline. Three candidate site categories were evaluated: equatorial mare regions, mid-latitude sites, and polar permanently shadowed regions (PSRs).

Polar PSRs, while hosting the highest confirmed concentrations of subsurface water ice, were deprioritized for this initial mission for two reasons. First, the extreme thermal environment, with temperatures dropping below 40 K in permanently shadowed craters, introduces thermal management complexity that exceeds Aurora's current TRL roadmap. Second, navigation and power generation in regions of permanent shadow place constraints on solar-powered rover operations that would require significant additional infrastructure investment beyond the scope of this mission concept. Polar water ice characterization remains a high-priority target for future Aurora iterations as the platform matures.

Mid-latitude sites were considered for their potential subsurface water ice stability at depth, where thermal conditions prevent ice sublimation. However, ilmenite concentrations at mid-latitude sites are significantly lower than equatorial mare regions, reducing He-3 prospecting yield and PRM confidence for the primary mission objective.

Equatorial mare regions were identified as the optimal site category, offering the highest ilmenite concentrations on the lunar surface, favorable solar power availability, and well-characterized surface geology that provides an existing ground-truth baseline for sensor validation. As established in the Mission Context, the regions of highest ilmenite content on the lunar nearside are concentrated in Mare Tranquillitatis and Oceanus Procellarum, both situated at and near the lunar equator [3, 6].

Mare Tranquillitatis was selected as the primary landing target over Oceanus Procellarum on three grounds. First, its TiO₂ weight percentage, the primary surface proxy for ilmenite abundance and He-3 concentration, represents one of the highest measured values on the lunar nearside, as shown in Figure 3 [1].

Second, its surface geology is the most extensively characterized of any mare region, with Apollo 11 providing direct sample data that serves as a calibration baseline for Aurora's spectroscopic and radar outputs, directly improving PRM confidence. Third, its equatorial position provides near-continuous solar illumination during the lunar day, maximizing available power for rover operations and sensor duty cycles without requiring supplemental power storage infrastructure.

The primary survey area within Mare Tranquillitatis will target ilmenite-rich basalt flows identified through existing TiO₂ mapping data, with Aurora traversing between high-priority spectroscopic targets identified during pre-mission orbital analysis. Subsurface water ice characterization, while a secondary objective at this equatorial site, will be pursued through GPR and LPR surveys targeting any thermally stable subsurface regions identified during traverse, contributing H₂O data layers to the PRM output.

C. Sensing Architecture & Instrument Selection

Aurora's sensing architecture is designed across two development tiers: a prototype system currently under validation, and a preliminary full-mission instrument suite derived from the System Requirements Review (SRR). The prototype validates core mechanical, electrical, and data handling infrastructure, while the full-mission suite represents the preliminary instrument candidates required to achieve PRM-quality resource characterization across the lunar surface.

Instrument selection for the full-mission suite was guided by a weighted trade study conducted across all Aurora team leads, evaluating candidate sensing approaches against four mission-critical objectives. Accuracy of He-3 and H₂O characterization was weighted most heavily at 43.3%, reflecting Aurora's primary obligation to produce a defensible PRM, followed by reusability at 26.7%, cost at 20.0%, and total information yield at 10.0%. These weighting will continue to guide instrument downselection as the design matures toward the Preliminary Design Review (PDR).

Table I: Trade Study Results

Objective	%
Accuracy	43.3
Total Info.	10.0
Cost	20.0
Reusability	26.7

Prototype Instrumentation

The current Aurora prototype validates the foundational sensing and mechanical systems necessary to demonstrate mission feasibility. The prototype integrates a retractable auger drilling system for subsurface bore access, a SparkFun Triad AS7345x multi-spectral sensor for surface composition analysis, and a thermal infrared camera for subsurface temperature gradient monitoring. DWM3000EVB transceivers were selected to provide communications necessary to prove downlink potential of sensing signals, as well as development of Position Navigation and Timing (PNT) using the Griffin Lunar Lander as a base station. These instruments were selected for the prototype specifically based on cost accessibility, power compatibility with the prototype platform, and their ability to demonstrate the core measurement concepts at a Technology Readiness Level (TRL) of 3-4. Onboard data handling is managed by a Jetson Orin Nano computing system, which processes, timestamps, and prepares data for downlink. The prototype does not include the full-mission instrument suite and is not intended to meet PRM confidence thresholds. Its purpose is to validate the mechanical integration of the drilling system, the communication architecture between Aurora and the Griffin lander, and the feasibility of multimodal sensor data fusion within the onboard computing framework.

Full-Mission Instrument Suite

The preliminary full-mission instrument candidates are derived from Aurora's System Requirements (SR-1.1.1.A through SR-1.1.2.A) and represent the sensing capabilities required to generate a surface and subsurface resource model at the confidence level necessary to qualify as a Probable Resource Model [5]. These instruments target the physical and chemical properties most strongly correlated with He-3

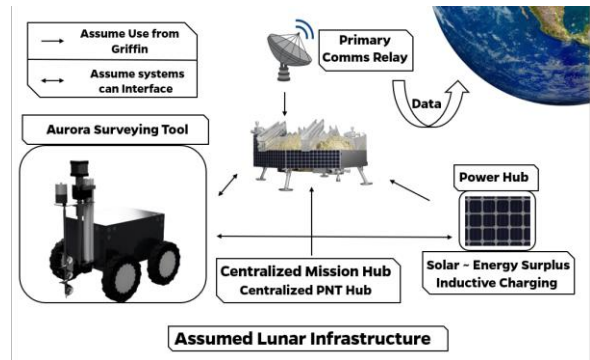


Fig. 5: Aurora system architecture displaying Position Navigation and Timing, as well as data throughput from Aurora to Griffin, and data downlink from Griffin to Mission Control.

concentration and H₂O presence in lunar regolith, as established by prior orbital and sample-based studies [3, 4]. It should be noted that while all instruments listed below are under active consideration, final instrument selection remains subject to trade study refinement, mass and power budget closure, and TRL advancement prior to the Preliminary Design Review.

The *Alpha Particle X-Ray Spectrometer (APXS)* (SR-1.1.1.A) provides direct elemental composition analysis of surface regolith, quantifying TiO₂ content as the primary ilmenite proxy and therefore the leading surface-level He-3 concentration indicator. APXS has significant flight heritage from Mars rover missions, providing a strong feasibility argument for lunar deployment within a five-year development window.

The *Multispectral Imaging (MSI) Camera* (SR-1.1.1.B) extends surface TiO₂ mapping to a wider spatial coverage area than contact instruments alone, enabling Aurora to prioritize high-value drilling and spectroscopy targets during traversal and building the georeferenced surface map layer of the PRM.

The *Flux Magnetometer (FMAG)* (SR-1.1.1.C) measures magnetic field anomalies and nanophase iron content in the regolith stratigraphically through the borehole, providing a direct indicator of regolith surface residence time — the duration over which solar wind-implanted He-3 has been retained in the ilmenite crystal structure [3]. This instrument, integrated with the auger drilling system, represents Aurora's most direct subsurface He-3 proxy measurement capability.

The *Electrostatic Analyzer (ESA)* (SR-1.1.1.D) characterizes the local solar wind flux environment at the survey site, providing real-time solar wind implantation rate data that contextualizes He-3 concentration measurements and improves the statistical confidence of the PRM output.

The *Neutral Particle Detector (NPD)* (SR-1.1.1.E) measures neutral gas flux from the regolith surface, providing an additional He-3 proxy signal by detecting thermally desorbed volatiles released from the regolith during the thermal cycling of the lunar day-night cycle.

The *Automated Grain Analyzer (AGA)* (SR-1.1.1.F) characterizes regolith grain size distribution, a secondary He-3 concentration indicator. Finer-grained regolith presents greater surface area for solar wind implantation and retains He-3 at higher concentrations than coarse-grained material, making grain size a critical parameter for PRM confidence [3].

A *Quadrupole Mass Spectrometer* was additionally evaluated as a direct He-3 detection instrument, offering the highest measurement specificity of any candidate in the suite. It remains under consideration pending mass, power, and cost trade study outcomes.

The *Lunar Penetrating Radar (LPR)* (SR-1.1.2.A) provides subsurface structural characterization, scanning for dielectric constant variations indicative of subsurface water ice deposits and resolving subsurface density profiles that inform stratigraphic He-3 distribution models. LPR is the sole instrument in the suite that simultaneously supports both the He-3 and H₂O characterization objectives, making it the highest-priority instrument for inclusion in the final design regardless of trade study outcomes.

Together, these instruments form a multimodal measurement architecture designed to triangulate He-3 and H₂O resource estimates from multiple independent physical observables, maximizing PRM confidence and reducing the risk that any single instrument failure compromises mission science return.

Aurora Drilling Probe

The Aurora Drilling Probe (ADP) is a core enabling element of the Aurora sensor architecture, providing the only direct physical subsurface access in the instrument suite. The ADP uses a motorized auger

mechanism to bore into the lunar regolith, exposing subsurface material to onboard sensing instruments including the FMAG and full-mission spectrometry suite. This direct subsurface access is what fundamentally distinguishes Aurora from orbital and surface-only resource mapping approaches, enabling the stratigraphic He-3 and H₂O characterization required to produce a three-dimensional Probable Resource Model rather than a two-dimensional surface map.

The ADP concept was developed and integrated into the Aurora prototype, with validation and verification testing conducted at the NASA Marshall Space Flight Center (MSFC) lunar regolith testbed. Testing confirmed that the auger mechanism successfully displaces regolith material under testbed conditions. However, trials using the basaltic regolith simulant at MSFC resulted in the auger failing to maintain a stable borehole wall, preventing the creation of a sustained bore hole. Preliminary analysis suggests this failure mode may be attributable to the coarse grain size of the basaltic simulant, the absence of fine-grained material appears to prevent the regolith wall binding behavior on the auger outer surface that is expected in mature fine-grained lunar regolith at Mare Tranquillitatis. This is a significant and relevant finding, as the target survey site's regolith grain characteristics differ meaningfully from the coarse basalt simulant used in initial testing.

Further analysis of the auger failure mode is currently underway, and future testing is planned using simulants more representative of the fine-grained ilmenite-rich regolith expected at Mare Tranquillitatis. Development of the ADP continues as a high-priority work item, with the next test campaign intended to validate borehole stability in fine-grained regolith and confirm the instrument's readiness for integration into the full-mission system architecture.

D. Innovative Design Concepts

Three novel design concepts were developed and evaluated during the conceptual phase. All three demonstrate the design rigor applied to Aurora's development and represent a roadmap of innovations for future mission iterations.

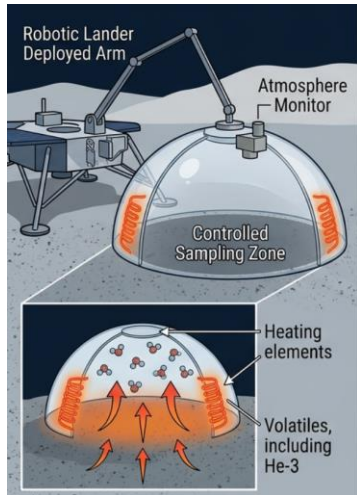


Fig. 6: Example figure of innovative Bowl Cut Dome Design for Helium-3.

The Bowl Cut Dome concept proposed enclosing a controlled sampling zone on the lunar surface beneath a sealed dome fitted with resistive heating elements, thermally liberating volatiles including He-3 from the underlying regolith and capturing the released gases for spectral analysis within a controlled internal atmosphere. This concept draws on a class of volatile liberation designs independently identified in the He-3 mining literature as scientifically promising. Aaron Olson's 2021 survey of lunar He-3 mining concepts describes various methods and designs specifically proposed for mining helium-3, including thermal extraction approaches, and summarizes research on helium extraction from lunar regolith simulant and potential synergies with ISRU propellant production. The dome-style thermal liberation approach represents one of the more direct He-3 extraction concepts in this literature, lending scientific credibility to Aurora's consideration of the design. However, for Aurora's prospecting mission, where the objective is characterization rather than extraction, the approach introduced significant mass, thermal management complexity, and regolith contamination risk that exceeded the feasibility threshold for the current mission scope. The design was used as a baseline for the ADP design [11].

The Integrated Regolith Maturity Package (IRMP) proposed a non-intrusive evaluation system combining solar wind implantation history analysis and space weathering assessment to characterize regolith maturity, a strong indirect He-3 indicator,

without requiring physical drilling. This concept has strong potential for future Aurora iterations as a lower-mass complement to the drilling system.

The Descent Deployed Penetrating Spike Array proposed ejecting an array of miniature sensor-equipped spikes from the Griffin lander during its descent phase, embedding them across a distributed surface area to provide simultaneous multi-point subsurface He-3 measurements without requiring rover traversal. The concept draws heritage from NASA's Deep Space 2 mission, which flew as a secondary payload on the Mars Polar Lander in 1999. Deep Space 2 carried two probes designed to impact the Martian surface and test new penetrator technologies, representing one of the first attempts to deploy descent-ejected subsurface probes from a planetary lander. While contact was lost with both the Mars Polar Lander and Deep Space 2 before surface data could be returned, the penetrator deployment concept itself demonstrated the technical feasibility of the approach and established it as a recognized heritage architecture for distributed subsurface sensing [12]. For Aurora, the spike array concept offers a significant coverage advantage over a single-rover traverse, as distributed probes could simultaneously characterize He-3 and H₂O indicators across a wide area in a single deployment event. However, the complexity of coordinating distributed sensor network communications, the uncertainty of spike survivability and orientation upon high-velocity impact, and the absence of a sufficiently mature TRL pathway within a five-year development window placed this concept beyond the current mission's feasibility threshold.

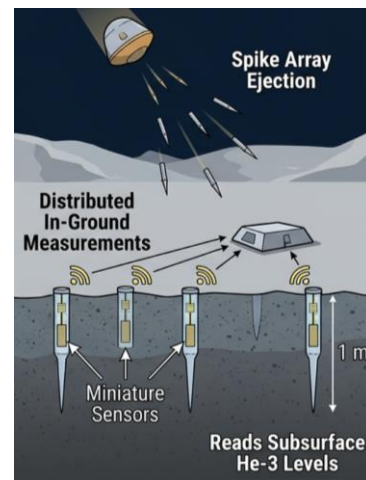


Fig. 7: Example figure of Descent Deployed Penetrating Spike Array.

The final Aurora design integrates the lessons from all three concepts: direct subsurface access via the auger drill, surface characterization via spectroscopy, and subsurface mapping via GPR, combining the physical measurement strengths of the dome concept with the non-intrusive coverage capability of heritage sensing methods.

Feasibility

A central evaluation criterion for any mission concept proposed under the NASA COSMIC Capstone Challenge is whether the design can be realistically developed and deployed within a five-year timeline and without requiring the development of entirely new space systems. Aurora's feasibility case rests on three pillars: a heritage rover platform that eliminates the need to design and qualify a new mobility system, a sensing suite built from flight-proven or near-flight-ready instrument classes, and a launch and delivery architecture that leverages existing commercial infrastructure already under contract with NASA.

A. Rover Platform: Astrobotic Polaris

Aurora's sensor payload is designed to be hosted on Astrobotic's Polaris rover platform, a commercially developed lunar rover built specifically to support payload delivery and surface operations in support of NASA's Commercial Lunar Payload Services (CLPS) program. Selecting the Polaris platform as Aurora's mobility baseline eliminates one of the highest-cost and highest-risk elements of any lunar surface mission, the development, qualification, and testing of a new rover chassis, and replaces it with a system that has already undergone significant design maturation and environmental testing by Astrobotic. This decision directly reflects Aurora's core design philosophy of reusability and cost-balanced architecture, prioritizing mission resources toward the novel science payload rather than infrastructure that can be acquired through existing commercial channels.

The Polaris platform's payload capacity and power interface are compatible with Aurora's confirmed system constraints of mass under 200 kg and power consumption within the 80 kW allocation provided by the Griffin lander, satisfying assumptions AC-1 and AC-3 respectively, as documented in Table II. Its wheel and suspension design is qualified for the basaltic mare terrain expected at the Mare

Tranquillitatis survey site, and its solar panel array provides sufficient power generation during the lunar day to sustain continuous science operations across Aurora's full instrument suite. By building on this heritage platform, the Aurora team compresses the development timeline significantly compared to a clean-sheet rover design, while inheriting Astrobotic's existing supply chain and integration expertise. The Polaris also maintains PNT with the Griffin using its onboard communications architecture.

Table II: Assumptions and Constraints

ID	Assumption / Constraint	Status
AC-1	The Griffin lander provides a maximum of 200 kg payload mass to the C3 mission.	Closed
AC-2	The C3 payload volume shall not exceed $\frac{3}{4}$ of the available Griffin payload volume.	Closed
AC-3	Griffin provides up to 5 kWe solar power generation during surface operations.	Assumption
AC-4	Griffin provides energy storage sufficient for ~ 100 hr lunar night survival.	Assumption
AC-5	Griffin provides a surface communications relay (≈ 60 Mbps) and Earth relay capability.	Closed
AC-6	Griffin base-station systems consume approximately 400 kg of total lander mass.	Closed

B. Launch and Delivery Architecture

Aurora will be delivered to the lunar surface as a payload aboard Astrobotic's Griffin lander, launched on a SpaceX Falcon Heavy launch vehicle. Astrobotic uses the Falcon Heavy for the Griffin-1 lander, and the Griffin lander is already under contract with NASA as part of the CLPS program for lunar surface delivery. Selecting this architecture means Aurora inherits a fully defined launch vehicle interface, a qualified translunar injection profile, and an established mission

operations framework, all without requiring Aurora's development team to negotiate or fund a new launch contract.

Upon landing at Mare Tranquillitatis, Aurora detaches from the Griffin lander and begins surface operations using Griffin as a permanent homebase for power recharge, data storage, and Earth communications relay. This base-station architecture, in which Griffin serves as the primary communications node and Aurora operates as the mobile science payload, significantly reduces the complexity and mass of Aurora's onboard systems — communications, power storage, and high-gain antenna requirements are all offloaded to Griffin rather than duplicated on the rover.

C. Instrument Heritage and TRL Pathway

The full-mission instrument suite identified in Aurora's System Requirements draws exclusively from instrument classes with significant flight heritage or active development programs, supporting the argument that the sensing architecture can reach the TRL level required for flight qualification within a five-year window. The Alpha Particle X-Ray Spectrometer has been deployed on multiple Mars rover missions including Curiosity and Perseverance, providing one of the strongest heritage arguments of any instrument in the suite. Fluxgate magnetometers have been flown on numerous planetary and lunar missions. Multispectral imaging cameras are among the most mature remote sensing instruments in planetary exploration. Lunar Penetrating Radar technology builds directly on the Chang'e-3 and Chang'e-4 LPR instruments, which successfully operated on the lunar surface. The Electrostatic Analyzer and Neutral Particle Detector instrument classes have flight heritage from solar wind monitoring missions.

The Quadrupole Mass Spectrometer (QMS) represents Aurora's highest-specificity He-3 detection capability and is the intended instrument for direct sample analysis in the full-mission architecture. The QMS is designed to operate in direct coupling with the Aurora Drilling Probe, receiving extracted regolith core material from the borehole and performing in-situ mass spectrometric detection and quantification of He-3 in the sample. This ADP-QMS coupling moves Aurora's measurement capability from proxy-based inference to direct physical detection, providing the highest-confidence data input to the PRM. The ADP-

QMS system is currently at a low TRL and represents the primary technology development challenge within the full-mission instrument suite, with maturation of this system identified as a high-priority research objective prior to the Preliminary Design Review.

D. Prototype Validation as Feasibility Evidence

Aurora's feasibility is further supported by the existence of a functioning prototype, currently at TRL 3-4, that has already demonstrated the core mechanical and data handling concepts in a relevant environment. The prototype's retractable auger drilling system successfully displaces regolith material, validating the fundamental borehole access concept. The Jetson Orin Nano onboard computing system has demonstrated real-time multimodal data processing and timestamped downlink preparation. The DWM3000EVB transceiver system has validated the communications architecture between Aurora and a simulated base station, confirming the PNT and downlink approach that will be scaled to the Griffin lander interface in the full mission system.

The MSFC testbed drilling trials, while identifying a borehole stability failure mode in coarse basaltic simulant, represent meaningful feasibility data rather than a program risk, the failure is attributable to simulant grain size mismatch rather than a fundamental flaw in the auger concept, and the fine-grained ilmenite-rich regolith at Mare Tranquillitatis is expected to behave more favorably. Continued testing with representative simulants is planned and underway, maintaining the development timeline toward a TRL 5 demonstration in further lunar testbed environments as the next milestone.

The combination of a heritage rover platform, a commercially contracted launch and delivery architecture, a flight-proven instrument suite, and a functioning prototype with active development underway establishes Aurora as a mission concept that is not only scientifically compelling but concretely achievable within the constraints of a five-year capstone-to-flight roadmap.

System Architecture & CONOPS

Aurora's system architecture is organized around five interoperating elements: the mission control center on Earth, the Astrobotic Griffin lander serving as a lunar homebase, the SpaceX Falcon Heavy launch vehicle, the Aurora rover payload, and the Astrobotic Polaris rover platform that hosts it. Together these

elements form an end-to-end architecture that spans from Earth launch through multi-lunar-day surface operations, with each element performing a defined and non-redundant role in the mission chain.

A. System Elements

The mission control center operates with a staffing complement of five mission operations personnel and three dedicated data processing specialists. Mission control is responsible for uplink of traverse commands and science stop instructions, monitoring of Aurora and Griffin system health telemetry, and processing of downlinked science data into PRM data products. Aurora operates autonomously during traverse segments between ground-commanded science stops, reducing the real-time operator burden and allowing mission control to focus personnel on data quality assessment and science targeting decisions rather than continuous rover driving.

The Griffin lander serves as Aurora's permanent lunar homebase throughout the surface mission. Griffin provides power recharge capability for Aurora upon return from traverse segments, onboard data storage for buffering science data between Earth downlink windows, and the primary communications relay between Aurora and mission control via its high-gain antenna system. Griffin's solar power generation provides the energy budget for both its own housekeeping operations and Aurora's recharge cycles, with the system designed to maintain an energy surplus during the lunar day sufficient to sustain continuous science operations. During lunar night, Griffin supplies power directly to Aurora while docked, enabling thermal survival across the approximately 14-Earth-day night period without requiring Aurora to carry an independent power storage system sized for night survival, a significant mass saving that contributes directly to staying within the 200 kg payload constraint.

The Aurora rover payload, hosted on the Astrobotic Polaris platform, carries the full onboard instrument suite, and the Aurora Drilling Probe, a ruggedized Jetson Orin Nano, equivalent computing system, Asics, or FPGAs. Aurora's onboard autonomy handles hazard detection and avoidance during traverse, instrument sequencing at science stops, data timestamping and compression for downlink, and state-of-charge monitoring to trigger return-to-base

recharge cycles when battery levels reach the defined threshold.

B. CONOPS: Mission Modes

Aurora's surface mission is organized into five operational modes that sequence from Earth launch through end-of-mission data delivery. These modes are not strictly time-bounded, with the exception of the transit phase, but are driven by system state, science objectives, and battery charge thresholds.

Mode 1 — Transit: Aurora and the Polaris rover are secured as payload aboard the Griffin lander, which is mounted to the Falcon Heavy upper stage at Launch Complex 39A, Kennedy Space Center. Following launch, Falcon Heavy delivers Griffin on a translunar injection trajectory. During transit, Aurora operates in a low-power payload support mode, with housekeeping telemetry monitored by mission control. Griffin manages attitude control, power, and communications throughout the transit and lunar orbit insertion phases.

Mode 2 — Landing and Deployment: Griffin executes powered descent and lands at the pre-selected site within Mare Tranquillitatis, targeting the ilmenite-rich basalt flows identified during pre-mission orbital analysis. Following touchdown, mission control conducts a full system health check of both Griffin and Aurora before commanding Aurora to detach from Griffin's deployment ramp and perform its initial surface checkout. Aurora's onboard sensors are powered on sequentially, communications with Griffin are verified, and PNT initialization is completed using Griffin as the base station reference.

Mode 3 — Science Operations (Traverse and Survey): Aurora departs Griffin and begins autonomous surface traverse toward the first pre-planned science stop target. During traverse, Aurora's MSI Camera operates continuously, building a georeferenced surface image mosaic and identifying surface spectral anomalies that may prompt mission control to add or reposition science stops during the next uplink window. At each ground-commanded science stop, Aurora halts traverse and executes the full instrument measurement sequence: APXS surface contact analysis, FMAG magnetometry, ESA and NPD atmospheric measurements, AGA grain size characterization, and LPR subsurface scanning. At designated high-priority stops, the Aurora Drilling Probe is deployed to bore into the regolith, enabling FMAG borehole magnetometry and subsurface spectral analysis. All

science data is timestamped, compressed, and queued for downlink to Griffin at the next communications window. Aurora then proceeds autonomously to the next science stop target, repeating the measurement sequence across the survey area.

Mode 4 — Recharge and Data Offload: When Aurora's onboard battery reaches its defined state-of-charge return threshold, Aurora autonomously navigates back to Griffin and docks for recharge. During the recharge cycle, buffered science data is transferred from Aurora's onboard storage to Griffin's data storage system for relay to mission control during the next Earth downlink window. Mission control uses the recharge period to assess incoming science data quality, update the traverse plan for the next sortie, and uplink revised science stop coordinates to Aurora before it departs for the next traverse segment. This mode repeats cyclically throughout the lunar day, with Aurora conducting multiple traverse sorties per lunar day depending on traverse distance and science stop density.

Mode 5 — Lunar Night Survival: As the lunar terminator approaches the survey area, Aurora completes its final traverse sortie of the lunar day and returns to Griffin for docking. Griffin supplies power to Aurora throughout the approximately 14-Earth-day lunar night period, maintaining Aurora's thermal survival. Critical housekeeping telemetry is maintained and downlinked at reduced cadence during the night period. Mission control uses the lunar night period to complete PRM data processing from the preceding lunar day's science data and to finalize science targeting priorities for the following lunar day's traverse plan. At lunar sunrise, Aurora resumes science operations from Mode 3, beginning the next lunar day's traverse sorties from the updated target list.

C. Data Architecture and Downlink

Aurora's data architecture follows a store-and-forward model in which raw science data is collected and timestamped onboard Aurora, transferred to Griffin during recharge cycles, and downlinked from Griffin to mission control during Earth communication windows. The onboard computing system manages data compression and prioritization, ensuring that processed map products and anomaly flags are transmitted ahead of raw instrument data in the downlink queue. This prioritization strategy ensures that mission control receives actionable science information at each downlink window even if

full raw data transfer is not completed within the available window.

Griffin's communications relay provides approximately 60 Mbps downlink capability to Earth, sufficient to transfer the compressed science data products generated during each traverse sortie within a single Earth communication window. Raw LPR data, which the computer subsystem estimates at approximately 170 GB per day of continuous operation, is managed through onboard compression and selective transmission, with full raw data archives maintained on Griffin's onboard storage for post-mission retrieval if required.

Command uplink from mission control to Griffin, and from Griffin to Aurora, follows a structured cycle tied to recharge periods. Traverse updates, science stop coordinates, and instrument configuration changes are uplinked to Aurora during each recharge cycle, ensuring that Aurora's autonomous traverse plan for the next sortie reflects the most current mission control assessment of science priorities.

D. System Interfaces

Aurora interfaces with Griffin through three primary interface types: mechanical, power, and data. The mechanical interface secures Aurora to Griffin's payload deck during transit and landing and provides the deployment ramp from which Aurora drives onto the lunar surface during Mode 2. The power interface provides recharge current to Aurora's battery system during Modes 4 and 5, drawing from Griffin's solar generation and storage capacity. The data interface supports bidirectional communication between Aurora and Griffin using the Polaris' communications system, providing both science data transfer during recharge cycles and real-time telemetry exchange during surface operations within Griffin's communications range.

All interface definitions are governed by the Aurora-Griffin Interface Control Document (ICD), which specifies mechanical mounting dimensions, electrical connector standards, power delivery parameters, and data protocol specifications. The ICD is designed to be compatible with Astrobotic's published Griffin lander payload user guide, ensuring that Aurora's interface requirements are achievable within the constraints of an existing commercial payload delivery architecture rather than requiring custom lander modifications.

Resource Mapping Methodology

Aurora's primary mission deliverable is a Probable Resource Model (PRM) of He-3 and H₂O distribution across the surveyed area of Mare Tranquillitatis. The PRM is not simply a collection of raw sensor measurements, it is a structured, georeferenced data product formatted to meet the evidentiary standard required for resource classification under the SPE Petroleum Resources Management System framework, adapted to the lunar resource context [5]. This section describes how Aurora's multimodal sensor outputs are collected, processed, and synthesized into the two-dimensional surface map and three-dimensional subsurface volumetric model that together constitute the PRM output.

A. PRM Classification Framework

Under the SPE-PRMS framework, a Probable Reserve is defined as a resource deposit characterized with sufficient confidence to justify economic planning and infrastructure investment, carrying a minimum 50% probability of recoverability [5]. This 50% recoverability confidence threshold is the authoritative design target for Aurora's PRM output and is codified in the mission's primary system requirement MS-1, which states that Aurora shall generate a resource distribution model of H₂O and He-3 at a 50% confidence level. It is important to distinguish this recoverability confidence threshold from the separate concept of sensor data confidence. Aurora's multimodal sensing architecture targets a 90% spatial data confidence in characterizing resource indicators across the survey area, meaning that the sensor outputs are designed to characterize He-3 proxy indicators and H₂O signatures with high fidelity across the surveyed region. The 50% PRM recoverability threshold is then applied to translate that high-fidelity sensor characterization into a resource classification that meets the evidentiary standard for infrastructure planning and commercial investment decisions.

B. Data Collection and Georeferencing

The foundation of the PRM is a georeferenced dataset in which every instrument measurement is assigned precise spatial coordinates derived from Aurora's use of Position Navigation and Timing, using Griffin as the base station reference. Each science stop generates a temporally and spatially tagged data record containing outputs from all active instruments in the measurement sequence: APXS elemental

composition, FMAG nanophase iron content at surface and borehole depth, ESA solar wind flux, NPD neutral gas flux, AGA grain size distribution, LPR subsurface dielectric profile, and MSI surface imagery. At science stops where the Aurora Drilling Probe is deployed, the borehole data record additionally contains stratigraphic FMAG measurements at multiple depth intervals, providing the vertical dimension of subsurface resource characterization that orbital and surface-only missions cannot achieve. The APD stores the drilled regolith, and directly measures He-3 content.

All data records are formatted to the NASA Planetary Data System version 4 (PDS4) standard, as implemented through Aurora's NASA Core Flight System (cFS) data architecture. PDS4 compliance ensures that every science data record carries a complete metadata label specifying instrument identity, measurement timestamp, spatial coordinates, calibration state, and data quality flags. This traceability is what qualifies Aurora's measurements as legally admissible inputs to a PRM under the SPE-PRMS evidentiary standard. Each data point can be unambiguously attributed to a specific instrument, location, and time, eliminating the interpretive uncertainty that undermines correlation-based orbital models [3, 4].

C. Two-Dimensional Surface Resource Map

The first layer of Aurora's PRM output is a two-dimensional georeferenced surface resource map covering the surveyed area of Mare Tranquillitatis. This map is constructed by interpolating the spatially distributed science stop measurements across the survey area, producing continuous coverage estimates of surface TiO₂ weight percentage, the primary ilmenite proxy, and surface He-3 concentration indicators derived from the combined APXS, FMAG, ESA, NPD, and AGA outputs at each stop.

The specific data fusion algorithm used to interpolate between science stop measurements and generate continuous surface coverage is an active area of research within the Aurora team, with methodology development ongoing in parallel with prototype sensor validation. Current prototype implementation is focused on establishing robust signal capture and relay from each instrument to mission control storage, validating the data pipeline end-to-end before fusing methodology is finalized. Future development will evaluate geostatistical interpolation approaches,

including kriging, which is the industry standard for spatial resource estimation in terrestrial mining applications and has been proposed for lunar ISRU resource modeling, as well as weighted correlation methods that account for the physical relationships between ilmenite content, grain size, solar wind flux, and He-3 concentration established in the existing literature [3, 4]. The MSI Camera's continuous surface imagery mosaic provides a high-spatial-resolution base layer over which science stop point measurements are registered, enabling visual identification of surface units and boundaries that guide interpolation decisions.

D. Three-Dimensional Subsurface Volumetric Model

The three-dimensional subsurface component of the PRM is constructed by integrating the surface map with the depth-resolved measurements generated at Aurora Drilling Probe deployment sites and LPR subsurface profiles collected during traverse. The LPR provides continuous subsurface dielectric profiles along each traverse path, resolving stratigraphic layer boundaries and identifying dielectric anomalies consistent with subsurface water ice or high-density regolith units.

At ADP deployment sites, the stratigraphic FMAG borehole measurements provide direct depth-resolved nanophase iron content profiles, which are the most reliable indicator of He-3 concentration variation with depth based on Apollo core sample data [9]. Critically, the ADP is designed to couple with a Quadrupole Mass Spectrometer (QMS) in the full-mission architecture, representing Aurora's most direct He-3 detection capability. Rather than relying solely on proxy indicators, the ADP-QMS system extracts regolith core material from the borehole and processes it onboard through the QMS, enabling direct mass spectrometric detection and quantification of He-3 in the extracted sample. This direct measurement capability is what most fundamentally advances Aurora beyond correlation-based resource models, proxy indicators such as ilmenite content, nanophase iron, and grain size estimate where He-3 is likely to be present, but the ADP-QMS system measures it directly, providing the highest-confidence data input to the PRM volumetric model. It should be noted that the ADP-QMS coupling is currently at a low TRL and represents the primary technology development challenge for the full-mission instrument suite. Its development is a high-priority research objective for

the Aurora team, and the system's maturation pathway will be a key driver of the overall mission TRL roadmap toward the Preliminary Design Review.

E. PRM Output and Delivery

The completed PRM is delivered to mission control as a structured set of PDS4-compliant data products comprising the georeferenced surface map, the three-dimensional volumetric resource model, the complete calibrated instrument data archive, and a PRM summary report characterizing the estimated He-3 and H₂O resource quantities within the surveyed area at the 50% recoverability confidence threshold. This data package is designed to be directly consumable by NASA mission planners for Artemis infrastructure site selection and by commercial partners evaluating extraction feasibility, without requiring additional reprocessing or reinterpretation of the raw instrument data.

The PRM data products are archived in PDS4 format and made available through NASA's Planetary Data System, ensuring long-term accessibility for the broader scientific and commercial community and contributing to the growing body of lunar surface ground-truth data that will inform future prospecting missions beyond the Aurora survey area.

Systems Overview

Aurora's system architecture is organized around seven primary subsystems, each governed by a dedicated set of system requirements derived from the mission's objectives and success criteria. The architecture is designed around the principle of modular interface standardization — every subsystem interfaces with adjacent subsystems through defined mechanical, electrical, and data interface control documents (ICDs), enabling future subsystem upgrades or payload swaps without requiring primary structure redesign. This section summarizes the architecture and key requirements governing each subsystem.

A. Instrumentation and Payload

The instrumentation subsystem encompasses the full-mission science tool suite described in the Conceptual Design section, governed by system requirements SR-1.1 through SR-1.5. All instruments share a common interface architecture: each tool shall transmit time-tagged, georeferenced measurement data to the onboard computer subsystem in a format compatible

with SR-COMP requirements, shall support duty-cycled operation consistent with available power modes, and shall remain mechanically compatible with the standardized payload interface defined in SR-STRUCT. Calibration traceability is a cross-cutting requirement, every instrument shall support pre-flight calibration and shall preserve calibration metadata with associated measurement data to enable post-mission uncertainty propagation into the PRM (SR-1.3.3, SR-6.4.1).

Confirmed instrument power allocations from the preliminary power requirements establish the following maximum average draws: LPR at ≤ 8 W (LPR-001), AGA at ≤ 5 W (AGA-001), APXS at ≤ 6 W (APXS-001), Fluxgate Magnetometer at ≤ 3 W (FGM-001), MSI Camera at ≤ 6 W (MSIC-001), ESA at ≤ 8 W (ESA-001), and NPD at ≤ 8 W (NPD-001). Combined peak instrument power draw from the defined suite is a key driver of the EPS design, and all instruments are required to support duty-cycled operation to remain within available power margins (SR-EPS.6).

B. Electrical Power Subsystem

The Electrical Power Subsystem (EPS) is governed by requirements SR-EPS.1 through SR-EPS.10 and the preliminary power requirements PWR-01 through PWR-09. Aurora operates on a $28 \pm 5\%$ V DC power bus, compatible with the Griffin lander's Standard Electrical Connector (SEC) specification (PWR-01, SYS-16). While attached to Griffin, the system draws a maximum of 200 W during nominal pre-deployment operations (PWR-02). Following egress, Aurora is fully self-powered, with all mobility, science, and communications power supplied by onboard solar arrays and battery storage (PWR-03, SYS-1a).

The onboard energy storage system shall be sized to support a minimum of one full traverse sortie and science measurement sequence without recharging (PWR-04), ensuring that Aurora can complete meaningful science operations between each return to Griffin for recharge. The EPS shall implement autonomous power management to monitor state of charge and safe non-critical systems before power depletion occurs (PWR-07), and shall provide load prioritization and shedding to preserve mission-critical functions, command, timing, and data storage, under power-limited conditions (SR-EPS.5). High-instantaneous-power events such as mobility and drilling actuation shall be supplied from onboard

energy storage rather than drawing directly from the power bus (PWR-09, SYS-1g), protecting both the battery system and the Griffin lander's circuits from transient overloads.

C. Communications Subsystem

The Communications Subsystem is governed by SR-COMM.1 through SR-COMM.11. Aurora's primary communications link is a short-range relay to the Griffin lander, which serves as the primary uplink and downlink node to Earth via its approximately 60 Mbps relay capability (AC-5). Aurora's onboard DWM3000EVB transceiver system, validated in the prototype, provides the short-range bidirectional data link between Aurora and Griffin during both surface operations and recharge cycles (SR-COMM.1, SR-COMM.6).

The communications subsystem shall support prioritized data transmission, ensuring that mission-critical health telemetry and high-value science map products are downlinked before lower-priority raw data (SR-COMM.3). Error detection and retransmission mechanisms including cyclic redundancy checks (CRC) and automatic repeat request (ARQ) protocols shall be implemented to ensure data integrity across the relay link, preventing corrupted data from entering PRM workflows (SR-COMM.9). The system shall retain all mission-critical data during communication outages without data loss (SR-COMM.4), with non-volatile onboard storage managed by the computer subsystem providing the buffer during extended outage periods. All downlinked data products shall carry time tags, georeference coordinates, and associated metadata to enable correct reconstruction of mapped products at mission control (SR-COMM.5).

D. Computer and Command & Data Handling

The Computer and Command & Data Handling (C&DH) subsystem is governed by SR-COMP.1 through SR-COMP.15. Aurora's onboard flight software is implemented using NASA's Core Flight System (cFS) architecture, with mission-specific logic implemented as configurable cFS application-level services rather than modifications to core cFS services (SR-COMP.14, SR-COMP.15). This approach preserves software heritage, reduces regression risk, and directly supports Aurora's modularity philosophy by enabling future payload additions without restructuring core software.

The C&DH subsystem acquires, time-tags, and stores all science and housekeeping data generated by onboard instruments (SR-COMP.2), and supports processing of data products from raw Level 0 through processed and fused Level 3 as applicable (SR-COMP.3). The processing split between onboard and ground processing is flexible, computationally intensive fusion operations may be performed at mission control rather than onboard, reducing the processing demand on the flight computer while preserving the complete raw data archive for ground reprocessing as models and algorithms evolve (SR-1.3.1, SR-1.3.2). The system implements Fault Detection, Isolation, and Recovery (FDIR) sufficient to preserve command, timing, and data storage functions autonomously following upsets or faults (SR-COMP.12), and shall quarantine or flag data products that fail integrity checks to prevent corrupted data from propagating into PRM outputs (SR-COMP.6).

E. Guidance, Navigation, and Control

The Guidance, Navigation, and Control (GNC) subsystem is governed by SR-GNC.1 through SR-GNC.11. Aurora's GNC provides the position and attitude estimates required to georeference all science measurements, using Griffin as the primary navigation reference base station through the DWM3000EVB PNT system validated in the prototype (SR-GNC.1, SR-GNC.7). Navigation state updates shall be provided at a rate sufficient to prevent spatial smearing and misregistration of measurements during traverse (SR-GNC.4), and navigation uncertainty shall be estimated and reported with each position solution to enable uncertainty propagation into PRM resource estimates (SR-GNC.6).

Aurora's autonomous traverse capability, ground-commanded science stops with autonomous hazard avoidance between stops, is governed by SR-GNC and SYS-34, which require navigation and hazard avoidance sensors sufficient for safe autonomous surface repositioning. The GNC subsystem shall maintain bounded navigation error during temporary loss of Griffin communications updates (SR-GNC.5), ensuring that Aurora can continue safe autonomous traverse even during brief link outages. The system shall support coordinate frame transformations between Aurora's platform frame and Griffin's reference frame, ensuring consistent spatial alignment of all science data products (SR-GNC.7).

F. Structures

The structural subsystem is governed by SR-STRUCT.1 through SR-STRUCT.10 and the overall system constraints AC-1 and AC-2. Aurora's total payload mass shall not exceed 200 kg including all instruments and mounting hardware (AC-1, SYS-2), and the payload volume shall not exceed three-quarters of the available Griffin payload volume (AC-2, SYS-3). The structural subsystem shall maintain alignment of mission-critical interfaces within allowable tolerances across all operational conditions (SR-STRUCT.3) and shall provide standardized mechanical interfaces to support modular payload integration and subsystem replacement without redesign of the primary structure (SR-STRUCT.4).

Dust mitigation is a cross-cutting structural requirement. All critical mechanical joints and electrical interfaces shall be protected from direct regolith particle contact through their full range of motion (RR1), all external electrical interfaces shall be equipped with dust covers or sealable surfaces (RR3), and all optical lenses shall be protected by a covering or window (RR7). All external surfaces with risk of regolith contact shall use solid-film lubricants rather than oil or grease-based lubricants to prevent regolith binding in mechanical joints (RR2). The structural subsystem shall withstand expected Falcon Heavy launch vibration and shock environments without damage to mounted payloads or avionics (SR-STRUCT.6, SYS-5).

G. Thermal

The thermal subsystem is governed by SR-THERM.1 through SR-THERM.9. Aurora must survive and operate across lunar surface thermal environments ranging from -30°C to $+80^{\circ}\text{C}$ during nominal operations (SYS-4), with survival temperature management extending across the approximately 14-Earth-day lunar night period during which Griffin provides power for thermal survival. The thermal subsystem shall maintain all mission-critical components within their specified operational temperature limits during nominal operations and within survival limits during non-operational and safe modes (SR-THERM.1, SR-THERM.2).

Radiators shall be oriented vertically to prevent thermal degradation from insulator dust buildup (RR5), and the thermal subsystem shall protect standardized mechanical and electrical interfaces from thermal degradation due to the combined effects of

dust accumulation and thermal cycling (SR-THERM.8). The thermal subsystem shall operate within the power budget allocated to thermal control (SR-THERM.6), with heater power representing a significant driver of the EPS design particularly during the lunar night survival period. Verification of thermal compliance shall be conducted through analysis and thermal-vacuum (TVAC) testing prior to mission deployment (SR-THERM.9).

Risk Analysis

Aurora's risk analysis was conducted using a standard likelihood-consequence matrix, with risks categorized across five likelihood levels (Most Likely to Least Likely) and five consequence levels (Negligible to Severe). Thirteen risks were identified and assessed across the mission's current development phase. Risks are designated R-1 through R-13 and are summarized in the Table III risk matrix below, followed by detailed treatment of the highest-priority risks and their mitigation strategies.

Table III: Risk Matrix

Risk ID	Description	Likelihood	Consequence
R-1	Inadequate spatial resolution prevents PRM-quality estimation	Possible	Severe
R-2	Insufficient power margin during peak science operations	Possible	Significant
R-3	Data loss during comm outages or radiation events	Unlikely	Severe
R-4	Griffin lander interface incompatibility	Unlikely	Severe
R-5	Thermal excursions during lunar night degrade instruments	Possible	Significant
R-6	Radiation-induced data corruption	Unlikely	Significant

Risk ID	Description	Likelihood	Consequence
	impacts PRM outputs		
R-7	Excessive TBD/TBR values delay requirement closure	Likely	Moderate
R-8	GNC accuracy insufficient for geolocation fidelity	Unlikely	Minor
R-9	Data processing architecture insufficient for multi-sensor fusion	Unlikely	Significant
R-10	Launch vehicle failure	Least Likely	Severe
R-11	Structural failure of the lunar surveyor	Unlikely	Significant
R-12	Physical failure of sensing instruments — chronic	Least Likely	Significant
R-13	Physical failure of sensing instruments — momentary	Likely	Minor

Risk Matrix	Negligible	Minor	Moderate	Significant	Severe
Most Likely					
Likely			R-7		
Possible		R-13		R-2, R-5	R-1
Unlikely		R-8		R-6, R-9, R-11	R-3, R-4
Least Likely				R-12	R-10

Fig. 8: Risk Matrix displaying risk in a stop-light configuration in accordance with Table III.

B. High-Priority Risk Treatment

R-1: Inadequate Spatial Resolution for PRM-Quality Resource Estimation

R-1 is assessed as the highest-consequence active program risk, rated Possible likelihood and Severe consequence. The core challenge is that a minimum spatial resolution threshold for PRM-quality He-3 resource estimation has not yet been formally defined, reflecting the broader state of the field, no prior surface mission has produced the direct ground-truth measurements against which such a threshold could be empirically calibrated.

Aurora's mitigation strategy for R-1 is architecturally embedded rather than externally imposed. The ADP-QMS system, which provides direct in-situ mass spectrometric detection of He-3 in extracted borehole core material, serves a dual function: primary He-3 detection and in-situ calibration of the spatial resource model. By correlating direct ADP-QMS He-3 measurements at borehole sites with the proxy indicator outputs of the surrounding multimodal sensor suite, Aurora will empirically develop the correlation coefficients needed to define and validate a spatial resolution threshold during the mission itself. This approach transforms R-1 from a pre-mission design requirement gap into an in-mission science objective, progressively building PRM confidence as the survey accumulates correlated data points. The 50% PRM recoverability confidence threshold defined in MS-1 is therefore treated as a floor that the correlation-driven methodology is designed to meet or exceed as the dataset grows across multiple traverse sorties and lunar days. Residual risk after mitigation remains moderate, the ADP-QMS system is currently at low TRL, and its successful development is a prerequisite for the R-1 mitigation strategy to function as intended.

R-2: Insufficient Power Margin During Peak Science Operations

R-2 is rated Possible likelihood and Significant consequence. Peak science operations, in which multiple instruments operate simultaneously during a science stop, including the ADP drilling system, FMAG borehole magnetometry, APXS contact analysis, and LPR scanning, represent the highest instantaneous power demand in Aurora's operational profile. The combined average power draw of the confirmed instrument suite approaches the upper bounds of the EPS design allocation, leaving limited

margin for simultaneous multi-instrument operation without careful duty-cycle management.

Likelihood reduction is achieved through conservative EPS sizing during the preliminary design phase, with instrument duty cycles explicitly scheduled to prevent simultaneous peak power events where possible. Consequence reduction is achieved through the EPS load prioritization and shedding architecture defined in SR-EPS.5, which preserves mission-critical functions — command, data storage, and communications — under power-limited conditions by autonomously shedding lower-priority instrument loads. The residual risk after mitigation is a reduced science data rate during power-constrained periods rather than a mission-ending failure.

R-3: Data Loss During Communications Outages or Radiation Events

R-3 is rated Unlikely likelihood and Severe consequence. Data loss represents a severe consequence because Aurora's PRM output is directly dependent on the completeness and integrity of the science data archive, gaps in the dataset reduce confidence intervals and may prevent PRM qualification at the 50% recoverability threshold. Two independent failure mechanisms contribute to R-3: extended communications outages that prevent timely downlink, and radiation-induced single-event upsets that corrupt stored data before transmission.

Mitigation against communications outage data loss is provided by Aurora's non-volatile onboard storage architecture, which buffers the complete science data archive during outage periods, and by the Store-and-Forward data lifecycle managed through the NASA cFS CFDP application, which guarantees data integrity and automated retransmission following link restoration (SR-COMM.4, SR-COMP.4). Mitigation against radiation-induced corruption is provided by CRC-based error detection on all stored and transmitted data products, with corrupted data quarantined and flagged before it can propagate into PRM workflows (SR-RAD.4, SR-COMP.5, SR-COMP.6). Residual risk after mitigation is a requirement to re-scan critically affected data areas if corruption is detected and retransmission is insufficient, this may consume available mission time and is noted as the primary residual consequence.

R-4: Griffin Lander Interface Incompatibility

R-4 is rated Unlikely likelihood and Severe consequence. Interface incompatibility between Aurora and the Griffin lander — in mechanical mounting dimensions, electrical connector standards, power delivery parameters, or data protocol specifications — could delay or prevent mission integration, with severe schedule and cost consequences. The mitigation strategy is the early development and maintenance of a comprehensive Interface Control Document (ICD) governing all Aurora-Griffin interfaces, designed to be compatible with Astrobotic's published Griffin lander payload user guide from the outset of detailed design. Early ICD definition reduces the likelihood of discovering incompatibilities late in the integration process, and manual operational constraints represent the residual mitigation if minor interface discrepancies are identified during integration testing.

R-5: Thermal Excursions During Lunar Night

R-5 is rated Possible likelihood and Significant consequence. The approximately 14-Earth-day lunar night imposes extreme cold temperatures that can degrade or permanently damage instrument electronics and optical components if thermal control systems are insufficient. Aurora's primary mitigation is the Griffin lander homebase architecture — during lunar night, Aurora docks with Griffin and draws power for active thermal survival rather than relying on passive thermal design alone, significantly reducing the thermal management burden on Aurora's onboard systems. Passive thermal design including vertical radiator orientation (RR5), solid-film lubrication of mechanical joints (RR2), and positive internal pressure fan systems (RR4) provide secondary mitigation during surface operations. Verification through TVAC testing prior to mission deployment (SR-THERM.9) provides the primary evidence of thermal compliance. Residual risk is a reduced operational timeline if thermal margins are found to be tighter than analysis predicts during TVAC testing.

R-7: Excessive TBD/TBR Values Delaying Requirement Closure

R-7 is rated Likely likelihood and Moderate consequence and represents the highest-likelihood active program risk in the current development phase. A significant number of system requirements across the instrument suite, EPS, structural, and GNC subsystems currently carry TBD or TBR designations for key threshold values including spatial resolution,

coverage area, instrument integration times, and power margins. This reflects the current conceptual design phase status of the program, many of these values are appropriately deferred pending trade study completion and instrument selection confirmation. However, unclosed TBD/TBR values that persist into the Preliminary Design Review represent a program risk, as they prevent definitive verification planning and may expose design incompatibilities that require late-stage redesign.

The mitigation strategy is a phased TBD/TBR closure plan tied to sensitivity-based prioritization, requirements whose threshold values most strongly drive the system design, particularly spatial resolution (MSC-1.2), coverage area (SR-1.2.1), and power margin (SR-EPS.2, SR-EPS.3), are identified as highest-closure priority and targeted for resolution through trade studies and instrument specification confirmation prior to the Preliminary Design Review. It is acknowledged that preparation for the prototype demonstration has constrained the team's bandwidth for requirement closure in the current phase. The closure plan will be reactivated following the final briefing, with trade study completion targeted to coincide with the transition into preliminary design.

R-9: Data Processing Architecture Insufficient for Multi-Sensor Fusion

R-9 is rated Unlikely likelihood and Significant consequence. Aurora's PRM relies on the fusion of multimodal sensor outputs, spectroscopic, radar, magnetometric, electrostatic, and mass spectrometric, into a coherent georeferenced resource model. The algorithms and methodologies for performing this fusion are currently under active research and development, with the current prototype focused on validating signal capture and relay rather than fusion. If the fusion methodology proves insufficient to combine these diverse data streams into a PRM-quality product, the mission's primary deliverable is at risk.

Mitigation is provided by the flexible processing architecture defined in SR-COMP.3, which permits computationally intensive fusion operations to be performed at mission control rather than onboard, allowing algorithm development and refinement to continue in parallel with and following the mission without requiring software changes to the flight system. The raw data archive maintained on Griffin's onboard storage ensures that even if the fusion

methodology is not fully mature at the time of data collection, the complete raw instrument dataset remains available for reprocessing as the methodology matures. This decoupling of data collection from fusion methodology maturation is a deliberate architectural decision that significantly reduces R-9's consequence from mission-ending to schedule-impacting.

C. Lower-Priority Risks

R-6 (radiation-induced data corruption) and R-11 (structural failure) are rated Unlikely likelihood with Significant consequence and are mitigated respectively by the CRC-based data integrity architecture and by structural compliance with Falcon Heavy launch vibration and shock requirements verified through analysis and test. R-8 (GNC geolocation accuracy) is rated Unlikely with Minor consequence and is mitigated by the Griffin base station PNT architecture which provides a fixed reference point for Aurora's navigation solution. R-10 (launch vehicle failure) is rated Least Likely with Severe consequence, as a program-level risk associated with the Falcon Heavy launch vehicle, it is outside Aurora's design control and is noted for completeness. R-12 and R-13 (chronic and momentary instrument failure) are mitigated by the multimodal redundancy of the instrument suite, no single instrument failure eliminates the mission's ability to produce a PRM, as multiple independent proxy indicators are available for both He-3 and H₂O characterization. Momentary data loss (R-13) is additionally mitigated by numerical estimation and filtering to patch gaps in the dataset where brief sensor outages occur.

Prototype & Technology Readiness

Aurora's development is organized across two tiers: a physical prototype currently under active validation, and a full-mission instrument suite at the conceptual design stage pending trade study completion and instrument selection at the Preliminary Design Review. The following table summarizes the current Technology Readiness Level of each system element, its validation status, and the next development milestone.

Table IV: Technology Readiness Levels

System Element	Current TRL	Status	Next Milestone
Aurora Prototype Rover	3-4	Physical prototype built and tested	MSFC testbed validation
Aurora Drilling Probe (ADP)	3	Auger tested at MSFC — borehole stability under investigation	Fine-grain simulant testing
DWM3000EVB PNT/Comms	3	Validated in prototype	Griffin relay simulation
Jetson Orin Nano C&DH	3-4	Processing and downlink validated	Multi-sensor data pipeline
Full Mission Instrument Suite	1-2	Conceptual — under trade study	Instrument selection at PDR
ADP-QMS Coupling	1-2	Conceptual — primary tech development challenge	Benchmark feasibility study
Multimodal Data Fusion Methodology	1-2	Research ongoing	Algorithm definition

Conclusion

Humanity's permanent presence on the lunar surface depends on knowing where the resources are. The Aurora Advanced Underground Resource Observation lunar surveyor represents a concrete, feasible, and architecturally mature answer to that foundational challenge, a mission concept that moves lunar resource characterization from the realm of orbital prediction into direct, ground-truth physical measurement.

This paper has presented Aurora's conceptual design, system architecture, and development status across a mission concept grounded in a single governing philosophy: build a modular, reusable platform that directly measures He-3 and H₂O resource indicators at the surface and subsurface, and do so in a way that generates a Probable Resource Model of sufficient confidence to support both NASA infrastructure planning and commercial extraction investment. The mission's alignment with NASA's Artemis architecture is not incidental, Aurora is designed from the outset to be the prospecting mission that Artemis IV's ISRU infrastructure planning requires, filling the critical data gap that existing orbital and predictive models cannot close.

Aurora's innovation lies not in any single instrument or technology, but in the integration of a multimodal sensing architecture with direct subsurface access through the Aurora Drilling Probe, culminating in the ADP-QMS coupling that provides the highest-confidence He-3 detection capability of any proposed lunar surface mission concept. By combining surface spectroscopy, ground penetrating radar, magnetometry, electrostatic and neutral particle sensing, and direct borehole mass spectrometry into a single modular platform deployed from the established Astrobotic Griffin-Falcon Heavy architecture, Aurora produces a three-dimensional Probable Resource Model that serves both NASA mission planners and commercial partners such as Interlune evaluating the economic feasibility of lunar He-3 extraction.

The development journey from concept to prototype has validated the foundational elements of Aurora's architecture. The physical prototype has demonstrated auger drilling, multimodal signal capture, PNT and communications relay through the DWM3000EVB transceiver system, and end-to-end data handling through the Jetson Orin Nano computing platform. Testing at the NASA Marshall Space Flight

Center lunar regolith testbed has produced the mission's first ground-truth engineering data, identifying the borehole stability characteristics of the ADP in coarse basaltic simulant and establishing the next research objectives for fine-grain regolith testing. The full-mission instrument suite, the ADP-QMS coupling, and the multimodal data fusion methodology represent the primary technology development challenges ahead, all assessed as achievable within the mission's development roadmap with focused

investment in the highest-priority TRL advancement activities.

Aurora does not merely map the Moon. It builds the foundation upon which the lunar economy will be constructed, providing the resource intelligence that transforms speculative extraction concepts into investment-grade infrastructure decisions, for NASA, for commercial partners, and for the broader human future beyond Earth. As the Artemis program advances toward crewed lunar landings and sustained surface operations, the data Aurora will generate is not optional, it is the prerequisite. The Orbital Gators team at the University of Florida is committed to advancing this mission concept through the next phases of development, and to delivering the prospecting dataset that humanity's permanent return to the Moon will require.

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