

An Ejectable Data Recorder Subsystem for the Ascent Abort-2 Test Flight of the Orion Launch Abort System

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Abstract—The Ejectable Data Record (EDR) subsystem was a unique development opportunity at NASA with challenges that necessitated innovation. EDR employed a “skunkworks” development approach in which we designed, built, and delivered 47 end items, not including ground support equipment. We used as many COTS components as possible, we looked for process efficiencies to meet our tight deadlines, and the EDR team was involved in the flight operations of the AA-2 test flight and responsible for the recovery operations of the ejected payloads. This paper will discuss the design and development of the EDR subsystem, as well as the results of the system performance during the AA-2 test flight.

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1. INTRODUCTION

NASA’s Artemis mission [1] is dedicated to putting the first woman and next man on the surface of the Moon by 2024. With this mission, NASA will explore more of the Moon’s

surface than ever before and the lessons learned from this mission will enable NASA to push the boundaries of human technology farther by going to Mars.

To enable the Artemis mission, NASA is developing four main vehicles. The Space Launch System (SLS) will launch humans and cargo into space. The Orion spacecraft will ferry humans from Earth to Lunar orbit. The crew will dock at Gateway, positioned between the Earth and the Moon. There they will live and work, with frequent expeditions to the surface of the Moon with the Human Landing System (HLS).

The Orion spacecraft [2] is a key piece of this architecture. Not only is it the vehicle that will carry the crew into space, but it also provides emergency abort capability, supports the crew on their journey to the Moon, and provides a safe trip back to the surface of the Earth when the crew’s expedition is complete.

One important aspect of this spacecraft is the ability to abort during launch ascent in the event that the booster encounters a problem. This feature is the Launch Abort System (LAS). The LAS is a rocket-powered tower on top of the crew module that will quickly, and safely, maneuver the crew module away from the booster, in the event of a launch issue.

As part of the development of the LAS, there were two main tests. The first was Pad Abort 1 (PA-1) that successfully completed on May 6, 2010. The second was the Ascent Abort 2 (AA-2) test flight that successfully completed on July 2, 2019 [3]. This paper will discuss the design and development of an ejectable data recorder that collected data from all the instrumentation on the crew module used for the AA-2 test flight.

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2. BACKGROUND

The Ascent Abort-2 Test flight was the fourth test in the Orion flight test program. The purpose of the test was to perform an ascent abort with the LAS under flight-like, high dynamic pressure conditions. The primary objective of the test was to demonstrate that the LAS would effectively maneuver the Crew Module (CM) away from the booster and jettison from the CM (See Figure 1). A secondary objective of the test was to collect flight test data, which NASA will use in the future to certify the Orion vehicle for use on crewed missions.

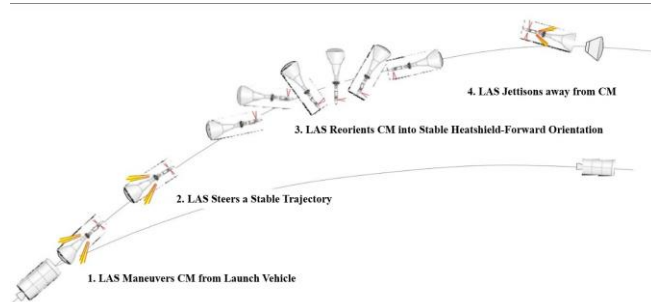


Figure 1: AA-2 Flight Test Profile

The flight test vehicle for AA-2 consisted of the LAS, the CM, the separation ring (SR), and the abort test booster. Initially, the CM contained the avionics, power, guidance, navigation, and control (GNC), flight software (FSW), developmental flight instrumentation (DFI), communications antennae, and pyrotechnics to run the flight test. Management for the crew module and separation ring (CSR) added the ejectable data recorder (EDR) subsystem to the CM due to a risk in the communication design about one year after design work on the AA-2 crew module had already begun.

In the original concept of operations, the primary method of obtaining the flight data from the instrumentation was to use a single string antenna network situated on the LAS. However, there would be data dropouts during abort from the booster and LAS jettison. Furthermore, the CSR team expected the CM to tumble after LAS-jettison, which would lead to further loss of data and the risk that the CSR team would not capture the mission critical data. To mitigate this risk, the DFI and communications team performed a trade study, which resulted in the addition of antennae on the CM, an onboard buffer and rebroadcast through the communications system after LAS jettison, as well as the addition of the EDR subsystem. By including the EDR subsystem, onboard recorders would capture all the test flight data during the test and jettison those recorders at the conclusion of the test flight, ensuring there would be no gaps in the flight data.

3. EDR SUBSYSTEM OVERVIEW

The EDR subsystem consists of a recorder system and an ejection system. There are two strings of each for redundancy, as shown in Figure 2.

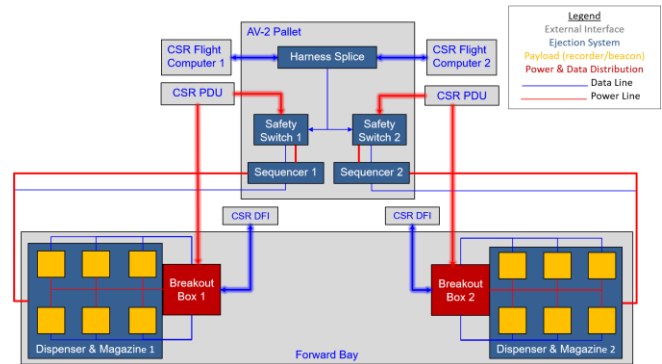


Figure 2: EDR Subsystem Block Diagram

Recorder System

The recorder system consists of a break out box and payloads. The breakout box receives and routes power and data to six EDR computers located inside the breakout box. There is one separate computer for each payload. The breakout box receives all the instrumentation data from the DFI system. The EDR computer then writes that DFI data to the memory card, which is located in the payload. The EDR computer also sends health and status information back to DFI about the recorder system. Furthermore, the breakout box provides a pass through for charging the payload batteries prior to launch.

The payloads store the data provided by the breakout box in a memory card and contain a beacon for recovery purposes. The payload beacon receives GPS coordinates and transmits them to a satellite network. Syntactic foam was also used to protect the electronic components within the payload and to provide buoyancy. To aid in the recovery efforts, the payloads were painted a neon orange color so that they would be visible when floating in the ocean. Two designs of the payloads were used during the test flight: the F-Series and the P-Series. Each dispenser had a mixture of the F-series and P-Series payloads. The payloads and breakout box were designed and developed in-house using a mixture of custom designed and COTS components, with an emphasis on using as many COTS components as possible. The recording software was an in-house design as well.

Ejection System

The ejection system consists of a safety switch, a sequencer, and a dispenser. The safety switch interrupts power to the sequencer to prevent inadvertent firing of a payload. The sequencer generates and routes firing power to a specific

location in the dispenser via commands from the flight computer. The dispenser carries and indicates when the magazine is present and transfers the information to the sequencer. Each magazine houses six cartridges, each containing a payload. The dispenser transmits the firing signals from the sequencer to the pyro device in each cartridge, thus ejecting the payload. The sequencer also provides health and status information back to the flight computer. The ejection system is all COTS hardware, with significant military heritage, and some in-house modification. The ejection system software is an in-house design.

Interfaces

The EDR subsystem interfaces with many CSR subsystems as shown in Figure 3. The recorder and ejection systems were located on the main power bus of the CM power. Many of the EDR subsystem components were housed in the forward bay of the CM, whereas the sequencer and safety switch were located on an isolated pallet in the CM habitable volume. Due to the locations of the EDR hardware, there was significant harnessing that spanned from the isolated pallets in the CM habitable volume through to the forward bay of the CM. The ejection system received commands from the main flight computer (CSR Avionics) and provided ejection system health and status back to the flight computer. Similarly, the recording system received data from the DFI system and provided recording health and status back to DFI. Finally, the software subsystem supported the development of the custom ejection system software and the custom recording system software.

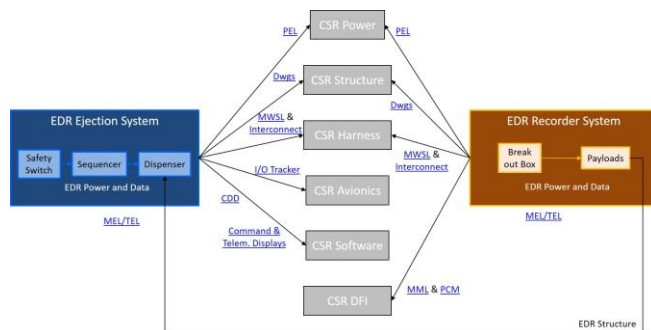


Figure 3: EDR Subsystem Context Diagram

Concept of Operations

The concept of operations for the EDR subsystem (Figure 4) is relatively simple. Given that the ejection system and recorder system are powered off the main bus of the CM, when the vehicle is turned on, both the ejection system and the recording system are initiated. The ejection system only provides minimal health and status information at this time. When the DFI system gets turned on, data begins flowing to

the EDR recording system and the EDR computers immediately begin recording data to the memory cards. From this point forward, the recording system continues to record until the connection is severed when the payloads are ejected.

Even though the ejection system is on and providing health and status information, it is not able to perform an ejection because there are multiple inhibits in place for safety reasons. In the software, there are two flags that are enabled after certain key events occur in the mission timeline. The first is when the abort of the booster occurs and the second is when LAS jettison occurs. After these key events, the power needed for the pyrotechnics to eject is turned on within the CSR power distribution unit. One of our requirements was to collect all the data of the mission from launch through 20 seconds after LAS jettison. Thus, the software commands the first ejection at 20 seconds post-LAS jettison and two payloads are ejected at once, one from each dispenser. Ten seconds after each ejection, another set of payloads is ejected, for six ejections. Using this schema enabled us to collect an additional 50 seconds of data beyond the requirement, which was highly desired.

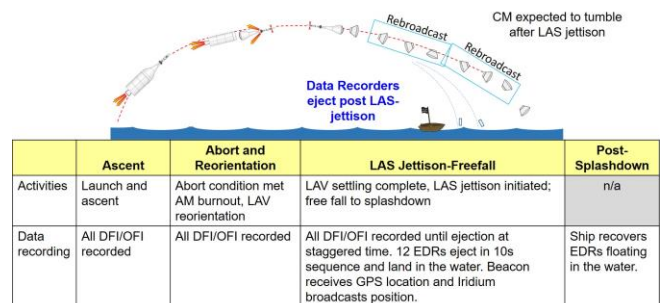


Figure 4: Concept of Operations for the data retrieval of the EDR subsystem.

As the payloads are ejected, the beacon is triggered to turn on and within five minutes, the beacon transmits GPS coordinates. The payloads land in the ocean and float until they are recovered. Once recovered, the payloads are washed of the salt water and brought back on land. Post-launch, the payloads are fully dried, the beacons are turned off, and the data is retrieved from the memory cards.

Key Requirements

Six key requirements were assigned to the EDR subsystem to successfully recover the data from the AA-2 test flight.

1. The data recorders shall capture all data in the DFI/OFI PCM data stream at a rate of 20 Mbps during all mission phases, starting with launch and ending with data recorder ejections.
2. The ejection system shall eject the data recorders on command from the CSR flight computer.

3. The data recorders shall be positively buoyant in salt water.
4. The data recorders shall provide active location signals for 14 hours after test flight to permit a very high likelihood of recovery.
5. The data from the data recorders shall be retrievable after ejection and immersion in salt water.
6. The EDR subsystem shall survive all applicable loads identified in the ERD [Environments Requirement Document], combined in an event-consistent manner.

The first key requirement was important for our system to meet because the DFI data rate was 20 Mbps and we did not want to miss any data in our recording. This requirement was successfully verified during acceptance testing of the hardware in our CSR Avionics and Software Testing Laboratory Environment (CASTLE).

In developing this subsystem, we attempted to keep everything as simple as possible, but also autonomous. A key function to this system was to eject the payloads so that they could be recoverable. Thus, the second key requirement was important to meet this function in the simplest way possible. It was verified via acceptance testing in CASTLE with the ejection system, as well as through a full ejection test in which we exercised the ejection system with live pyrotechnics.

Given that this test flight occurred over the ocean and that we needed to successfully retrieve the payloads, it was imperative that the payloads floated. Therefore, the third key requirement ensures that the payloads float upright and in such a manner that they are visible from a boat when floating in the ocean. This requirement was verified for each payload as part of its assembly process. Once the payloads were assembled, they were inserted into a bucket of salt water to verify positive floatation and to be balanced appropriately.

To be successful, we needed to ensure that we had enough opportunity to retrieve the payloads, given many possible situations on launch day. If, for example, the test flight launched on time, but then a storm arrived before or during recovery operations could commence, we wanted to ensure that the beacons would continue to operate so that we could track the payloads throughout the day and still recover them before nightfall. Ensuring that the design could withstand beacon transmissions every five minutes, over fourteen hours, was the fourth key requirement to encompassing all possible scenarios during recovery operations. This requirement was verified with multiple long duration beacon tests. In the first case, an engineering unit payload was left outside with the beacon transmitting GPS coordinates every five minutes for a total of 20 hours. After this verification was completed, there were design changes associated with the switchboard that triggered the beacon to turn on. Thus,

another verification occurred with qualification units after a full ejection test, in which the beacons turned on with the ejection and then transmitted GPS coordinates for 14 hours after the ejection test was complete.

Given the concept of operations for the payloads, they must survive the vibration and abort during launch, LAS-jettison, the ejection after LAS-jettison, the impact of landing in the ocean, and the salt water environment for the duration of the recovery operation. After all that exposure, we still need to ensure that we can retrieve all of the data off the memory card without issue. Thus, the fifth key requirement focuses on ensuring that the hardware used to store the data and the interface by which the data is retrieved does not get damaged during the flight and recovery. This requirement was verified piecemeal with a live ejection test and a drop test. For the ejection test, qualification payloads were ejected using engineering unit ejection hardware and then the payloads were left in a bucket of salt water for 14 hours. For the drop test, qualification payloads were dropped from an altitude of 5,000 ft into the ocean and recovered via the same means planned for launch day.

The sixth key requirement was a complex one in that involved all the environments the subsystem would encounter (i.e. vibration, acceleration, shock, and acoustics). These environments were quite intense and thus it was important to ensure the subsystem could perform its functions successfully while simultaneously contending with these environments. This requirement was verified via multiple stress analyses, vibration tests, acoustic tests, ejection tests, and drop tests.

4. BREAKOUT BOX

The Breakout Box (BOB) has two main functions. The primary function is to receive the DFI data and write data at 20Mbps to six payloads during all required phases of flight. The secondary function of the BOB is to serve as a passive feedthrough for payload battery charging.

Breakout Box Design

The Breakout Box is powered by 28VDC from the CM Power Distribution Unit. This 28VDC is delivered to an internal DC – DC Converter Power Board that produces eight channels of output power. The eight channels of output power are used to power the clock splitter, data splitter, and the six Field Programmable Gate Array (FPGA)/Raspberry Pi 3 Model B pairs. These design details can be seen in the block diagram of Figure 5.

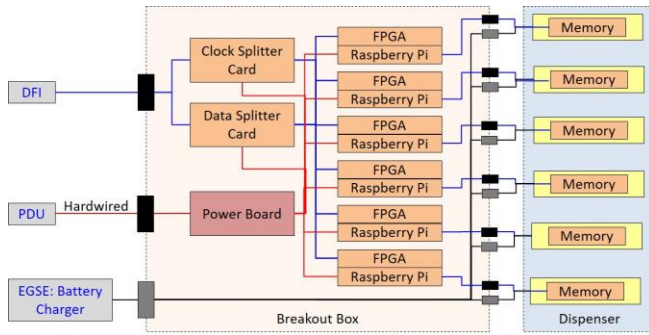


Figure 5: Block diagram of the Breakout Box and its external interfaces.

In the original design, the BOB only contained the power and data splitting, where as the Raspberry Pi was intended to be embedded within the payload. However, the Raspberry Pi alone was unable to handle the required data throughput of 20 Mbps. Thus, the FPGA was added to the design to support that requirement and stacked with the Raspberry Pi. The FPGA/Pi stack was larger than the payload packaging could withstand and thus this computing element was then housed in the BOB.

The recording software had the primary objective of ensuring that the DFI data was robustly and properly recorded over the required phases of flight. A secondary objective was to provide a system status, as much as possible, so that a decision about the recording status could be made in the control room. It was understood that at a certain point the payloads would be installed for a final time and that their removal would no longer be possible before flight. The data on the payloads could only be reviewed after the removal of a payload from the system. The control room did have a payload USB mount status, which provided indication of whether a drive was mounted appropriately. A positive indication that a drive was mounted was a significant indication that data would successfully be recorded, based on all prior testing. Similar to a flight data recorder, the new data would need to overwrite the prior data given a finite limit on storage capacity. Thus, the entire set of flight data had to be capable of being recorded within the allowable data storage limit of the payload USB, as well as a methodology for determining the beginning and end of the flight data of interest.

The design intent of the Breakout Box was to be cost effective and design efficient. In order to achieve this, we focused on using COTS items and designs already in use. The cost effective computational power of the Raspberry Pi 3 Model B made it a great solution for producing the USB protocol required for writing data to the payloads. The Clock and Data Splitters were based on an existing in-house design.

Breakout Box Testing

The BOB production design was primarily validated during the engineering unit phase. Therefore, the objective to ensure

a quality flight build, was to reduce the risk of a failure at the integration level by performing intelligent tests intermediate to integration. An individual test of the power splitter boards was performed on each board. There was also a functionality test performed on each FPGA/Pi stack to screen out any failures. The result was that at the integration level, each BOB performed per its design requirements and no re-work was required. The BOBs were then put through thermal and vibration acceptance testing, as an integrated system, to ensure that there were no latent failures and that they were performing in accordance with their intended design.

Lessons Learned

The testing at intermediate levels of build resulted in a one hundred percent throughput yield on all three flight BOBs at the integration level, which was an exciting result given the complexity of build. Thus, future projects of this type should consider the importance of intermediate testing to mitigate assembly risks that could require rework.

Another lesson learned was to ensure that the software and hardware side of the design were in close communication. The two aspects go hand in hand and the more collaboration that exists, the better the design.

Finally, having the ability to know what data was recorded, the quantity of data, or something similar, without removal of the payloads, would have been invaluable. However, adding this level of detail to the health and status information received would have also increased the complexity.

5. EJECTION SYSTEM

The data recorders were dispensed from the CM using a modified version of a flare/chaff ejection system used on combat aircraft, namely the AN/ALE-47 Airborne Countermeasures Dispenser System (referenced to as ALE-47 from here on out). This system uses a pyrotechnic charge to energize the ejection of the flare/chaffs, which were deemed suitably close in mass and volume specifications to the mass and volume constraints achievable by the EDR design. The ALE-47 flare/chaffs are designed to self-activate upon ejection, with no electrical commanding necessary. Thus, the off-the-shelf version of the ALE-47 system does not include an electrical interface to the flare/chaffs themselves. In this system, the ejectable flare/chaffs (along with a gas sealing 'piston') are loaded into metal cartridges and retained by caps that are preloaded and crimped into place in a factory operation. Upon field installation, electrically actuated squibs (pyrotechnics) are loaded into the base of the cartridge and a set of prepared cartridges are loaded into the dispensing system such that upon receipt of the firing signal, the gas pressure of the squib pushes the piston to force the chaff/flare against the crimped cap and out of the cartridge. The pyrotechnic firing pulses are provided by a remote avionics unit that is an integral part of the ALE-47 system and receives ejection commands from the vehicle

flight control computer. The modular dispensing system can accommodate a varying number of different sized cartridges; in the case of the AA-2 EDR subsystem, we used the largest size cartridge which led to several unused squib channels.

Modifications to off-the-shelf hardware:

NASA AA-2 designers modified the ejection system to include eight electrical conduction paths to each payload, using a pair of phono jack style electrical connectors at the aft end of each payload. The unused squib channels provided the physical locations for these payload interface paths. One payload jack was used for charging the payload's three-cell battery, while the other was used to pass the flight data to the memory card storage device. One noteworthy finding is that the memory card storage device's ability to properly receive data was very sensitive to the order in which the four conductors (power, ground, signal +, and signal -) were configured on the in-line jack. Only when the signal + and signal - lines were separated by the ground conductor was the vehicle able to pass its data to the memory card storage device within each payload.

The vibroacoustic loads during the abort sequence of the AA-2 flight also necessitated modification to the ALE-47 system from its off-the-shelf design. The system was not rated for the high vibration environment of the abort regime, and required a mounting interface that included vibration isolators (Figure 6). Typically, the dispenser for an ALE-47 system includes only a structural interface near the muzzle of the dispenser, but in its use for AA-2 an additional set of structural fasteners engaged the breech end of the dispenser. This provided a non-cantilevered structural path to the isolation brackets, whose collective centroid was designed to be close to the center of gravity of the isolated mass in order to avoid cross-coupling of the vibration motion axes. Even though the AA-2 abort vibroacoustic environment was an order of magnitude more intense than the rating of the off-the-shelf ejection system, the provisions stated above allowed the modified system to pass qualification vibration testing to abort levels.

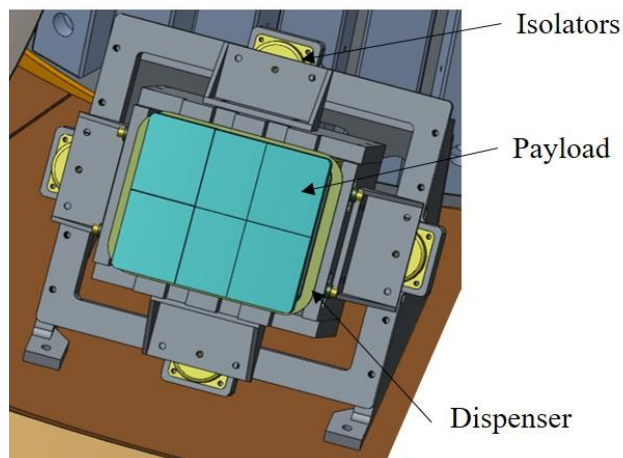


Figure 6: Dispenser isolator additions to accommodate the AA-2 vibroacoustic loads.

Selection trade-offs:

Although early development options for the EDR ejection system considered pneumatic and mechanical ejection systems, the modified ALE-47 was selected due to its heritage and availability. There were significant benefits, from a cost and schedule perspective, of using a system that required only partial modification, rather than a full in-house development. However, whenever using a COTS system, there will be some disadvantages in that the existing design may not conform to NASA best practices and will have to be accepted as-is. One example we encountered is that the ALE-47 system is designed such that the electrical return path for the pyrotechnic firing pulse is electrically bonded to the vehicle chassis, which is in violation of NASA protocol. This led to significant resources being used to satisfy that the system was still acceptable despite the violation.

Testing:

The EDR subsystem employed a strategy of development through iterative and incremental risk reduction testing to meet compressed schedule and tight budget constraints. The testing started with initial feasibility assessments and grew more integrated and complex with each iteration (Figure 7).

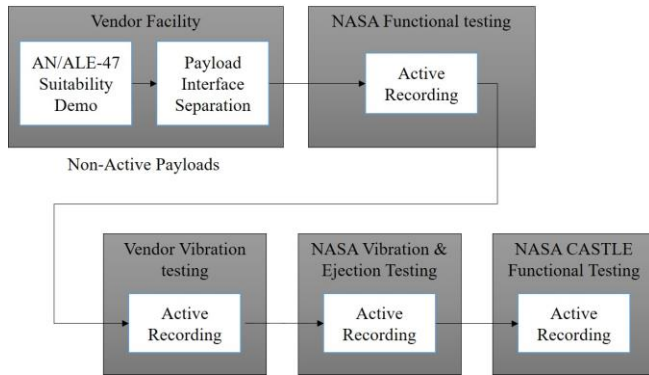


Figure 7: Ejection System Testing Flow.

In accordance with this strategy, ejection system testing commenced at the earliest stages of the project to demonstrate suitability of the ALE-47 system. To accomplish this test efficiently and cost effectively, we used an existing test unit at a vendor facility to eject inert mass and volume representatives of an EDR payload. With this testing, we needed to ensure that the ejection force was sufficient to overcome the crimp on the cartridge that held the payload inside, as well as propel the payload with enough velocity so that it would clear the CM upon ejection. We optically measured the ejection velocity and showed that the payloads would cleanly separate from the CM. We also used a force gauge measurement to show that the crimp of the cartridge exceeded what was necessary to hold the payload inside the cartridge so it would not prematurely eject during the acceleration and vibration environments of launch. Conducting this early testing validated using the existing ALE-47 COTS system, even though the environments at this stage were not fully defined. The payload separation interfaces at ejection are between the payload, the cartridge, and the dispenser. To demonstrate the feasibility of the EDR payload data and power connector separation concept required non-active development payloads and modified cartridges, along with the vendor's existing test unit. Performing these early feasibility demonstrations, focusing on the ejection system capabilities, allowed us to retire major design risks as early as possible.

Given that the ALE-47 system is a military COTS system, we were unable to perform significant stress analysis of the hardware. Furthermore, the vibro-acoustic environments of the AA-2 mission were substantially greater than the rated capabilities of the standard ALE-47 system. Therefore, vibration testing of the combined payload and dispenser system was also initiated early in the development process. Initial testing demonstrated that the dispenser and associated ALE-47 avionics components could survive the anticipated environment. This testing also showed that the crimped cartridges could retain the EDR payloads against the high vibration levels. Note that we learned in an early vibration test that properly preloaded cartridge crimping was critical to

payload retention. In that early test, a set of development payloads, loaded in cartridges, did self-eject during vibration testing due to improper crimping.

Next, testing focused on demonstration of data transmission integrity through the interfaces between the dispenser and the payload. Initial functional testing appeared to proceed successfully. However, when testing the recording capability during exposure to the vibration environment, we found issues with data integrity. The issue with data integrity was a twofold problem. The first issue was that the software tools we developed for evaluating data integrity had flaws. Once those defects were corrected, we then found that the phono plug data interface was corrupting the data. Troubleshooting of this issue, via dedicated transmission testing with the integrated system, revealed impedance issues with the proximity of the high frequency data signal paths in the phono connector, which inhibited the transmission of a clear signal. This issue was resolved by changing the pin order on the phono plug to physically separate the data signal paths.

With confidence established in the core functionality of the ejection system, we then performed vibration of the integrated ejection system with live pyrotechnic squibs to verify the squibs could also withstand the environment without firing during vibration and still eject appropriately after the exposure. This test culminated in live ejections of payloads. High-speed video evaluation of the ejection performance confirmed that the system performance remained adequate when used with the fully realized payload design.

Finally, a complete EDR ejection system was integrated into the AA-2 CASTLE test rig in order to demonstrate functionality of the ejection commanding and data recording interfaces with the flight vehicle systems. To verify the ejection system performance without having to perform live ejections, we developed a low-cost squib test set for end-to-end assessment of simulated ejection signals. This test set was constructed from used ejection system components, consumer grade lab instrumentation systems, and a laptop computer with a simple custom script capable of detailed signal evaluation of the squib firing pulses.

Findings and Lessons Learned:

The status of the ejectable data recorder subsystem as a latecomer to the mission architecture and as a backup subsystem allowed the design team to approach their objectives in an unconventional manner. Engineering design and development proceeded in the absence of a complete set of requirements, and in retrospect this resulted in design closure more rapidly than the typical approach of settling on final requirements first before initiating development. Because design is inherently an iterative process, in many cases it is advantageous to begin early with an incomplete set of requirements, relying only on engineering judgment to accommodate any requirement deficiencies. This allows

more time to see where the critical margins are and which parameters of the design are the most sensitive. These findings in turn inform the requirements of the system and result in faster convergence on a final solution.

6. PAYLOAD

The EDR payloads (Figure 8) are data recording devices and beacons that are connected to the DFI system through the breakout box and contained inside the ALE-47 dispenser during launch. The payloads have three main functions: store data from the flight test, survive the environmental conditions of the flight test, and transmit their coordinates for recovery. There were twelve payloads used for flight, consisting of two different flight designs: the F-series and P-series.

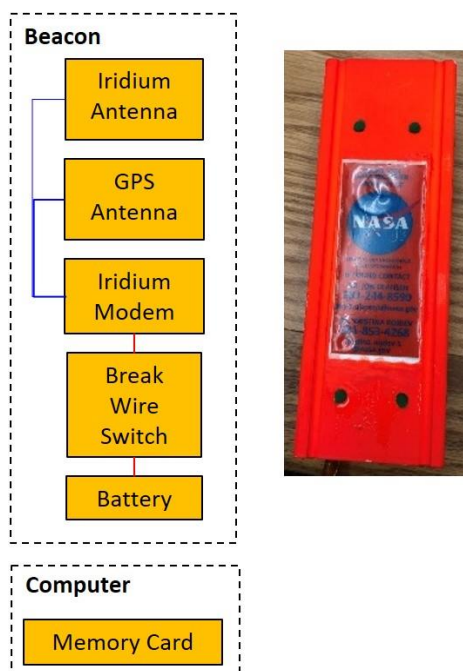


Figure 8: Payload block diagram (left) and flight payload image (right).

Payload Design

The EDR payload mass and volume were designed as drop-in substitutes for the typical decoy chaff/flares of the ALE-47 system. In order to survive the AA-2 flight environments, the ejection, and water impacts, as well as remaining afloat after impact, the payload structure was composed of a plastic shell completely filled with a syntactic foam composed of marine grade epoxy and glass micro balloons. The foam mix was designed to ensure buoyancy of the complete unit with sufficient stability necessary to achieve adequate antennae pointing. The fully potted nature of the foam ensured the survivability of the payload electronics. The plastic shell and

support structure was designed for low-cost fabrication using additive manufacturing techniques.

To enable quick and cost-effective development and assembly, the payloads incorporated multiple COTS items that were integrated and encased in syntactic foam. The internal COTS components included a USB memory card, an Iridium modem, a GPS antenna, an Iridium antenna, and a hobby Lithium Polymer battery. Internal harnessing and the switchboard that turned on the beacon were designed and fabricated in-house or contracted out. While the primary COTS components were uniform throughout all twelve payloads, there were fundamental differences in the electronic switchboards that would switch the system from a ‘stand-by’ state into a transmission state.

The system used two separate phono plug receptacles: one was tied to the battery for charging and battery monitoring, and the other was tied to the memory card for data storage. The switchboard was connected to the battery. While the payload was inside the dispenser and the phono plugs were connected, the beacon system stayed in a non-transmitting, standby state. This kept the battery from directly powering the modem until the payload was ejected.

The F-Series payloads were the culmination of multiple iterative designs developed over the course of the project. The switching mechanism was a novel design that used friction contacts between metal clips externally mounted to the payload and the metal cartridge case in which the payload was housed, as well as internally tied to the switching circuit. As the payloads were ejected from the cartridge, the contact was opened and would trigger a state change in the board to initiate antenna transmission. Once the beacon was switched on, it was latched in that state and would have to be reset via a special process to unlatch it and turn off the beacon. This latching feature was due to the concern of an open short occurring with the exposed phono receptacle contacts after the payloads splashed down in the ocean.

The P-Series payloads were a backup design to meet technical and schedule objectives of the EDR subsystem, given technical difficulties encountered with the F-Series development that required continued modifications. Given schedule constraints, the P-Series switchboard was proposed as a parallel design that removed the latching capability and significantly reduced design complexity, with the aim to supplement the primary F-Series in case of continued performance shortcoming. The P-Series payloads operated using a photo-resistor to control the state of the payload between the deployed (transmitting) and stored (charging) states. The photo-resistor had a low impedance when the photo-resistor was exposed to light (i.e. sunlight encountered once the payload was ejected), and a high impedance when the photo-resistor was absent of light (i.e. the payload was encased in the cartridge and in the dispenser). The sensitivity of the photo-resistor circuit was tuned such that beacon would be sensitive enough to stay in the “on” state while the photo-

resistor was occluded by the water, but not so sensitive that it would remain in the “on” state while in its cartridge. Given that the P-Series was a backup payload design, and was introduced later in the development process, the development of the P-Series payloads was highly expedited in order to meet the install date of the EDR system.

Payload Testing

Early development testing of the EDR payload concept focused on demonstrating feasibility of the fully potted syntactic foam concept. The primary risk of mechanical survivability against water impact loads was answered by dropping and recovering simulated payload shapes of representative foam construction, without any electronics, from sufficient altitude to ensure impact at greater than estimated terminal velocity. In subsequent testing, fully capable engineering unit payloads were dropped off-shore in the Gulf of Mexico using a NASA aircraft asset and recovered with a chartered off-shore vessel.

To ensure reliability of the flight payloads, the individual piece parts and assembled payloads underwent an exhaustive test program through all expected flight test environments. Prior to assembly, the USB memory card underwent an 11 hour burn in test, the beacon underwent a functional burn in test, and the battery underwent three rounds of charge and discharge cycles. The switchboard underwent several rounds of functional testing, as well as thermal cycling to find any defects in the boards. Once assembled, the payloads were subjected to multiple rounds of environmental testing to ensure that they would be able to survive the relatively short duration mission. To validate that the payloads maintained active data retention during the vibration profiles, the payloads were integrated with the dispenser and mounted to a vibration table. A data generator was used to mimic the DFI data stream to the breakout box, which was then connected to the payloads via the dispenser interface. By initiating data recording prior to vibration exposure, the team could use test time stamps to discern where, if any, dropouts in data retention were occurring and on which channel. This helped lead to a robust design that ultimately was successfully tested to levels higher than seen on the actual flight test.

Another component of the qualification testing was to validate that the payload was not damaged during the ejection process, where a pyrotechnic squib was used to eject the payload from its retention cartridge. There were two live ejection tests performed. In the first one, live data was recorded during vibration and then the payloads were ejected after the vibration was complete. In the second ejection test, live data was recorded during the ejection to verify there was no corruption to the data because of the severed interface during ejection. In both cases, after ejection, the team recovered the payloads and oriented them with the antennas facing towards the sky, so they could make satellite connections. Once we verified that the payloads were

transmitting their location, we left the payloads transmitting for 14 hours to verify the full beacon functionality.

Lessons Learned

Through rigorous environmental, qualification and functional testing, multiple lessons learned were gathered for future developments. The most overarching lesson was seemingly the most straight forward: Keep the design as simple as possible to meet requirements. One example, in retrospect, was the latching ability of the switchboard. While there was no specific requirement to add latching, there was an early assumption that without latching, the payload could short in the water. This decision was made early-on and without any developmental testing. The F-Series was designed to latch, which greatly increased the complexity and inherent failure modes possible with that payload build. In contrast, the P-Series did not have that latching mechanism and the overall complexity of the total system was greatly reduced.

Another lesson learned that stems from the notion of keeping the design simple is to protect the key functions of the design. Originally, the payload switchboard operated by detecting the presence of a USB connection when in the dispenser. Unfortunately, this design decision led to multiple unexplained failures of the USB memory card, which, if implemented in the final design, would have resulted in failure of the payload’s main function to record the data. After discovering this failure mode and understanding the root cause, we decided to divorce the USB and switchboard in order to protect the main function of recording the data. This was implemented on both F- and P-Series payloads and ensured virtually no errors in recorded data during final testing and day of launch.

7. RECOVERY OPERATIONS

The recovery operations were designed to ensure successful collection of all the payloads post-launch. The nominal operations assumed most of the beacons would function as intended, but contingency operations were also developed in the event that there were a number of non-operational beacons.

Recovery Strategy

The planned strategy used two boats for nominal recovery operations and a third boat for off-nominal situations during the recovery:

- If boat 1 or 2 had a problem, boat 3 would continue operation
- If there was a personnel health issue on one of the boats, boat 3 would continue operation while the person was taken to shore

- If position coordinates were not received by any of the payloads, boat 3 could support contingency operations

To ensure adequate data collection on ocean drift patterns for the contingency operations and to ensure all the boat assets were staged sufficiently outside of the keep out zones, recovery operations were planned to begin two hours prior to launch. Enroute to the staging location, one of the boats was to deploy two spare payloads near the projected splashdown location in order to collect ocean current heading and speed, which enabled recovery planning in the event that none of the flight payloads transmitted their location after jettison. Figure 9 below shows the keep out locations, boat staging areas, and the spare payload deploy point.

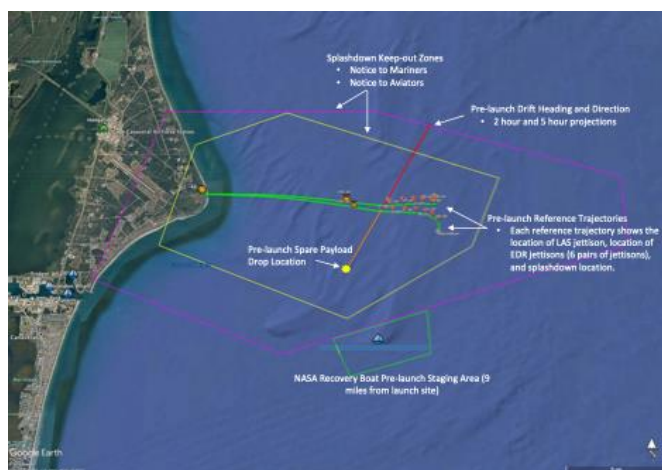


Figure 9: Pre-Launch Payload Drop Zone

The nominal payload recovery plan was to focus on retrieving payloads where location information was received. If we regularly received GPS coordinates on console from a specific payload (within 20 minutes), the beacon was considered a healthy beacon and high priority for retrieval. After those payloads with healthy beacons were recovered and the likelihood another beacon ping might not arrive, then the contingency procedures were enacted. These procedures consisted of the three boats performing a grid search pattern, led by the prime boat, and informing the console operators when payloads were recovered.

Suspension of recovery operations would have occurred due to bad weather (lightning, sea state), darkness (sunset), or the remaining payloads were not transmitting position coordinates and the grid search was not successful.

Console Operation and Beacon Tracking Software

The nominal recovery operations were directed from the mission control center through EDR console positions. One position was the primary recovery position and communicated with the boats, the test director, and weather. The other two console positions were dedicated to flight operations during the launch. The two flight console

positions were reconfigured to support recovery operations after splashdown. The console operators each had a copy of the beacon tracking software so that they could independently track the payload and boat locations.

The beacons of each payload contained a GPS-Iridium modem that automatically collected geolocation (latitude/longitude), timestamp (date & time), health status information (supply voltage) and payload identification information with a frequency of approximately five minutes. The actual data acquisition frequency, however, was dependent on GPS satellite availability and Iridium satellite network visibility within the payload's antenna horizon. Once a GPS lock was attained and the corresponding ancillary data was captured, the information was transmitted via the Iridium Short Burst Data (SBD) data package protocol through the Iridium satellite network, which immediately resulted in a system-generated email message. This email message was sent to the EDR console operators, and contained the aforementioned SBD data.

In order to establish and monitor the current locations of the EDR payloads in real-time, customized Python and Linux code was developed to autonomously parse the individual SBD data packets. The code was designed specifically to leverage off currently available open-source software tools, and therefore allowed for the direct interfacing with the Google Earth (GE) geospatial visualization software. Upon the arrival of an Iridium email message containing an SBD message, the software tools automatically extracted and parsed the geolocation, timestamp, system health and payload identification information in order to generate individualized xml KML files for use in GE. This approach allowed for automatically and simultaneously tracking and visualizing multiple EDR payloads in GE as a result of the updated KML data generated from the incoming Iridium messages. The resulting availability of real-time positional data that showed the locations, tracklines and status of all active payloads in GE was then used for directing and coordinating the boat recovery efforts for retrieving the EDRs (Figure 10). Additionally, all incoming SBD data was summarized and displayed in a customized color-coded tabular Python display that served as a "quick look" tool for determining overall payload performance and individual elapsed time of the last known location.



Figure 10: Payload locations, drift tracks, and predicted locations.

In addition to simultaneously displaying the current locations for all the payloads, the software was designed to autonomously generate predictions on where the payloads could be located at 5-minutes and 10-minutes in the future. These predictions were generated using the last two known payload locations and corresponding timestamps, since this information allowed for deriving dispersal velocities based on the elapsed time between each reported location and the distance between the reported locations, as well as the dispersal trajectories (i.e.: heading). When combined with an Earth sphere model, this information allowed for calculating the predicted latitude and longitude locations for each payload at any given point in time. Data collected before and after the AA-2 launch demonstrated high accuracy of the derived real-time prediction locations (approx. 38 meters).

8. SUBSYSTEM FLIGHT PERFORMANCE

Recording System Performance

The final installation of the payloads into the CM was on March 15, 2019. From that installation date through the flight test, the system recorded over 2800 minutes of data (> 430 GB) onto each payload drive. Per the design of the recording software, once the drive space was full, the data would wrap and overwrite old data. The only data of interest was the data associated with the flight test.

On the day of launch, all the payload drives mounted as intended and there were no anomalies noted on console. After recovery of the payloads, the EDR team retrieved the data from the payloads without any issues. We analyzed the data and found virtually identical recordings for the period from launch through LAS jettison. After LAS jettison, the ejection system ejected a pair of payloads every ten seconds, and thus the pair of payloads that ejected last had the most data on them. Of the twelve payloads, only one payload had a discrepancy with two minutes fewer data than its ejected pair. This payload connected to a channel in the breakout box with

a known recording issue at the time of launch. So, this outcome in the data was expected.

With the data from the sixth ejections, we retrieved a complete set of continuous data from prior to launch through 80 seconds post-LAS jettison. We were only required to retrieve data through 20 seconds post-LAS jettison, but were able to fulfill a desirement of the aerosciences community to gather an additional 50 seconds of data. If the project had not added the EDR subsystem, there would have been data loss during abort and LAS jettison, as well as a few small drops throughout the flight. Due to the quality of data recovered from the payloads, the EDR data became the primary source of data for the AA-2 test flight.

Ejection System Performance

On console, leading up to launch, there were no anomalies encountered. The ejection system ejected the payloads as expected and per the nominal sequence. However, in review of the data post-launch, we discovered an anomaly in the payload inventory information provided as part of the health and status data received from the ejection system. In the ejection software, there is a parameter called the software expected inventory, which starts at a value of six and then decrements by one each time the software commands the system to eject. In the sequencer health and status information, there is a parameter called sequencer inventory, which is health and status information provided to the computer by the ejection system. The sequencer inventory is the number of payloads the ejection system thinks it currently has in the dispenser. The anomaly occurred around the time of abort and when the booster was jettisoned. At this time, the sequencer inventory drops out and flickers between zero and six, which does not align with the software expected inventory. Fortunately, the ejection system software was written to use the software expected inventory and not the sequencer inventory. Thus, the ejection system properly ejected payloads at the appropriate time.

Recovery Operations Performance

Prior to launch, the EDR recovery team deployed two drift payloads in the drop zone so that we could gather information on the drift speed and direction in preparation for contingency operations in case the beacons did not operate as intended. The drift payloads were moving at 0.5 knot and a bearing of 65-75°.

After the payloads ejected, on average, we received information from the payload beacon within 9 minutes. However, since approximately four months had elapsed since the last time the beacons were powered on and connected to the GPS and Iridium constellations, we did not receive accurate GPS coordinates until approximately 40 mins after ejection, on average. That being said, we placed the recovery crew near the drop zone during the launch to enable efficient recovery of the payloads once the crew was cleared to enter the drop zone. In general, we recovered a payload every 4

minutes and recovered all twelve payloads within 52 minutes (Figure 11).



Figure 11: Successful recovery.

The ability to recover all the payloads was partly due to how closely packed the payloads were after ejection. Given the winds and launch parameters, the events of the launch occurred within a short area off the coast of Cape Canaveral with very little dispersion, as shown in Figure 12.

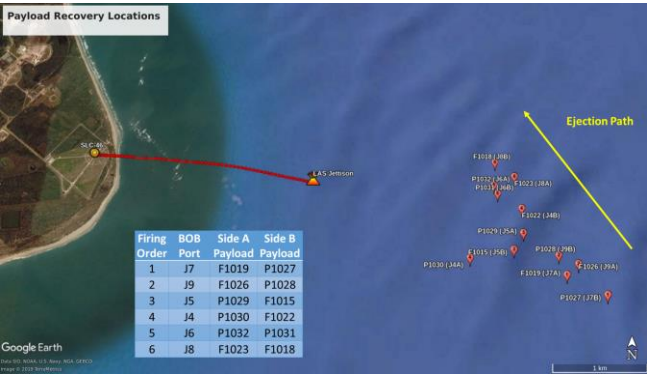


Figure 12: Locations of where the EDR team recovered each payload and the ejection path of the payloads.

Finally, with our drift payload speed and heading information, along with the LAS jettison location, we pre-planned a grid search area as part of our contingency operation. If we had need of the contingency operation, we would have most likely found all the payloads since their recovery locations fell within our pre-planned grid search area (Figure 13).



Figure 13: Pre-planned contingency grid search area shown by the red box. The pushpin icons show the payload recovery locations.

9. SUMMARY

In summary, the EDR subsystem hardware, software, and operations development was a tremendous amount of work in a short amount of time. Many lessons learned were gained throughout the course of the project, but a couple of overarching themes exist.

First, keep the design as simple as possible to meet the requirements. In our case, we inadvertently added in complexity due to a risk that we assumed would be an issue, rather than first testing to verify whether it actually was an issue. Along with that is the notion of protecting the key functions of the design and making those as simple as possible to meet the requirements.

Second, we focused on testing early on to trade and down select designs, as well as mitigate risks. In many cases, we performed risk-reduction testing without fully formed requirements or fully known environments. This enabled us to converge rapidly on a design in which we had confidence of success. Furthermore, we performed intermediate testing throughout the build to ensure no issues during assembly and reducing or eliminating the need for rework later on.

The unconventional processes we used and the ability to incorporate lessons learned quickly enabled us to develop a system that was fully successful on day of launch.

ACKNOWLEDGEMENTS

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BIOGRAPHY



Kristina Rojdev received a B.S. in Aerospace Engineering from the University of Michigan and a M.S. and Ph.D. in Astronautical Engineering from the University of Southern California. She has been with NASA for over 15 years working on deep space habitats, lunar landers, radiation effects of materials, and shielding of crew from deep space radiation. Her expertise lies in applied systems engineering and radiation research. On AA-2, she was initially part of the CSR systems engineering team and then the Ejectable Data Recorder subsystem lead. She is currently the systems engineering lead for the NASA Habitat & Logistics Outpost.



Rosa Obregon received a B.S. in Aerospace Engineering from the Massachusetts Institute of Technology and an M.B.A. from the University of Southern Mississippi. She has been with NASA for over 15 years primarily testing rocket engines for commercial companies. She is currently working on projects for the Orion program and supporting projects with commercial companies. On AA-2, she was part of the Ejectable Data Recorder systems engineering team.



David Petri received a B.S. in Aerospace Engineering from Purdue University, M.S. in Engineering Sciences from Stanford University and General Management Certificate from Harvard Business School. He has been with NASA for 30 years, working a variety of Program and Systems Engineering assignments including GN&C, Integration and Test, S&MA including Space Shuttle Return to Flight and Exploration Flight Test 1. David is currently the Integration and Test lead for the VIPER lunar rover mission. For AA-2, he worked

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Jeff Hagen received a B.S. in Mechanical Engineering and a M.M.S. in Mechanical Engineering from Rice University. He worked 10 years with Lockheed Martin supporting NASA JSC, followed by 15 years with NASA, working on design, development, and sustaining engineering of mechanical and structural systems for various human space flight programs including Space Shuttle, X-38, Orion, and conceptual entry and landing systems. On AA-2, he worked on the mechanical design of the ejection system and recoverable payloads. Jeff is currently working on advanced docking system development and Orion docking system oversight.



Eric Vineyard received a B.S. in Aerospace Engineering from Texas A&M University. He has been working as a NASA contractor for over 21 years supporting human rated space flight programs in the area of embedded flight software including Space Shuttle GN&C Flight Software, Orion Flight Software, and Common Communications for Visiting Vehicles Software. On AA-2, he was a member of the CSR software development team and the EDR software lead. He is currently working on the Gateway Vehicle Systems Manager Software.



Paolina Povolotskaya received a B.S. in Electrical Engineering from the University of Houston. She has been working as a contractor for NASA for over 7 years working on electrical design and testing of space flight hardware. She is currently working on projects for the Orion program and the Exploration Extravehicular Mobility Unit. For AA-2, she worked on the electrical design, assembly and testing of the Ejectable data Recorder.



Michael Grace received a B.S. in Mechanical Engineering from the Rutgers University. He has been working as a contractor for NASA for just over 1 year working on assembly and testing of space flight hardware. He is currently working on projects for the International Space Station hardware sustaining and the Exploration Extravehicular Mobility Unit battery. For AA-2, he worked on EDR payload assembly, testing and recovery operations.



Andrzej Jackowski received a B.S. in Electrical Engineering at the NYU Polytechnic School of Engineering. He is an early career engineer, and the youngest member of the EDR team, with 3 years of experience with NASA. He has supported Seeker, a robotic inspection vehicle, the EDR subsystem, and is currently working on the avionics and control systems

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Joshua Wilkins received a B.S. in Mechanical Engineering from the University of Texas Pan American, and a Masters of Systems Engineering from Stevens Institute of Technology. He has been working as a

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Michael Burlone graduated in 2007 from Texas A&M University with a Bachelor's degree in Mechanical Engineering. He has worked at NASA as a designer for mechanical and structural systems since graduation, specializing in computer aided design, stress analysis, vibroacoustic attenuation, tolerancing, rapid manufacturing & prototyping,

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Lance Oelke received a B.S. in Engineering Physics from the University of Oklahoma and a Juris Doctor Degree from the University of Houston. He previously worked at Gulfstream Aerospace and was the responsible engineer for electrical power distribution systems, windshield heat systems, and radomes on the Gulfstream GIV, GIV-SP, GV, and GV-SP. He has 10 years of experience as a scientist and engineer working as a contractor at NASA JSC, including being the responsible engineer for design and sustaining of 10 megawatt arc heaters used for testing re-entry vehicle thermal protection systems. He has supported projects including the Space Shuttle Return to Flight, the Orion Hybrid Electronic Radiation Assessor (HERA), the ISS External High Definition Camera(EHDC) System, and the Orion AA-2 Ejectable Data Recorder (EDR). He is currently the subsystem manager for Orion Displays and Controls.