Advancing Low Earth Orbit: Achievements and Lessons from the DARPA Blackjack Program

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I. Introduction

The Defense Advanced Research Programs Administration (DARPA) Blackjack program, initiated with the goal of integrating advancements from the commercial sector in Low Earth Orbit (LEO), emphasizes cost savings through the miniaturization of space systems and lower launch costs. This approach aims to enhance affordability in achieving LEO orbits, with the ultimate objective of demonstrating performance comparable to current systems in geosynchronous orbit that employ longer design and development timelines.

Blackjack showcases the on-orbit application of high-capability/low-SWaP payloads, enabling small satellites to operate independently or collaboratively within constellations for various missions. The program's architecture is built on Blue Canyon's ESPA-Grande Saturn bus, housing the SEAKR Pit Boss Processor, Stormking Radio Frequency (RF) Payload, and four Optical Inter-Satellite Link (OISL) terminals. Applications range from basic RF missions to Space-to-Space and Space-to-Ground data transfers, Over-The-Air (OTA) updates, and on-orbit data processing with Zero Mass Payload Development capabilities.

Launched in June 2023, the program has completed a year of operations, leading to significant achievements and insights. This paper provides a comprehensive overview of the DARPA Blackjack program's on-orbit milestones, offering insights into its history and accomplishments. It delves into the successes of the program, focusing on both the bus and payload perspectives. Additionally, the paper explores various system design and implementation considerations that have contributed to mission success. Furthermore, it discusses lessons learned from challenges encountered during operations and highlights the evolution of spacecraft, payload, and mission operations products, aiming to address the requirements of future missions in the dynamic space systems landscape.

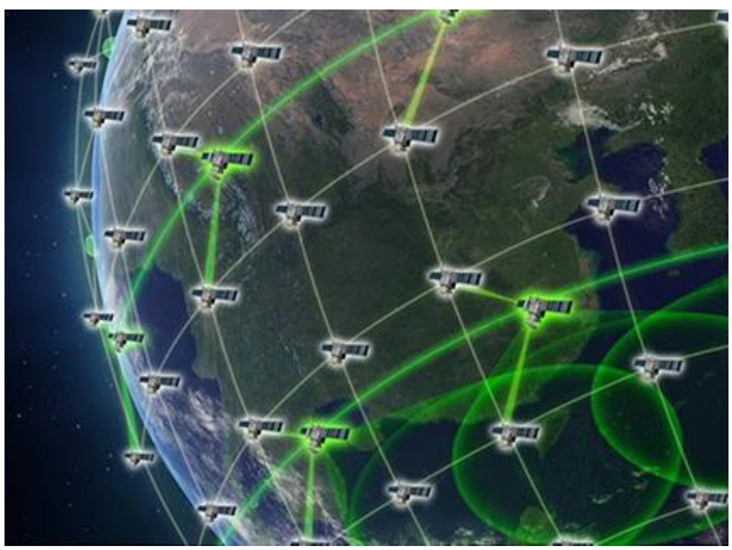

Figure 1*: DARPA Blackjack program looked to leverage commercial LEO Mega-Constellations to Demonstrate order of battle architectures.*

Finally, this paper delves into some of the mission successes identified during the operational phase of the program, these include constellation phasing and constellation control, demonstration of the utility of the Optical Inter-Satellite Communications system in the Space-to-ground and space-to air domain, demonstrated capability of the SEAKR developed RF-Payload, demonstrated safe mode operations on-orbit, autonomy in operation of the system with variable customer “level of autonomy”, autonomy in ground contacts and operations, on-board processing on a versil-based FPGA processing architecture, and many more finding from organizational, programmatic, system design and development, and Mission operations perspective.

II. Blackjack Program Overview

Background of Blackjack

The history of the DARPA Blackjack mission stems from DARPA's recognition of the evolving strategic landscape and the increasing importance of distributed and proliferated space-based capabilities in modern warfare. Traditional satellite systems have often been characterized by high costs, long development cycles, and limited flexibility, making them less than ideal for rapidly evolving military requirements. In response to these challenges, DARPA initiated the Blackjack program to explore alternative approaches to space architecture that could offer greater resilience, responsiveness, and affordability.

Since its inception, the Blackjack program has focused on leveraging advancements in commercial space technology to develop and deploy a constellation of small satellites that can deliver military-grade capabilities at a fraction of the cost and time typically associated with traditional satellite programs. By harnessing commercial off-the-shelf components, rapid manufacturing processes, and innovative mission architectures, DARPA aims to demonstrate the potential of LEO satellite constellations to meet the diverse needs of the defense community more effectively and efficiently.

Throughout its development, the DARPA Blackjack mission has evolved through various phases, including technology development, prototype demonstration, and operational experimentation. These phases have involved collaboration with a diverse array of industry partners, including established aerospace companies, innovative startups, and leading research institutions, to bring cutting-edge capabilities to fruition.

Ultimately, the DARPA Blackjack mission represents a strategic investment in the future of space-based capabilities, with the potential to enhance national security, enable new operational concepts, and drive innovation in the broader space industry. By pioneering new approaches to satellite architecture and deployment, DARPA seeks to maintain U.S. military superiority in space while advancing the state of the art in space technology for the benefit of all.

BCT & SEAKR in context of Blackjack

The DARPA Blackjack program represents a cutting-edge initiative at the forefront of space technology, aiming to revolutionize the way we perceive and utilize space assets. At its core, DARPA Blackjack seeks to demonstrate the feasibility of deploying a constellation of low Earth orbit (LEO) satellites for military purposes, including surveillance, communication, and reconnaissance.

Two key players in the realization of this ambitious program are Blue Canyon Technologies and SEAKR Engineering. Blue Canyon Technologies, renowned for its expertise in small satellite development and deployment, brings to the table a wealth of experience in crafting compact yet powerful spacecraft capable of navigating the complexities of space with precision and efficiency. With a focus on providing cost-effective solutions without compromising performance, Blue Canyon Technologies plays a pivotal role in the realization of the DARPA Blackjack program's vision.

Complementing Blue Canyon Technologies' contributions, SEAKR Engineering brings its formidable prowess in advanced space electronics and payloads to the forefront. Specializing in the design and manufacturing of high-performance spaceborne processing systems, SEAKR Engineering adds a critical dimension to the Blackjack program, ensuring that the satellites deployed are equipped with state-of-the-art capabilities to fulfill their mission objectives effectively.

Together, these two entities form an indispensable partnership driving the DARPA Blackjack program forward, pushing the boundaries of what is achievable in the realm of space technology. With their combined expertise and dedication, they are instrumental in shaping the future of space-based operations, ushering in a new era of innovation and capability in defense and beyond.

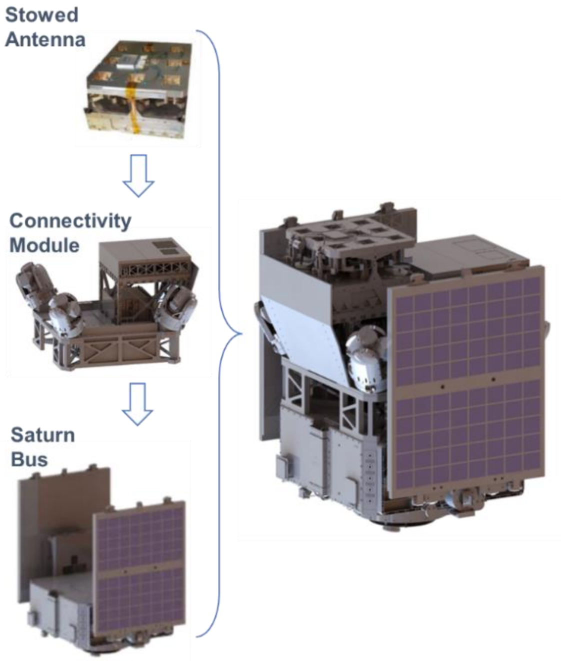

Figure 2*:The Blackjack Space Segment Configuration was composed of the Saturn Spacecraft Platform, the SEAKR Connectivity Module, and a RF payload.*

Space Segment Architecture / Configuration

The BCT-SEAKR space segment represents a cutting-edge assembly of spacecraft components designed to meet the demanding requirements of modern space missions. Comprising a blend of proven technology and innovative systems, this segment serves as a robust foundation for the blackjack Space Vehicle baseline configuration. The Blackjack space segment is composed of three fully modular systems developed separately as commercially available commodity subsystems. **Figure 2** captures the high-level architecture of the Blackjack space segment, showing how the BCT spacecraft bus, the SEAKR connectivity module (integrated with PL support structure) and the SEAKR Ka-Band Steerable antenna come together. A more detailed description of these space segment sub-systems:

1. BCT Saturn Spacecraft: At the core of the BCT-SEAKR space segment lies the Saturn spacecraft, a standardized ESPA-Grande class spacecraft bus. Drawing upon the legacy of flight proven Microsat buses, the Saturn platform inherits a robust architecture and core components. Designed to accommodate various mission profiles, the Saturn spacecraft fulfills essential functions including propulsion, power management, thermal regulation, and guidance, navigation, and control (GN&C).

2. SEAKR Connectivity Module: Developed by SEAKR, the connectivity module serves as a time-saving infrastructure within the BCT-SEAKR space segment. This module integrates optical communications terminals (OCTs), a Ka-band communications payload, and a potent networking and encryption subsystem (NES). Seamlessly integrated with the spacecraft platform, the connectivity module offers versatility, allowing for the integration of multiple payloads tailored to specific mission objectives.

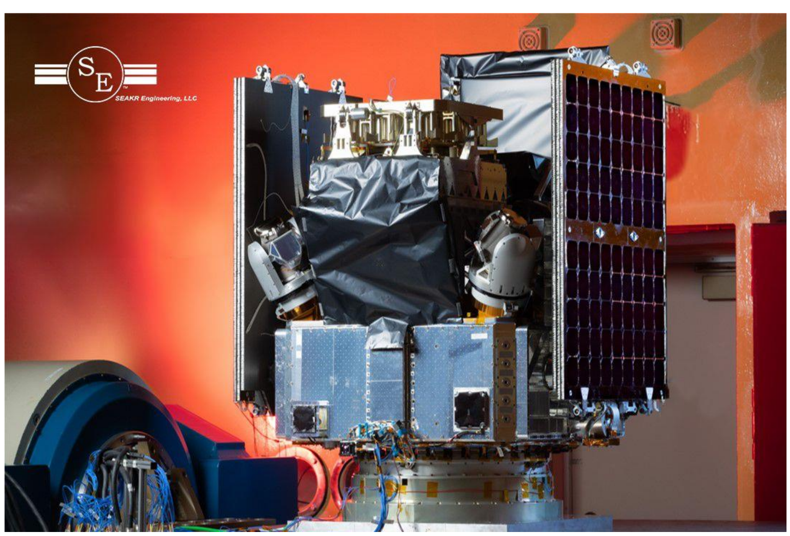

Figure 3: Fully Integrated Blackjack Space Segment Ready for System-Level Testing

3. SEAKR Storm-King Payload: Central to the BCT-SEAKR space segment is the Stormking Payload, a sophisticated component designed to facilitate robust communication between the spacecraft and ground stations. Incorporating an electronically steered Ka-band communications payload, the Stormking system enables bidirectional data flow, utilizing two array antennas and a software-defined radio (SDR). Enhanced by precision timing circuitry, amplifiers, and antenna control, the Stormking Payload ensures reliable and efficient data transmission in challenging space environments.

Finally, the seamless integration between the spacecraft and payloads is enabled by a dedicated mechanical structure providing the necessary interfaces between the BCT Spacecraft platform, the SEAKR connectivity module, and the Storm-king Payload. This structure effectively decouples the satellite and payloads, enabling modular integration and enhancing operational flexibility of the system overall. The BCT-SEAKR space segment represents a harmonious integration of state-of-the-art spacecraft technology and purpose-built subsystems enabling the Blackjack mission. With its versatile architecture and robust components, this segment stands ready to support a wide range of space missions, offering reliability, flexibility, and performance excellence.

III. Overview of program history and launch operations

The project lifetime of Blackjack began in 2019 when BCT was awarded the bus contract from DARPA. DARPA also awarded another bus vendor for a different configuration spacecraft, and a variety of payload and subsystem providers were awarded contracts as well, notably for this paper, SEAKR Engineering. DARPA, as the mission prime, also contracted with Lockheed Martin to serve as the system integrator at their facilities in Sunnyvale, California.

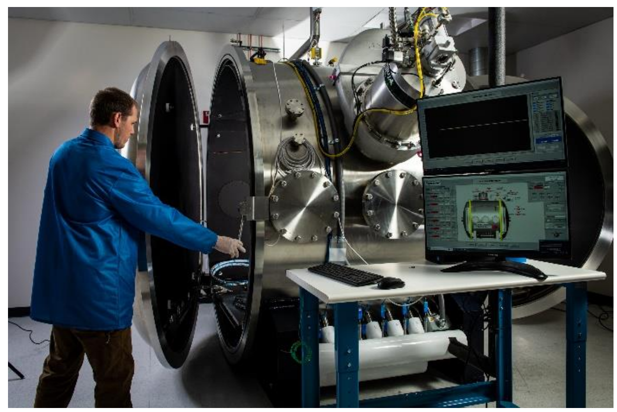

Figure 4: BCT's Largest TVAC Chamber

BCT's work was performed at its facilities in Boulder and Lafayette, Colorado, initially on contract for bus design to support a number of different payloads that DARPA had envisioned for the program. BCT's design and manufacturing is all done in-house and is collocated, ensuring smooth transition between program phases with additional reach back support during integration efforts. Additional scope was also added to various parties throughout the program as gaps were uncovered. Notably, BCT took on the top level thermal and mechanical design and configuration for the entire space vehicle.

This program, like most that existed in the early 2020s, suffered delays due to the Covid pandemic for a variety of reasons, none of which were uncommon to the broader industry. Supply chain, personnel, and facility restrictions, etc. caused issues for all parties involved. Due to the vertically integrated nature of BCT and the common use of components and subsystems across the product lines, hardware was rerouted to support the program when possible. Additionally, BCT and SEAKR were able to leverage its parent company, RTX, for access to any additional parts or personnel that were not available at certain points throughout the program.

Through these challenges, the program progressed, with bus and payload deliveries to LM occurring in November 2022 and after for final assembly and test at Lockheed Martin. Four buses were integrated at the Lockheed facilities with support from all parties. The program launched 4 satellites in June 2023 on the SpaceX Transporter 8 rideshare mission where on orbit operations and mission performance began soon after. The details of this phase are covered in later sections of this paper.

Figure 5: Launch Vehicle Stack, Credit: SpaceX

IV. Spacecraft Development, Integration, and Test at Blue Canyon

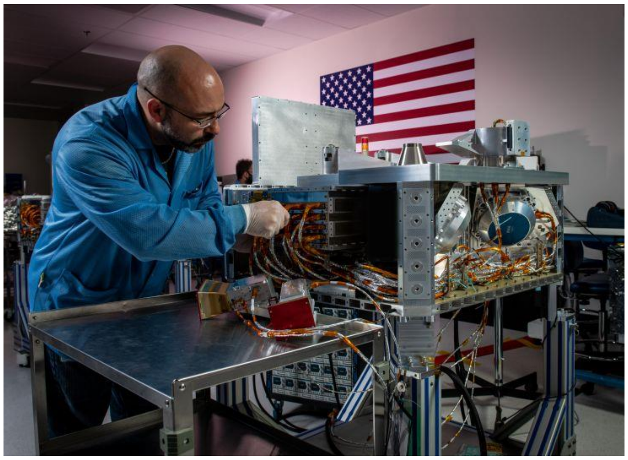

Figure 6: A Blackjack Saturn Bus in Assembly

Programmatic and Organizational lessons learned.

Project Blackjack was a pivotal endeavor undertaken by BCT during a period characterized by scaled-down processes and team structures tailored for smaller projects. However, the existing execution model within BCT proved inadequate for the demands of Project Blackjack, necessitating a significant restructuring effort to meet program requirements. The primary challenges stemmed from a shortage of personnel, equipment, and resources, exacerbated by the company's prior focus on smaller-scale programs. This deficiency led to engineering teams struggling to keep pace with the aggressive project schedule, resulting in overwork and bottlenecks in both production and engineering phases. To address these organizational and staffing deficiencies, BCT implemented a multifaceted approach:

- **Personnel Organization:** Restructured personnel around product lines to enhance expertise and streamline capabilities development.
- **Dedicated Facilities:** Established dedicated facilities for the production and manufacturing of the Saturn product lines to optimize efficiency.
- **Rapid Workforce Expansion:** Expeditiously hired additional personnel to augment the existing workforce.
- **Key Leadership Identification:** Identified and filled key leadership positions to bolster technical management approaches.
- **Collaboration with Sister Company:** Leveraged capabilities and resources from sister company SEAKR to supplement and address gaps within BCT.

These measures aimed to alleviate personnel constraints and enhance operational effectiveness. However, ongoing personnel issues and disparities in program management proficiency necessitated continuous refinement of program planning and execution practices within the company. In response to these challenges, BCT implemented several strategic initiatives:

- **Infrastructure Investments:** Made internal investments in essential infrastructure such as TVAC chambers, RF test equipment, thermal chambers, and automated test capabilities.
- **Standardized Management Plans:** Introduced standardized program management plans encompassing risk and opportunity management strategies tailored to mitigate high-impact risks.
- **Talent Acquisition:** Continued recruitment of experienced space industry program managers, contract managers, and system engineering leaders to strengthen program management capabilities.

These initiatives were critical in adapting BCT's organizational structure and operational practices to meet the demands of Project Blackjack. By addressing personnel shortages, enhancing program management proficiency, and investing in essential infrastructure, BCT successfully navigated the challenges posed by this transformative project.

Vertical integration and system architecture

From a technical perspective, Project Blackjack marked a significant milestone for BCT as it ventured into uncharted territory. The program focused on combining proven technologies utilized in our CubeSat and minisat spacecraft to enhance the mass and power capabilities of the spacecraft.

The system architecture of Project Blackjack relied heavily on modular componentry, capitalizing on off-the-shelf systems previously developed and refined by BCT to high Technology Readiness Levels (TRL). This approach facilitated seamless integration with new avionics and power delivery systems. Notably, BCT implemented design modifications by segregating the heritage FAU avionics design into distinct modules: the avionics module KFAU and the power delivery electronics module KEU.

Figure 7: Blackjack program drove many changes to our production, test, and engineering processes.

In addition to leveraging established components, Project Blackjack incorporated design updates to address recurring issues encountered in previous programs. Notable enhancements included updates to memory storage to rectify past memory issues and the introduction of the autonomous mission reset FSW to mitigate system resets experienced in heritage programs. The autonomous mission reset FSW offers customers flexibility in determining the level of autonomy required to address on-orbit resets.

From a software (SW) perspective, Project Blackjack necessitated a substantial overhaul of our flight software. Not only did this revamp aim to rectify known issues, but it also aimed to accommodate the integration intricacies between the KFAU and KEU modules. Key updates encompassed consolidating the flight software into a unified "trunk" architecture, facilitating seamless interaction between modules. Concurrently, a comprehensive test program was devised to validate the functionality of the updated software. This entailed adapting previously established tests to operate within varied hardware configurations, coordinating testing efforts across disparate teams, and even orchestrating tests across different organizations spanning multiple companies. Such endeavors were essential to ensure the robustness and interoperability of the flight software across the entirety of Project Blackjack's ecosystem.

Figure 8*: Propulsion system*

Integration of a New Propulsion System

Internally, BCT implemented numerous modifications to both hardware and software components within the Blackjack architecture, extending beyond updates to BCT-built hardware to integrate various new third-party capabilities into the spacecraft architecture. A significant aspect of these enhancements involved upgrading the propulsive capabilities of the spacecraft, particularly notable within the larger spacecraft architecture.

During the platform's construction phase, the propulsion industry experienced notable growth, with several startups offering propulsion solutions at unprecedented price points. In response, BCT conducted extensive evaluations, strategically down-selecting capabilities for integration into the platform. However, challenges emerged during integration and testing (I&T) at the spacecraft level, where comprehensive end-to-end testing was unfeasible. Consequently, final validation of the system's end-to-end operation relied on piecemeal assessments of system performance. Further insights were gained during on-orbit operations, particularly during commissioning and operation phases, where critical tasks such as propulsion system initialization and meticulous performance calibration were scrutinized. Various performance calibration analyses were undertaken to optimize system usage, addressing factors like xenon impurities, thruster performance errors, and power system performance discrepancies. (add reference to Kimberlyn and Dane paper once approved). To date, On-orbit performance has been demonstrated over multiple maneuvers over varying durations, with orbit-determination-based thrust estimates within 10% of values expected based on measurements made in ground testing.

Mission Operations

On-orbit, the operational complexity stemmed from the simultaneous launch of four buses. This meant managing multiple vehicles at once, which presented challenges in coordinating tasks and handling telemetry. A significant aspect was beaconing, where the customer insisted on having it enabled well into the commissioning phase to ensure continuous monitoring of each vehicle's status. However, this led to complications such as interference between buses and inconsistent telemetry when multiple vehicles beaconed simultaneously, necessitating the halt of downlinks for all but one vehicle during contact time, thus reducing operational efficiency.

Navigating the complexities further, even with a single vehicle, demanded meticulous tracking of beacon on/off times and adjusting downlink commands accordingly. While BCT recommended early disabling of beaconing to streamline operations and maximize contact time, the customer prioritized continuous beaconing, despite prolonging the commissioning phase. Moving forward, better communication regarding the benefits of disabling beaconing when systems appear nominal, alongside assurance of robust fault response mechanisms, could facilitate smoother operations and align expectations between BCT and the customer.

Addressing unexpected resets became a focal point, emphasizing the importance of instructing the customer on vehicle recovery procedures at different stages of commissioning. Despite encountering numerous resets caused by command timeouts and a handful of Single Event Upsets (SEUs), the majority of timeouts stemmed from ground station limitations rather than spacecraft issues. Establishing a concise flowchart outlining the steps for swift recovery post-reset notably expedited the restoration of operations, underscoring the value of proactive preparation and clear communication in mitigating disruptions.

A notable distinction between the XB1 buses and the larger buses pertained to the behavior of GPS and Star Trackers following a reset or post-separation event. Unlike the XB1 buses, these crucial components were not automatically powered on in the larger buses, necessitating manual intervention during the recovery process. This manual activation significantly prolonged the time required for recovery from resets caused by timeouts, thereby increasing operational downtime. Moreover, the dependency on manual intervention underscored that the BJK buses consistently relied on human intervention for determining time and position after each reboot. This discrepancy in design philosophies between the XB1 and larger bus models emphasized the need for alignment across all bus lines regarding the operational status of components following a reboot. Addressing this misalignment could enhance operational efficiency and streamline recovery procedures, ensuring consistency and minimizing downtime across all bus variants.

V. SEAKR lessons learned

Three main suppliers with interfacing into a community of customers poses several integration challenges and successes. One of our fundamental assumptions proved to be incorrect leading to a more nuanced understanding of implementation of concepts such as Time. We also found an autonomous payload could generate conflicting commands with the bus causing additional uncertainty in vehicle attitude. Despite these challenges, we’ve had success in demonstrating our Edge Computing solution we call Pit Boss.

During our early Optical Inter Satellite Link (OISL) experiments with our Naval Research Laboratory (NRL) ground station, we found interesting artifacts in our telemetry. We had apparent static offsets, and sweeps that were not expected, and oddly, at times we would see sparkles from the emitting laser despite telemetry reporting we were pointed elsewhere at that moment in time. These artifacts generated a lot of discussion and late nights for the team to understand resulting in two major findings: We have a race condition onboard the vehicle affecting the spacecraft attitude, and we have an inconsistency in the understanding of time. Both of these issues took a lot of effort to diagnose and develop a ConOp plan to minimize these risks.

Our spacecraft has several attitude modes. The most nominal flight configuration is Local Vertical Local Horizontal (LVLH) with special modes for antenna pointing for T&C or sun pointing. Our autonomy sends macros that set/confirm the bus is in LVLH then send Azimuth and Elevation commands to an OISL to control the pointing vector. Pit Boss drives this pointing vector dynamically to track a point on the ground. When analyzing post-pass telemetry, we were discovered at times were sweeping a path on the ground instead of tracking a point. We questioned all of our assumptions with all coordinate rotations performed on the vehicle that would affect pointing taking us through Bus and Payload algorithms. We ultimately discovered three sets of payload macros that had parameters and priorities that controlled spacecraft attitude. Once discovered, we were able to properly manage the behavior of priorities which subsequent operations proved out expected operations.

With the attitude element of off-target pointing better understood, we still had other artifacts that didn't seem to make sense. Analysis with tools such as STK would show a pointing vector with an offset to our target. This was inconsistent with other observables such as positive light reception on the target while telemetry showed a offset of 10s of kilometers. We discovered that various systems, be they subsystems on the spacecraft, or other systems on the ground used different time standards. We discovered we were dealing with time standards for UNIX, Global Positioning System (GPS), Universal Time Constant (UTC), International Atomic Time (TAI), and Terrestrial Time (TT). These systems have inconsistencies regarding Epoch and the handling of leap seconds. Each subsystem had telemetry timestamps recorded in its local understanding of time and reported back to the Operations Center. Once we were able implement a translation between different standards we've been more consistent in tracking ground targets to the point of establishing links and idle frame data transfer. A key lesson learned for future missions a periodic synchronization pulse that will allow ground operator to clearly see and align time stamps generated by various systems.

Implementation of Edge Computing has provided experience with capabilities that help break down barriers for future work. Use cases include quick reaction to events or anomalies without ground intervention and to solve problems on-orbit with limited or no ground interaction. It can also help maximize the value of data sent across bandwidth constrained communication channels by prioritizing data that is sent to the ground for analysis. One challenged posed is the sheer volume of data generated and downloading all data to reconstruct autonomy decision making and verifying behavior is as intended. This leads into a cycle of updates that can be slow based on file sizes and contact constraints. Once OISLs downlinks are stable and available bandwidth is measured in Gbps vs Kbps this should become less of a barrier.

VI. Mission Achievements

The Blackjack Mission has provided many learning opportunities and has successfully proved out several key technologies. We've proved out the next generation of our On-Board Processors (OBPs) and Software Defined Radios (SDRs) as well as bringing together for our first time an end-to-end payload solution with our Stormking RF Payload. We've successfully integrated our hardware with technologies provided by other partners such as OISLs, Bus and its subsystems, and Antennas resulting in an ability to manage the mission from a single point.

To date we have successfully commissioned 3 of 4 Electrical Propulsion (EP) modules which allows the Mission Integration team to configure the constellation as needed. Since EP can only be fired in a vacuum, this required experimentation and on-the-job learning of how to operate this module. We were able, through several iterations, to be able to reliably control the thrusters allowing us to manage the constellation in configurations most optimal to our experiment set. Initially we were flying two pairs of two allowing us to contact two vehicles (one from each pair) for each pass over a ground station. For future experiments we will re-phase the vehicles into a string of pearls.

Autonomy for repetitive tasks has been imperative with our small team to reduce burnout while maximizing the use of available contacts. Sometimes it’s the simple things that make a team appreciate the complex systems they’ve implemented. Our Mission integration team developed an automation tool they’ve named Weekend Warrior to prepare for multiple missions prior to a pass then automatically executes all tasks, actions, missions, scripts, without manning the console real-time. This allows our team to deliberately plan all keystrokes sent to the vehicle minimizing typos and maximizing the utility of each contact.

One of the more exciting successes of this mission is the successful tracking and lock to an Optical Ground Station (OGT) for our Space to Ground (S2G) experiments. To date we have demonstrated our ability to frame lock and synchronization and share idle data frames. Our next steps are to expand the duration of these contacts and operationalize the connection to use as a high-speed data terminal enabling faster data retrieval and faster Over-The-Air (OTA) software updates. An extension of this effort will be tested in the summer of 2024 with a Space to Air (S2A) attempt with an aircraft in-flight.

Blackjack has been a testbed for our Pit Boss processor and Stormking SDR. Early on in the mission we were able to establish secure tunnels to Pit Boss during contacts effectively making it a node on our network. This has opened up many opportunities for monitoring payload performance, data management, updating software, and mission execution. We were able to demonstrate initial Stormking capability using a Very High Frequency Omnidirectional Range Station (VOR) which are commercial aircraft navigational beacons throughout the world. Each VOR emits a Morse Code series of tones as a station identifier. Knowing the frequency, we were able to detect the following example from the VOR at Denver International Airport which emits the Morse Code for DEN which is “**-.. . -.**” which can be seen visually below

The collection of this signal proved out our integration of a supplier provided antenna with our SDR payload and integrated onto the Blue Canyon bus which was a first for SEAKR Engineering LLC.

Not everything works smoothly, especially on a demonstration mission. To this end, features and redundancies that have been built into the vehicle have saved the mission many times. As a belt and suspenders approach the automatic recovery processes embedded into the BCT Saturn Bus such as 36-hour ground contact watch dog reset and other off-nominal resets have saved this mission several times and kept the mission going.

VII. Conclusion

Incorporating the lessons learned from DARPA's Blackjack program into advancing capabilities in Low Earth Orbit (LEO) presents major steps in advancing proliferated, distributed satellite architectures and the associated technologies for broader mission sets, especially in the LEO domain. The program created a strong industrial base for critical product lines like the commoditized Saturn smallsat bus, SEAKR’s processing and RF capabilities, and general infrastructure for manufacturing these products at scale. These technologies are serving as the basis for several different Space Development Agency tranches and are looking to be leveraged in other mission domains and orbital regimes. These invaluable lessons will propel the broader US military and civil space architectures and be a core contributor to space exploration and defense efforts to come.

VIII. Acknowledgement

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To Lockheed Martin for your efforts in final assembly and test.

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