BLUE ORIGIN

De-orbit Descent and Landing Tipping Point

Program Final Report

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ABSTRACT

The purpose of this document is to provide a final report on the Deorbit, Descent, and Landing (DDL) Tipping Point program, a public-private partnership between Blue Origin and NASA that is partially funded by NASA contract 80LARC19C0005. In this report we summarize the results of the entire contract, including recommendations and conclusions based on the experience and results obtained. Only the portions funded by the government with associated unlimited rights are documented in detail in this report. For the work funded by Blue Origin, summaries with unlimited rights are provided for context and completeness. The Blue Origin funded work exceeded 25% of the originally proposed total program cost and included a mixture of hardware procurement and critical technology maturation.

The scope of this document is a discussion of all the major tasks performed under the contract including the sensor flight demonstrations on New Shepard, the hardware in the loop lunar landing navigator demonstration, and the ground testing of the Flash LiDAR hazard sensor. The contributions from the multiple NASA teams – Johnson Space Center, Langley Research Center, Goddard Space Flight Center, and Jet Propulsion Laboratory – are described along with the contributions from Blue Origin. This document is the Final Report for statement of work item 4.1.2.10 as Deliverable 5.8.

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ACRONYMS

ASC	Advanced Scientific Concepts, LLC
BlueNav	Blue Origin Navigator
CC	Crew Capsule
CON	Center of Navigation
COR	Contracting Officer Representative
COTS	Commercial Off the Shelf
DDL	Deorbit, Descent, and Landing
DEM	Digital Elevation Map
GPU	Graphics Processing Unit
HWIL	Hardware-In-the-Loop
ICD	Interface Control Document
IMU	Inertial Measurement Unit
JSC	Johnson Space Center
kg	Kilogram(s)
km	Kilometer(s)
LaRC	Langley Research Center
LiDAR	Light Detecting and Ranging
m	Meter(s)
m^2	Square Meters
m/s	Meters per Second
NASA	National Aeronautics and Space Administration
PL&HA	Precision Landing & Hazard Avoidance
PM	Propulsion Module
s	Second(s)
SPLICE	Safe & Precise Landing - Integrated Capabilities Evolution
SR	Super Resolution

REFERENCES

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1. INTRODUCTION

1.1. Background

NASA Space Technology Mission Directorate "seeks aggressive technology development efforts that may require undertaking significant technical challenges and risk to achieve a higher potential payoff. (SpaceTech-REDDI-2018)" Work completed was the result of a proposal submitted by Blue Origin, LLC for award under the NASA Headquarters Space Technology Mission Directorate (STMD) NASA Research Announcement (NRA) entitled Space Technology Research, Development, Demonstration, and Infusion-2018 (SpaceTech-REDDI-2018)".

The NASA/Blue Origin 2018 De-orbit Descent and Landing (DDL) Tipping Point Program includes integration of NASA developed technology into a Blue Origin, LLC state-of-the-art launch vehicle, New Shepard, providing opportunities to mature critical sensor technology and algorithms that enable precision and soft landing.

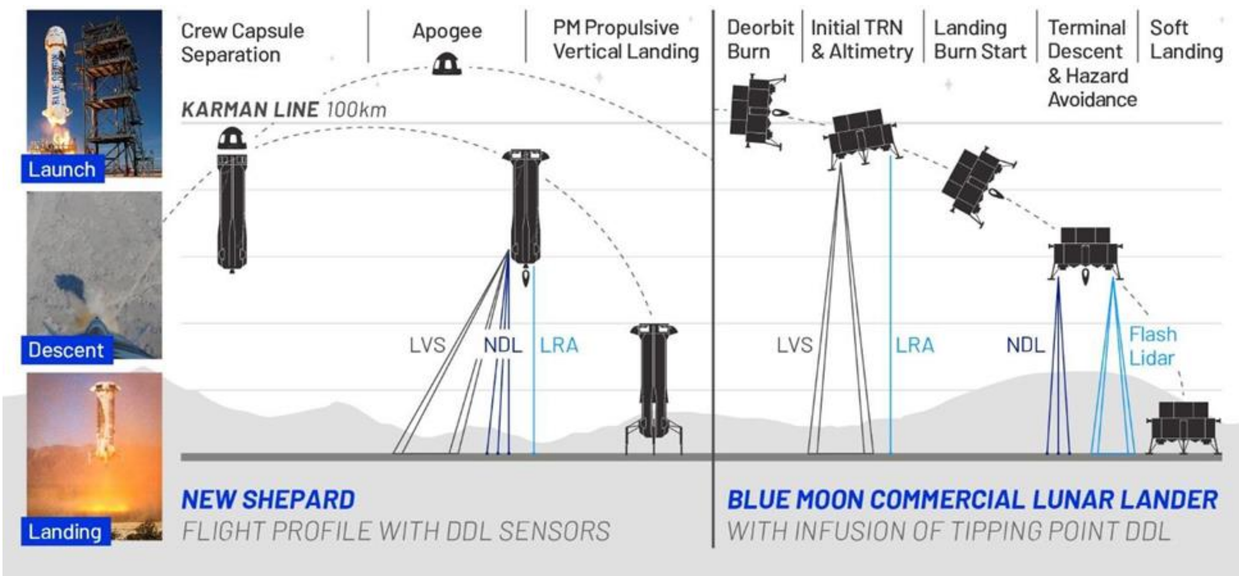


Figure 1: Infusion of Upgraded DDL Sensors Tested on New Shepard into Blue Moon.

The testing was performed up to approximately 100 km altitude on-board the flight proven New Shepard vertical takeoff vertical landing suborbital vehicle. Figure 1 depicts the flight profile, expanding the flight envelope beyond previous NASA airborne tests (generally <1 km), capturing the full range of operation for each DDL sensor. Figure 1 represents the proposed sensors for the flight demonstrations, some of which, during the program, we learned were not robust or mature enough to fly on New Shepard. Where appropriate they were still evaluated in ground tests. Blue Origin and NASA continue to use the flight data to anchor analyses and models and support follow-on development. The NASA-developed or commercial sensor suite will enable Blue Moon to precisely land anywhere on the lunar surface, from the equator to the poles, from the rim of Shackleton crater to permanently shadowed regions, from the far side locations on the South Pole/Aitken basin to lunar lava tubes.

This program has three high-level technology objectives:

1. Demonstrate the performance of NASA-developed and contractor provided precision landing sensor and processing technology (including, but not limited to, Descent Landing Computer (DLC) and Navigation Doppler Light Detection and Ranging (LiDAR, NDL)) in an

operating envelope (altitude, velocity, and vehicle environments) from space environments through soft propulsive landing operations on a commercial vehicle (the New Shepard Propulsion Module)

2. Demonstrate a commercial navigation system for safe and accurate lunar landings using NASA-developed Terrain Relative Navigation (TRN) algorithms as part of a Hardware-in-the-Loop (HWIL) simulation environment
3. Develop and demonstrate a Flash LiDAR prototype for hazard detection derived from NASA-developed Flash LiDAR sensor design and image processing software

Each of these objectives advances a critical DDL capability by building on completed and ongoing NASA-led development efforts, including Mars 2020 Lander Vision System (LVS), Autonomous Landing and Hazard Avoidance Technology (ALHAT), CoOperative Blending of Autonomous Landing Technologies (COBALT), and Safe & Precise Landing – Integrated Capabilities Evolution (SPLICE). Objective 1 removes the flight envelope limitations of currently available flight test vehicles (e.g., helicopters, propulsive "hoppers"). Compared to previous flight tests, the New Shepard flight profile is similar to that of a lunar landing by increasing attainable altitude from <1 km to ~100 km, increasing vertical velocity from ~25 m/s to ~900 m/s, and providing access to the space environment.

Objective 2 lowers the cost of GN&C computing elements and sensor fusion, while addressing the processing requirements of fusing optical and LiDAR sensors (e.g., limitations identified during COBALT that prevented integration of NDL and LVS) and generating surface relative position and attitude navigation data in real-time. The resulting BlueNav-L hardware and simulation environment will facilitate development of Blue Moon landing concepts, operations, and requirements. Furthermore, sensor test data from Objective 1 can directly inform and be incorporated into these simulations to anchor results and increase fidelity.

Objective 3 addresses desired improvements in Flash LiDAR performance identified as part of ALHAT, leveraging image processing software advancements. Compared to the ALHAT version, the LiDAR prototype to be demonstrated is expected to improve resolution by making use of the super-resolution software. The super-resolution technique takes advantage of sub-pixel shifts between multiple, low-resolution images of the same scene to construct a higher resolution image and is expected to increase the effective image resolution of the Flash LiDAR by 4x to 8x. These sensor capabilities enable generating a Digital Elevation Map (DEM) of 100x100m, with 10 cm resolution from an altitude of 1 km.

With the Tipping Points, NASA "continues to embrace public-private partnerships to achieve its strategic goals for expanding capabilities and opportunities in space" to "deliver technologies and capabilities needed for future NASA, other government agency, and commercial missions." [1] To help ensure commercial infusion of these space technologies, NASA requires the offeror to fund at least 25% of the total project cost inclusive of any NASA costs. The contract mechanism is a firm-fixed price, requiring all overruns of the industry portion to be covered by the offeror.

1.2. **Document Overview**

This integrated final report combines the summaries of the work completed under the three tasks within the DDL Tipping Point program. In Section 3 we review the sensors flight demonstration task that included two successful flights on New Shepard with various landing sensors. In Section 4 we review the testing of the Blue Origin lunar navigator that incorporated JPL's Map Relative Localization software. In Section 5 we review the Flash LiDAR ground testing performed primarily by NASA Langley with support from Blue Origin. We conclude in Section 6 with the program level conclusions and recommendations.

2. SENSORS DEMONSTRATION TASK

This section of the final report describes the work performed during the sensors flight demonstration task consisting of two flights on the New Shepard launch vehicle with NASA and commercial sensor payloads. We begin with an overview of the task followed by the results of the flight demonstrations. The overview describes the design development and key decisions regarding which sensor payloads ultimately made it to the flights. Both flights successfully demonstrated the utility of the New Shepard system. The flight profiles began from the ground, continued to approximately 100 km altitude, and then returned for a propulsive landing of the Propulsion Module (PM) and a parachute landing of the Crew Capsule (CC). The tests expanded the flight envelope for each DDL sensor beyond previous airborne tests (generally <1 km) and captured their full range of operation. We close with task level conclusions and recommendations. Additional details are available in References 2, 3, 5, and 7.

2.1. Task Overview

As seen in Figure 1, the original proposal proposed flight demonstration of NASA Langley's NDL and LRA along with JPL's LVS. All three were proposed as environmentally hardened versions of sensors previously flown on ALHAT or COBALT programs. These were ruggedized versions of the early Commercial Off the Shelf (COTS) hardware prototypes. Following award and during negotiation we were able to take advantage of the developments under the NASA SPLICE program and adjusted the planned sensors. We baselined for flight the next generation of the NDL in development at that time at NASA Langley, preserved the ruggedized COTS LVS scope, and then added NASA JSC's Descent Landing Computer (DLC) to the flight plan. We also decided to include at least preliminary design integration of NASA Goddard's Hazard Detection LiDAR. It is important to note none of these sensors had yet been built and all required extensive design work to be performed in parallel to the integration activity and preparation of the New Shepard Propulsion Module for the payloads. However, including these changes offered a substantial increase in the technology learning and partnership between Blue Origin and NASA. The contract Authority To Proceed was 22-April-2019 with a virtual kickoff held shortly thereafter.

We performed a System Requirements Review (SRR) on 22-23-May-2019 which covered the sensor and launch vehicle interface requirements. The review was held in person at Blue Origin facilities in Kent WA. Figure 2 shows the snapshot of the different sensors and the integration options being considered at the time of the SRR. Extensive collaborative design work was performed over the next few months leading to the Preliminary Design Review 30-July-2019. The full day technical review held at NASA Langley facilities in Hampton VA included defined expectations and was led by a combined Blue Origin/NASA technical evaluation committee. The purpose of the PDR was to confirm the following activities had been completed to the appropriate level of maturity:

1. Finalize locations for the NASA sensor elements on the PM4 vehicle
2. Define sensor interfaces to the level of maturity needed to achieve the program goals of recording integrated vehicle and sensor flight data sets
3. Present the high-level test scope for all program activities including the sensor demonstration effort and the ground demonstration task
4. Present PDR-level maturation of the Hazard Detection LiDAR (HDL) and provide a recommendation on continuing integration and flight test within the program

The configuration at PDR is shown in Figure 3. We achieved the expectations of the PDR with some gating actions which were subsequently closed. A major decision was to remove the HDL from further consideration. Another major accomplishment was finding feasible locations for the sensor chassis and sensor heads on the PM using the transition tunnels and forward section. Work then proceeded to detailed design.

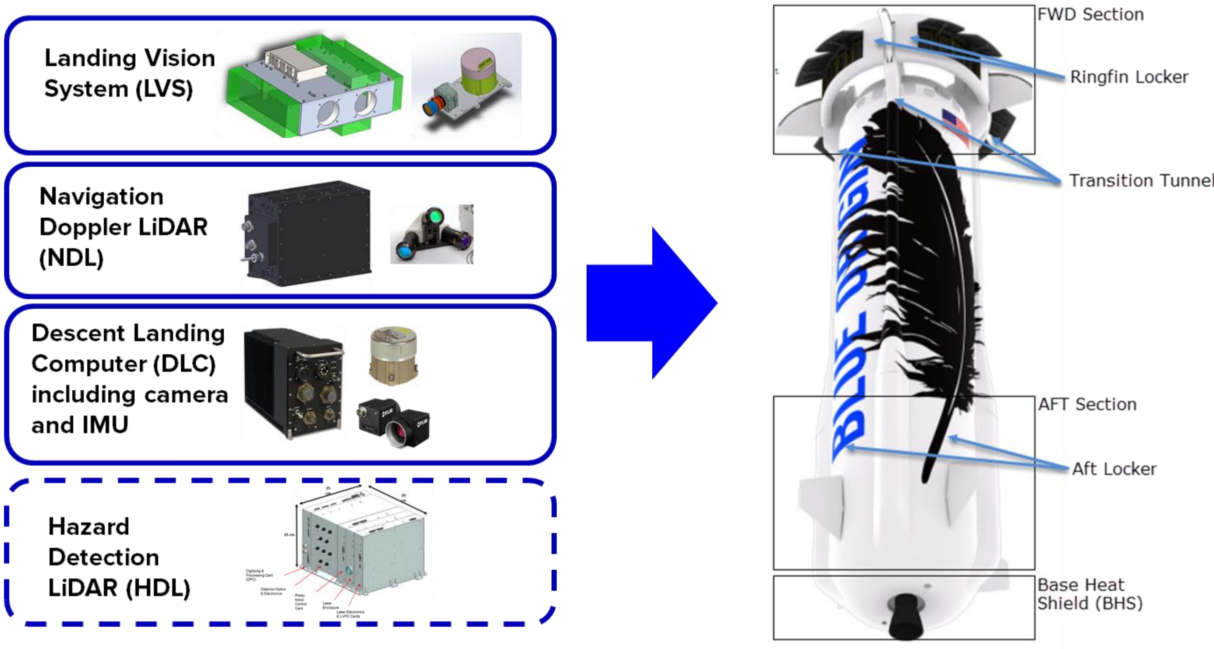


Figure 2: Sensors and integration options being considered at the System Requirements Review.

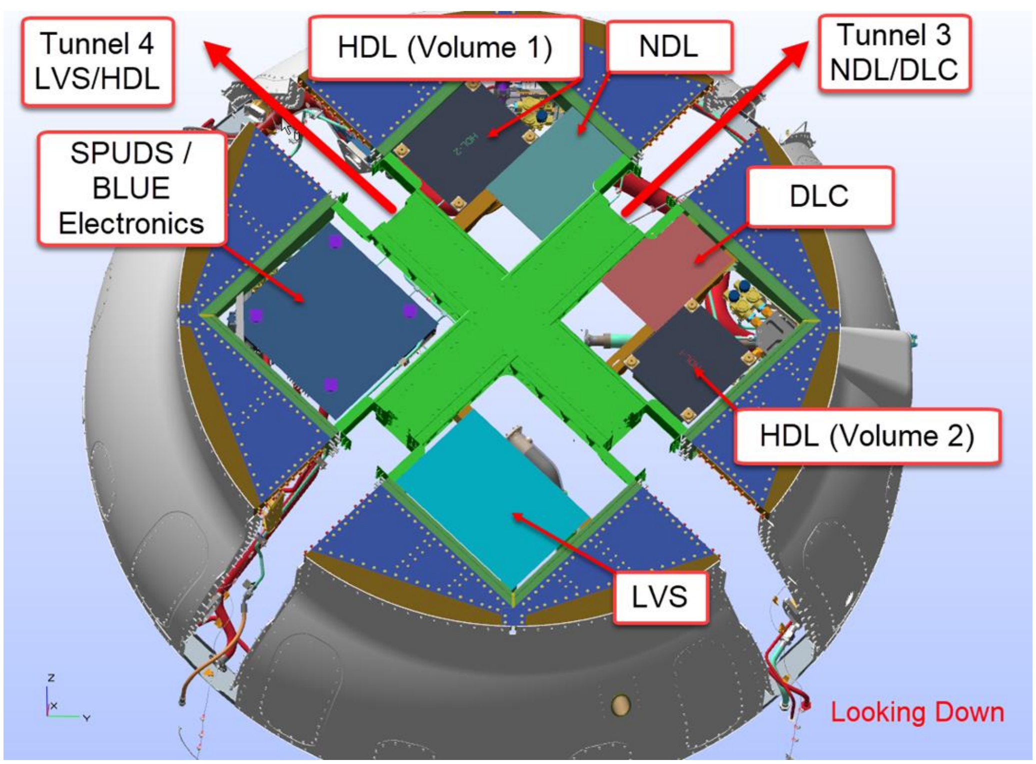


Figure 3: Maturity at the Preliminary Design Review showing feasible locations for all the sensors.

The Critical Design Review (CDR) took place on 30-October-2019 at Blue Origin facilities in Kent WA. A combined Blue Origin/NASA Technical Evaluation Committee was formed to ensure the coordinated set of review expectations were met. We reviewed the detailed design of the structural and avionics accommodations on the New Shepard Propulsion Module along with the critical design maturity of the NASA payload sensors. The build, operations, and test plans were also reviewed. The expectations were met and gated the program activity to build the flight hardware. Shortly after the review, however, it became clear that ruggedizing the COTS hardware prototype of the LVS could not be made ready for flight on New Shepard. Note that this COTS hardware prototype was significantly different from the Mars 2020 LVS Vision Compute Element. A contract modification executed on 13-December-2019 removed the LVS from flight and added replay of the DLC recorded IMU and camera imagery through the JPL software instead. This still supported the objective of evaluating two different Terrain Relative Navigation applications now using a single common data set. This also freed up a payload location on the Propulsion Module that was already past CDR maturity and in build. Fortunately, Blue Origin had separately procured a commercial Doppler LiDAR from Optical Air Data Systems (OADS) called the Optical Moon Proximity Sensors (OMPS) that could be qualified and installed in time for the flights. A rapid design cycle was able to update the design of the sensor chassis location and particularly the sensor head location.

The sensor chassis and the supporting items such as batteries, payload controller, and switches were built-up in three separate assemblies. The three assemblies are shown in Figure 4 in the benchtop testing configuration. The benchtop testing was performed to confirm the function of the elements and compliance with the interface definitions. Non-flight sensor heads were used as needed for interface and functional verification as the flight versions and associated harnesses were being installed on the vehicle in parallel to the benchtop testing. The testing also exercised the operational procedures and was successfully completed 23-August-2020. The subassemblies and the sensor head assemblies were installed on the PM for the integrated system testing and for the two flights. Each unit consists of a chassis located under the PM "table-top" and a sensor head located in the transition tunnel/ring fin support to provide view to the ground during launch and descent. Figure 5 shows these installations in a CAD view and Figure 6 shows photos of them as installed. Also shown in the CAD view is the BlueNav IMU and navigator which provided the "truth" data and are located between the two sensor head assemblies. The installation included metrology of the as-installed sensor head assemblies and a camera calibration and LiDAR beam finding activity. These preparations ensured the highest possible accuracy and knowledge of the installed sensors. All integration and pre-launch test activities were completed 16-September-2020 and the system was ready for flight.

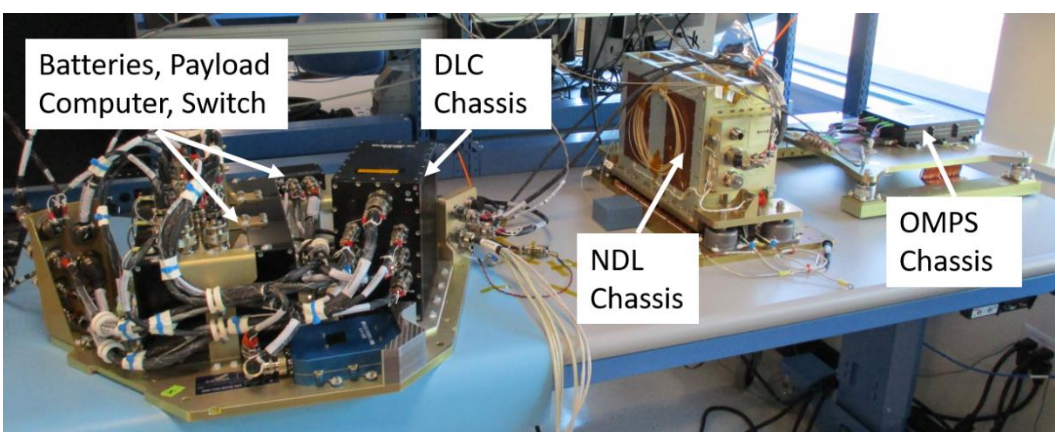


Figure 4: The DDL Sensor payload chassis and supporting payload services subassemblies.

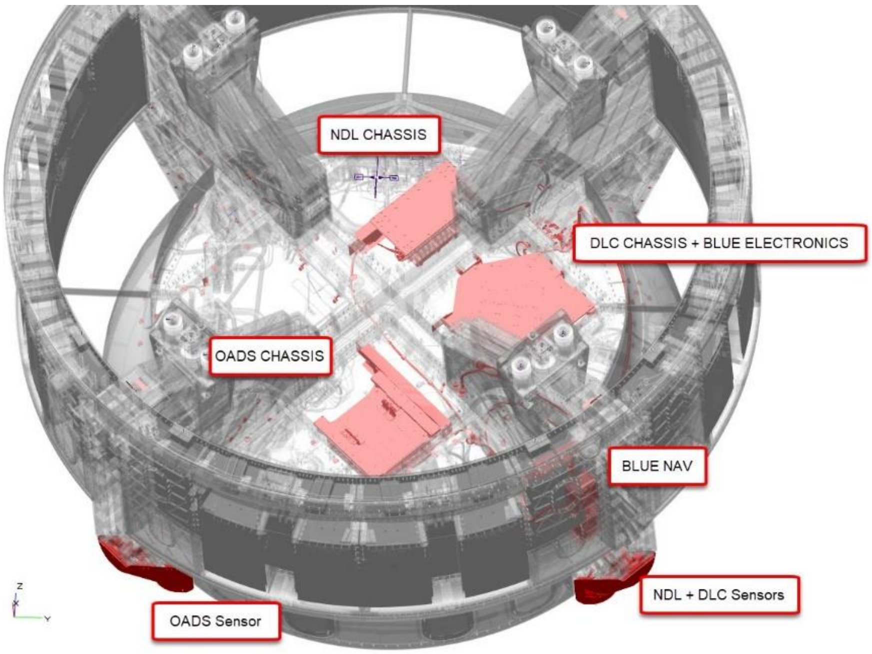
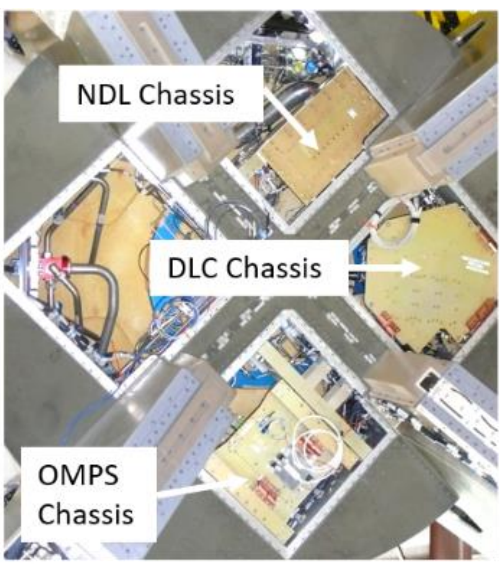


Figure 5: Locations of the DDL payload components on the PM.



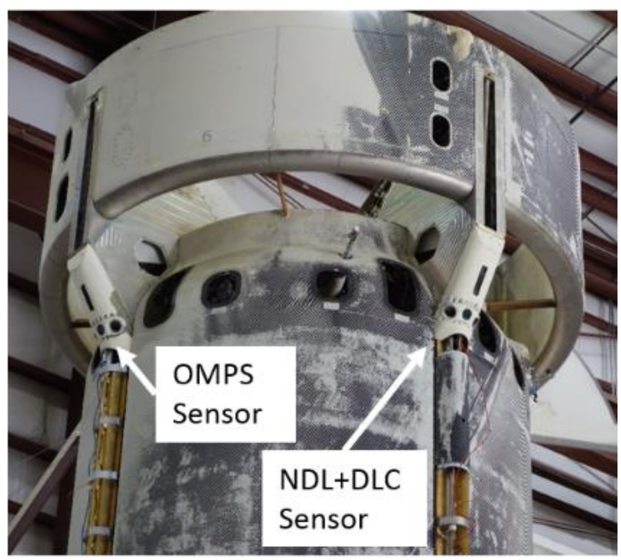


Figure 6: PM installation of the DDL Sensor payload chassis and sensor heads.

2.2. **Summary of Sensor Flight Demonstrations**

Two flights of New Shepard with landing sensors installed were performed under the DDL Tipping Point collaboration. The first took place on 13-October-2020 and the second on 26-August-2021. In between these dates significant updates and modifications were made to the NASA sensors recover from anomalies or to enhance the quality and quantity of data obtained. No changes were made to the vehicle side installations or software.

2.2.1. Flight 1: 13-October-2020

The first flight was successfully completed on 13-October-2020 at Blue Origin facilities in West Texas. A first attempt of the flight was performed 24-September-2020 and the sensor payloads were operated through their first power cycle prior to the scrub for reasons not related to the DDL payloads. This attempt gave the team valuable practice in the launch operations, displays, and procedures. Between the first attempt and the flight no changes were made to the DDL payloads; however, additional situational awareness aids specifically for the NASA personnel were made available. One DDL payload specific constraint – requiring less than 30% cloud cover – was a concern during the countdown and lead to a waiver. Blue Origin was responsible for providing the flight opportunity and delivering the associated trajectory truth data. These data included timing and key events, coordinate frames, and flight trajectory and attitude. These data and other aspects of the mission are described in more detail in Reference 2. Blue Origin also provided the required interfaces and data needed to successfully operate the payloads throughout the flight. Blue Origin included in its scope data gathering from an additional commercial landing sensor, a Doppler LiDAR system from Optical Air Data Systems. Based on analysis of the flight trajectory data, the PM met the mission requirements and performed as expected. The detailed trajectory time histories are shown in Figure 7. The PM achieved the 100km altitude objective and performed a propulsive landing.

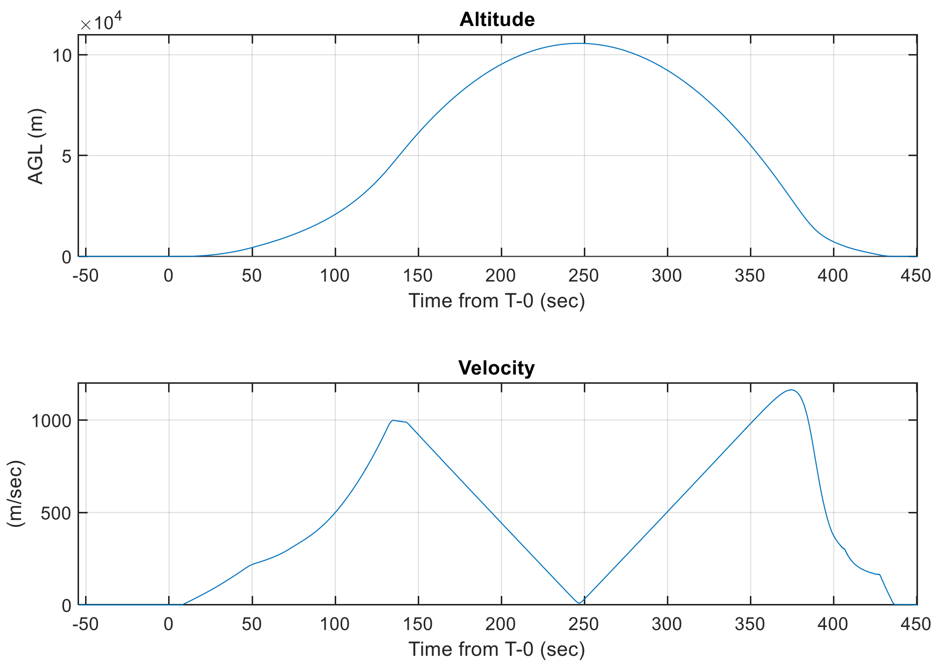


Figure 7: Vehicle altitude and velocity from Flight 1.

The vehicle data was transmitted real-time and logged for detailed post-processing. The estimated errors in the truth position are generally sub 0.1 m, 1-sigma for instance for the descent. Based on analyses of the interface data, the PM met the expected mission environments for thermal and power. The thermal environment was within the predicted range albeit on the colder side. The DLC and OMPS were not adversely affected; however, the NDL did experience issues. A clear field of view for the camera and LiDARs was provided during the flight and most critically on descent. Some dust was observed in both ascent and descent recorded data for the commercial LiDAR. On ascent, lens flare was observed in the DLC camera images. The sensor payloads were successfully operated during the mission. NASA technical personnel were on-site and able to perform real-time monitoring of the payloads. In addition, the NASA Contracting Officer Representative (COR) was on-site and able to make consolidated recommendations and review waivers as required. The post-flight data review and assessment indicates the sensors received the expected commands and were successfully operated. The NASA provided payloads included a large number of steps and checks that were required to operate them successfully. The commercial LIDAR from OADS called the Optical Moon Proximity Sensor (OMPS) provided range and speed measurements using four telescopes. Collected measurements were compared against a sensor model and the differences seen between measurements and predictions were within expectations.

Reference 2 provides a detailed report of the NASA JSC findings from Flight 1. The DLC and sensors were expected to process 400 Hz IMU data, 20 Hz NDL data, and 2 HZ TRN camera images. The IMU and NDL data were successfully processed at the expected rate. However, the camera image rate for flight was 1Hz due to a firmware issue with the camera. The hardware performed throughout the flight and was robust to the thermal, vibration, and shock environments. The DLC included the core flight executive software as well as multiple other applications. The software successfully achieved the primary objective of interfacing with the camera, IMU, NDL, and host vehicle and recording the data during flight. Issues with the timestamping were identified and the recorded data was corrected. Changes were proposed for Flight 2 to correct the real-time performance of this primary objective. Due to the timing issue, the TRN, navigation, and guidance algorithms hosted on the DLC did not perform as expected. Post-flight replay of the data through the software was, however, able to show the expected performance, as detailed in Reference 2.

Reference 2 provides the detailed assessment of Flight 1 by NASA Langley Research Center for the NDL. While NDL operated throughout the flight, the data quality was compromised by elevated background levels which significantly limited the amount of valid range or Doppler speed data collected. The elevated background levels resulted from the operational temperatures being more than 20°C lower than those at which the background was gathered. Approximately fifteen seconds of navigation data during landing and a few seconds during ascent were valid. It was expected to collect about 70 seconds of navigation data in this flight. Reference 2 provides detail on the operational anomalies observed during the flight, presents the valid flight data, and identifies the corrective actions that were pursued for Flight 2.

Reference 2 documents the work performed by JPL to post-process the recorded DLC camera and IMU data through its prototype Terrain Relative Navigation Visual Odometry (VO) and Map Relative Localization (MRL) software. MRL was performed on the data from 25 km during ascent to touchdown on the 20 m/pixel map. The position error, after correcting a simulated position and velocity initialization error, is on the order of 500 m per axis, and converging to 60 m at touchdown. The last image update using the 20 m/pixel occurred at 4000 m altitude due to image/map scale mismatch. The final 23 km of descent were processed separately using the 3 m/pixel map and achieved 5 m position error at touchdown, with the last update occurring at 750 m altitude. Those results are described in JPL's final report contained within Reference 2. The VO algorithm was run on the data from 25 km altitude on ascent through touchdown. The VO received and used close to 50 features per image (the maximum number for this implementation), >90% of which are treated as inliers. We fail to make updates during the final approximately 20 seconds of descent due to high frame-to-frame motion. The VO keeps the velocity error bounded between +/- 12 m/s per axis. As expected, the absolute position error is unobservable and remains close to the initial error.

2.2.2. Flight 2: 26-August-2021

The second flight was successfully completed on August 26, 2021. Based on analysis of the flight trajectory data, the PM met the mission requirements and performed as expected. The detailed trajectory time histories are shown in Figure 2. The PM achieved the 100km altitude objective and performed a propulsive landing. The vehicle data was transmitted real-time and logged for detailed post-processing. The post-processed trajectories have been provided to the partners for comparative analyses. The accuracy of the truth was not as high as that obtained during Flight 1 but was still within +/-1m 1-sigma. Based on analyses of the interface data, the PM met the expected mission environments for thermal and power. The thermal environment was within the predicted range albeit on the warmer side especially early in the countdown. Humidity was higher than the previous flight. The DLC and OMPS were not adversely affected by the conditions; however, the NDL did experience issues attributed to the environments which are described in more detail in the NASA Langley Flight 2 report [2]. The power architecture was sufficient although adjustments had to be made operationally to handle to case of simultaneous operation of the NDL laser and the NDL heater. The maximum predicted vibration and shock were in family with some deviations at specific frequencies notably for the NDL installation. Additional details on the interface data and findings can be found in Reference 2.

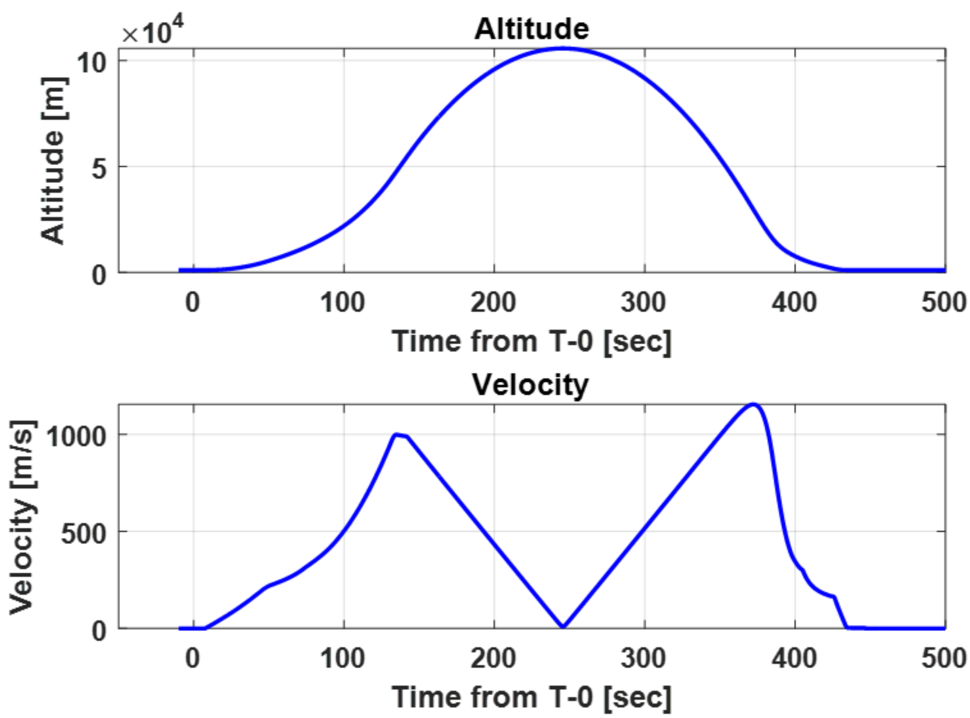


Figure 8: Vehicle altitude and velocity from Flight 2.

A clear field of view for the DLC camera was provided from liftoff through descent. Note this ring fin support included local Helium purge which may have help to provide the clear field of view. The commercial LIDAR experienced nearly complete obscuration at liftoff as did the Blue Origin camera installed in a separate ring fin support. These locations do not have the Helium purge. The field of view cleared approximately 20 seconds after liftoff with data then obtained on ascent until out of range. Based on the recorded data, during landing the field of view was clear. Dust was observed in separate landing videos but did not affect the recorded data. The sensor payloads were successfully operated during the mission. NASA technical personnel were on-site and able to perform real-time monitoring of the payloads. In addition, the NASA Contracting Officer Representative (COR) was also on-site and able to make consolidated recommendations and review waivers. The post-flight data review and assessment indicates the sensors received the expected commands and were successfully operated. Between Flight 1 and Flight 2 numerous changes were made to the NASA sensor hardware and software. This required us to repeat functional tests, calibrations, and integrated tests. Summaries of those activities are provided in Reference 2. There were recorded failures in the procedure steps on launch day for operations from L-1hr through launch. The specific step failures were the checks of the NDL and were due to the NDL anomaly. Multiple attempts were made to recover the performance of the NDL during the countdown. However, these were not successful and there was no clear path to resolution even in the case of an abort. As a result, we proceeded with the launch without the NDL performing as expected. See Reference 2 for more details on the anomaly. The OMPS commercial LIDAR from OADS was re-flown on Flight 2. As mentioned previously, there was clear evidence of the ice and fogging on the Blue Origin optical windows and likely the OMPS windows were similarly affected. The result was loss of 50% of the beams measuring range and nearly all measuring velocity on ascent. Effects of the dust plumes for ascent and descent were not observed in the data. Several velocity measurements did not function as expected and the cause is still being investigated. Collected measurements were compared against a sensor model. Overall, the differences seen between measurements and predictions are within expectations given the performance specifications and the limitations of this analysis.

Reference 3 provides a detailed report of the NASA JSC findings from Flight 2. The DLC and sensors were expected to process 400 Hz IMU data, 20 Hz NDL data, and 10 HZ TRN camera images. The IMU and camera data were successfully processed at the expected rate. No valid NDL data was received during the mission. Aside from some frame drops (including only one during flight), the camera functioned without issue. More than 77,000 TRN camera images were recorded during the pre-flight, flight, and post-flight activities. The hardware performed throughout the flight and was robust to the thermal, vibration, and shock environments experienced on Flight 2. The DLC included the core flight executive, the mode commander, the navigation, the terrain relative navigation, and the dual quaternion guidance software. The detailed assessment of each is provided in Reference 3. In general, all the software components functioned as expected and achieved the primary and secondary objectives for the mission. The corrective actions taken following Flight 1 were demonstrated.

Reference 3 provides the detailed assessment of Flight 2 by NASA Langley Research Center for the NDL. While NDL operated throughout the flight, due to an anomaly there was no valid data obtained. The anomaly is postulated to be a result of susceptibility to Helium [3]. The Helium environment between Flight 1 and Flight 2 was very similar, making it unclear at the time of this report why no data was obtained. Initial testing has been performed on a separate benchtop NDL to identify the susceptibility. Following return of the flight hardware additional investigations are planned to better understand the anomaly. The observed beam pattern prior to and following Flight 2 displayed anomalous characteristics [3]. Recorded data from the integrated functional testing showed fringe patterns on one beam pre-flight and on multiple beams post-flight. This resulted in reduced returned beam power but due to the anomaly mentioned previously the actual effect on performance is unknown. However, it is clear there is a susceptibility of the telescopes to the environmental conditions and cleanliness. The telescopes are being returned and hopefully disassembly and detailed inspection of the telescopes will reveal the root cause. Reference 3 provides detail on the operational anomalies observed during the flight and identifies the planned forward work.

Reference 3 documents the work performed by JPL to post-process the recorded DLC camera and IMU data from Flight 2 through its VO and MRL software. Overall, the VO and TRN performance for Flight 2 was slightly poorer than for Flight 1. These may be due to residual misalignment between the IMU and the camera. Both algorithms, however, still were shown to perform well over the flight which now provided a second data set confirming performance over an expanded altitude and speed envelope. MRL was performed on the data from 30 km during ascent to touchdown on the 20 m/pixel map. The position error, after correcting a simulated position and velocity initialization error, is on the order of 500 m per axis, and converging to 60 m at touchdown. The last image update using the 20 m/pixel occurred at 4000 m altitude due to image/map scale mismatch. The final 23 km of descent were processed separately using the 3 m/pixel map and achieved <15 m position error at touchdown. The VO algorithm was run on the data from 30 km altitude on ascent through touchdown. Reference 3 provide detail on the performance of the software on the Flight 2 data.

2.3. **Conclusions and Recommendations**

The sensors demonstration task successfully completed both of its flights with a combination of commercial and NASA provided sensors. The program objectives of providing the flight opportunity to significantly expand the operational envelope of the sensors was accomplished. While not all the sensors performed as expected or hoped, a large volume of high-quality data was obtained and significant understanding of the maturity, operational complexity, and commercial potential of the sensors. We further demonstrated the utility of the New Shepard Propulsion Module for payloads and future flights have already been manifested through NASA's Flight Opportunities program.

The program highlighted the mutual benefit of an aggressive technology demonstration that included coupled maturation of the payload offering and the payloads themselves. Critical to the success was the ability to perform a second flight to fold in the lessons of the first. Another important element was to carry backup payloads to utilize the opportunity in case one was not ready. We had to exercise this on several occasions during the program. In the end, we flew only 1 of the 3 originally proposed sensors, and 2 of the 3 originally contracted. We added a commercial alternative late in the design cycle that added significant value to the program. The data sets and analysis under the program have provided insight into two optical Terrain Relative Navigation capabilities and two range and Doppler speed LiDARs. The information obtained is guiding the decisions for our commercial lunar lander.

The partnership was formalized in the contract with Blue Origin providing the flight opportunity and NASA delivering the payloads as GFE and associated GFI. This worked but did cause challenges since in multiple reviews the perception was the program was responsible for successful operation of the sensors or that the program was a pure flight contract with Blue Origin as a more traditional launch service provider. The Tipping Point mechanism, however, is about maximizing the learning to the commercial partner – in this case Blue Origin – with NASA supplying the payloads to be evaluated by that commercial partner. This also did drive substantially more effort in integration than expected and compared to a supplier delivered sensor. The contrast was very evident due to the inclusion of the commercial LiDAR in the flights with its substantially lower integration and operational overhead. We will discuss this aspect in more detail in Section 6 when we summarize the maturity and commercial use of the sensor capabilities.

3. BLUE ORIGIN NAVIGATOR – LUNAR VARIANT TASK

This section of the final report describes the work performed on the Blue Origin Navigator – Lunar Variant (BlueNav-L). We begin with an overview of the task and then describe three elements: Blue Origin's contributions, JPL's contributions, and results of the hardware-in-the-loop demonstrations. The first demonstration achieved the task objectives under the contract by showing the integration for the final landing phase. The second demonstration extended the capability to the complete powered descent. We close with task level conclusions and recommendations.

3.1. Task Overview

The NASA/Blue Origin 2018 De-Orbit Descent and Landing (DDL) Tipping Point included infusion of JPL's Terrain Relative Navigation (TRN) software capabilities into the Blue Origin navigator to provide a commercial navigation system for precise and safe lunar landings. The task was to mature the system to TRL 4 (validation in a laboratory environment) through a hardware-in-the-loop real-time demonstration.

The Lander Vision System (LVS) from JPL is a mature TRN used for the Mars2020 Perseverance landing. The LVS was used to achieve safe Mars landing by correlating observed camera images with a priori maps to within 40m 99% confidence. The complete system included a camera, a vision computing element, firmware, and software. All aspects are high maturity with demonstrated performance for Mars landings. The DDL Tipping Point made use only of the firmware and software portions.

Blue Origin has matured navigation capabilities for its flight systems. The Blue Origin navigator (BlueNav) is a GPS/INS system designed in-house, ruggedized, and built in the company's avionics lab. Blue Origin developed the navigation software, simulation, and analysis tools to support the development. BlueNav has successfully operated on multiple New Shepard flights. It is high maturity and provided the point of departure for this task under the DDL Tipping Point.

The task combined the JPL LVS and Blue Origin navigator and adapted them for lunar landings. The effort included updates and developments to both portions and ported the resulting software to candidate high performance spaceflight computing to enable real-time operation. The system was evaluated in representative lunar landing scenarios in a hardware-in-the-loop environment.

3.2. Summary of Blue Origin Contribution

Blue Origin contributed to the successful completion of this task through the regular cadence of coordination meetings and reviews, extending in-house simulation and navigation software, procuring computing hardware, and implementing and leading the demonstrations. Blue Origin's work under this task was funded as corporate contribution to the 2018 DDL Tipping Point contract. In this section, we discuss the Blue Origin contributions for each of the two demonstrations. The demonstration results will be discussed in Section 3.4.

3.2.1. Demo Period Contributions

Blue Origin provided task leadership including coordinating 5 reviews starting from the task kickoff on September 11, 2019 and ending with the first demonstration on November 16, 2020. In addition to kickoff and demonstration, the reviews included a technical interchange for the BlueNav-L task, the interim program review which covered all tasks, and a demonstration workshop planning meeting. Blue Origin conducted weekly working meetings with JPL to coordinate the technical activities.

Blue Origin technical scope for the Demo period included simulation development, navigation application development, avionics hardware and avionics software build-up, and hardware-in-the-loop (HWIL) implementation and testing. These efforts all used the prior work on Blue Origin launch vehicle navigators as the starting point. Figure 9 shows a block diagram of the HWIL demonstration. The simulation focused on 6-Degree of Freedom development of lunar trajectories, modeling the landing sensors and conducting performance analysis. The latter included assessing the performance impact of various execution rates. The navigation application development focused on integrating and processing the JPL LVS code, updates to the navigation filter for the lunar scenario, and interfacing to the various sensor models. For the avionics build-up, Blue Origin procured candidate hardware, the Xilinx Ultrascale+, performed initial benchmarking, and built all the required harnesses. The avionics software focused on sensor device drivers and integration of the software elements onto the computing platforms. For the HWIL integration, the plant side simulation was built-up and deployed to existing Blue Origin assets. The flight side hardware was prepared with the candidate hardware and interfaced to the HWIL. The required playback and simulation integration tools were also updated. Finally, Blue Origin executed the HWIL tests in its facilities in Kent, WA.

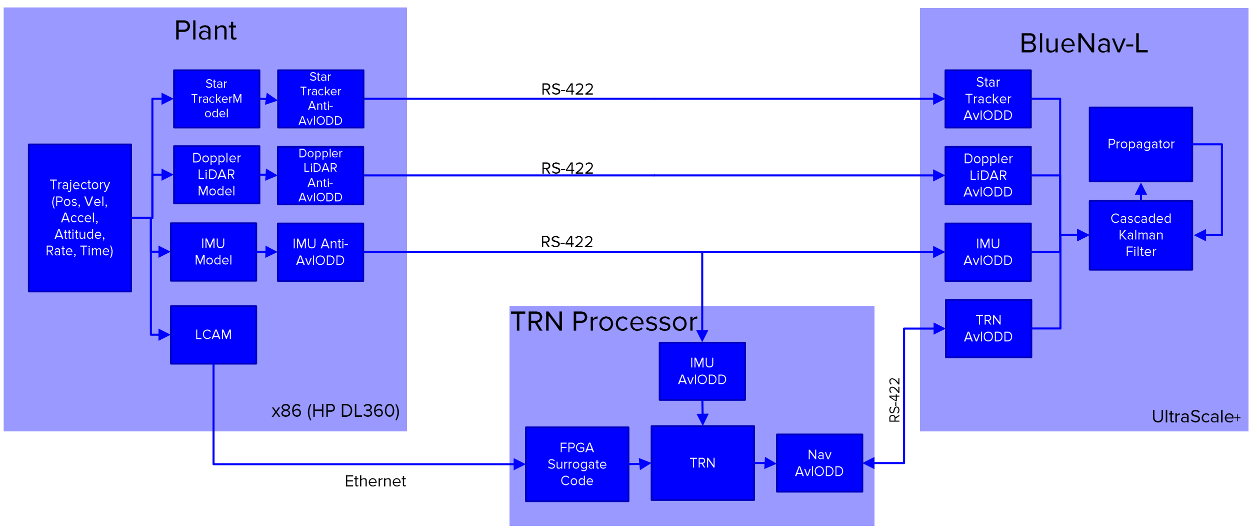


Figure 9: BlueNav-L Hardware-in-the-Loop Demonstration Configuration.

As detailed in Section 3.4, the Demo was successfully completed. Significant developments and contributions were made by Blue Origin and provided foundation for continued development leading to Demo+. The demonstration highlighted the real-time performance and integration of the JPL LVS and the Blue Origin navigator and plant models. Several key limitations from the initial demonstration included considering only the final portion of the complete landing trajectory, use of a readily available and not representative map and scene of the lunar South Pole, and lower fidelity in other sensor and filter models. These were all remedied as part of the follow-on demonstration.

3.2.2. Demo+ Period Contributions

Blue Origin continued the task leadership through the second demonstration on March 30, 2021. A single additional review, corresponding to the actual demonstration, was conducted. The weekly working meetings continued to coordinate the technical activities up to the demonstration.

The limitations identified during the first demonstration were the focus of the contributions during the Demo+ period. The most significant contribution was to utilize South Polar region maps and elevation data. These are shown in Figure 10. Blue Origin obtained and generated the maps required by the LVS and the demonstration. Updates to the LVS software and the related Blue Origin software and interfaces were also completed to address the limitations of the first demonstration. This included embedding the terrain databases and performing map management over the longer trajectory.

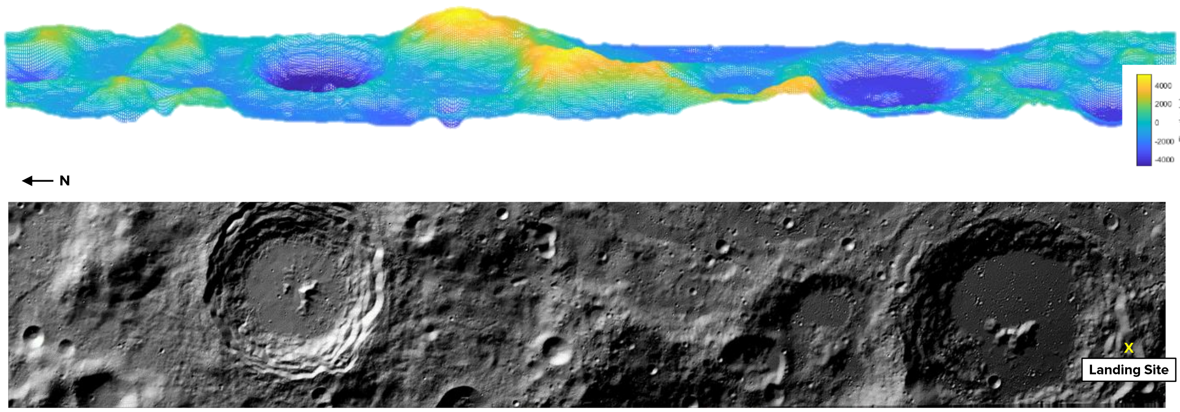


Figure 10: Elevation and map for the extended demonstration from pre-powered descent to landing. Elevation relief (top), Rendered imagery (bottom).

The second major set of updates related to the LiDAR sensor modeling and processing. The large relief of the lunar South Polar regions required updates to the sensor simulation, sensor processing, and filter. These different updates were implemented by Blue Origin and successfully demonstrated in the HWIL.

3.3. Summary of Jet Propulsion Laboratory Contribution

JPL contributed to the successful completion of this task through the regular cadence of coordination meetings and reviews, delivery of Government Furnished Information (GFI) required, and support to the demonstrations. JPL also provided other contributions to the DDL Tipping Point associated with post-flight analysis of the New Shepard flights. These are described in more detail in Reference 6.

In this section, we start with a background of the JPL technology that provided the starting point for this effort. We then discuss the support provided and updates performed during task execution for each of the two demonstrations. The demonstration results will be discussed in Section 3.4. We conclude this section by summarizing other JPL contributions to the DDL Tipping Point.

3.3.1. Technology Background

3.3.1.1. State of the Art

The state of the art TRN is the LVS from JPL developed for the Mars2020 mission. The system operated when the spacecraft was between 4.2km and 500m altitude and determined the lander's position accurately in less than 10 seconds. The LVS was designed for 40m 99% confidence position accuracy and was critical to the safe landing of Perseverance on Mars on February 18, 2021. The precise position was combined with reconnaissance-based safe landing maps to determine if a divert was needed to achieve a safe landing.

The Lander Vision System uses an initial 5 seconds to take three images and process them to calculate a rough position relative to the Martian surface (coarse matching). Large segments of the stored map are used to remove the initial position uncertainty, reducing it from 3200m to 200m 99% confidence. Then, using the initial location solution, additional images are taken and processed every second (fine matching). The fine matching uses an Extended Kalman Filter to reduce the position uncertainty to 40m 99% confidence. The accuracy is dictated by the map resolution. For Mars landing a pair of maps is used as the trajectory is nearly vertical and their resolution was 12m/pixel for the coarse map and 6m/pixel for the fine map.

Current state of the art practice requires that sufficient maps exist to achieve the desired landing precision, that suitable lighting will be available, and that a safe site within the lander capability exists within the targeted site. This is a substantial effort that occurs in advance of launch and has been required for all lunar or Mars landers to date.

3.3.1.2. Application to South Polar Lunar Landing

The first major difference for lunar landings compared with Mars landings is the trajectory. Mars landings utilize the atmosphere for braking, resulting in near vertical trajectories for the landing phase when Terrain Relative Navigation is active. Lunar landings, however, have landing phases that start at 15km of altitude and require nearly 500km of downrange distance for landing. TRN is required at multiple intervals throughout this phase to achieve the desired landing accuracy.

The second major difference for South Polar landings is the low sun lighting angle. This poses challenges for visual spectrum cameras due to large shadowed regions and dependence on the selected landing epoch (date and time of landing). For instance, at locations near the South Pole the sun elevation never exceeds 4 degrees above the local horizon. This is in strong contrast to both the Apollo and Mars lander missions that all have much higher sun elevation angles. The reference maps must be created for the expected illumination and be available over the entire planned trajectory. A single parent map with two resolutions was used for Mars landings, while lunar landings require multiple maps. Map resolution is also a challenge. For Mars, imagery is available with 30cm/pixel resolution, while for the Moon imagery is more commonly 100-200cm/pixel in the South Polar region.

3.3.2. Demo Period Contributions

During the period leading up to the first demonstration, referred to as Demo, JPL supported task management, provided multiple software releases, and coordinate the scope of the demonstration. For the task management, JPL provided materials and supported 5 reviews including the actual demonstration starting from the kickoff on September 11, 2019 and ending with the demonstration on November 16, 2020. The additional reviews included a technical interchange for just the BlueNav-L task, the interim program review which covered all tasks, and a workshop planning meeting. JPL also supported weekly working meetings to coordinate activities and provide subject matter expertise. JPL provided the Mars 2020 LVS software for performance testing in simulation and in the Blue Origin hardware-in-the-loop testbed. JPL refactored the software to the minimum required for LVS functionality on a workstation and included landmark matching and feature tracking (Visual Odometry Simulator (VO-Sim)). The delivered software included navigation state estimation, C-code version of image processing firmware, camera/sensor models (LCAM), and a pre-existing, non-flight lunar map for testing. A government software usage agreement (SUA) was also signed between JPL and Blue Origin allowing use of the LVS core and LCAM software during the contract period of performance. Leading up to the demonstration JPL delivered 7 versions of the LVS core software and 3 versions of the LCAM software. These releases corrected bug fixes, resolved issues identified by Blue Origin during the integration activities, and added features to better support the demonstration. The version used for the demonstration was delivered on October 21, 2020. In addition to the delivered software, JPL supported simulation studies and analysis in preparation for the demonstration. Samples of the image processing steps for a lunar landing simulation from the Demo are shown in Figure 11. Both the coarse matching and fine matching are shown and were used to determine position, velocity, and attitude along the demonstration trajectory. A critical item for the South Polar landings is the sensitivity to lighting. JPL provided analysis results that were shared during the demonstration presentation.

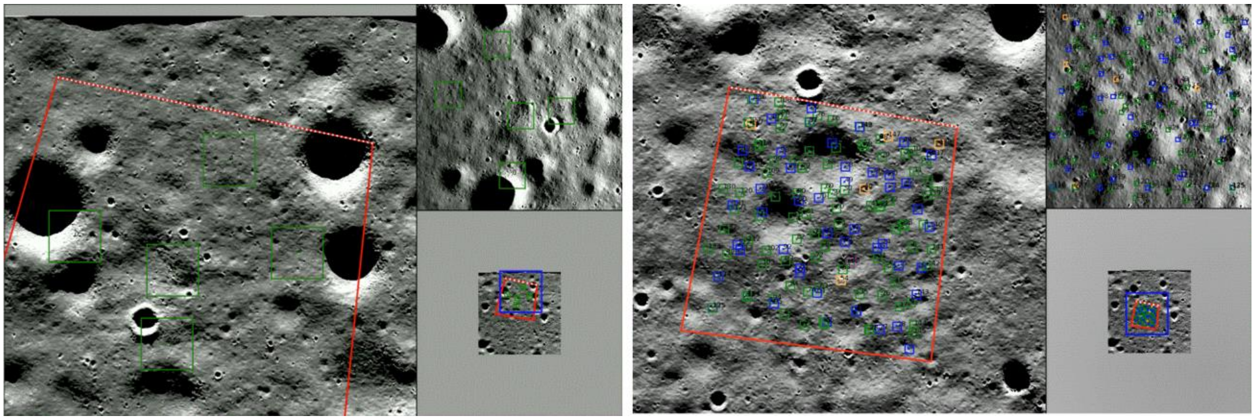


Figure 11: Simulation of JPL Lander Vision System for lunar landing: coarse matching (left) and fine matching (right). In each: camera image upper right, cropped reference map on left, and complete map with comparison regions shown lower right. Matched features shown in green.

3.3.3. Demo+ Period Contributions

During the period leading up to the second demonstration, referred to as Demo+, JPL continued to support task management and provided additional software releases with key added features. JPL also supported the actual demonstration. For the task management, JPL supported weekly working meetings to coordinate activities and provide subject matter expertise. JPL provided an updated version of the LVS core software to manage the lunar horizontal trajectory, updates based on the New Shepard post-flight analysis from DDL TP Flight 1, and several other updates. Multiple map capability was added on top of the LVS core software by Blue Origin and was particularly critical to the performance of the demonstration.

3.3.4. Summary of Other JPL Contributions under DDL Tipping Point

The LVS software was also used to post-process the flight data recorded on the New Shepard DDL Tipping Point flights. The flight recorded camera imagery, inertial measurement unit data, and host vehicle truth data. The JPL results included comparisons to recorded truth data and were documented for Flight 1 [2] and Flight 2 [3]. They are also provided in Reference 6. Most notable was ability of LVS to provide a navigation solution comparing well with truth at 100km altitude and at the high speeds associated with New Shepard propulsion module landing. These represent a significant increase in its operating envelope.

3.4. Summary of Hardware-in-the-Loop Demonstrations

Two demonstrations were performed under the DDL Tipping Point collaboration. As mentioned previously, all the Blue Origin efforts were internally funded and the demonstrations were successfully set up and conducted in the Kent, WA facilities. The original project proposal only planned for the first demonstration, however a second was added to fully utilize the partnership and demonstrate a complete lunar landing scenario. In this section, we summarize each of the demonstrations and document the key findings.

3.4.1. Demo

The primary task demonstration combined the Blue Origin and JPL contributions to show the application of Terrain Relative Navigation and the Blue Origin navigator for lunar landings. The scenario trajectory started at an altitude of 2000m and used JPL's provided available lunar map. The lighting was set to represent the South Pole with the sun angle 5° above the horizon. The map was centered up-range of the landing site and had a resolution of 2m/pixel. The image frame rate of ¼ Hz was used.

The Demo showed BlueNav-L operating during the last 2-min of landing using a single reference map. The navigator was able to fuse the LVS software with measurements from a medium-fidelity LIDAR model with no terrain knowledge. The navigation accuracy was within expectations and consistent with linear covariance studies. All elements executed in real-time on the target hardware.

The demonstration was successful and met the objectives of the task. Several findings were results from the demo. First, LVS/TRN and the BlueNav-L worked at the lunar south pole with lunar imagery and at low sun elevations. These were both new situations for the LVS software and camera simulation. The lunar scenario was also new to the Blue Origin navigator. Second, we achieved flight like compute performance with the C code version of the LVS software. The demo showed ¼ Hz update rate of the software on Ultrascale+ (ARM A53 quad core) hardware. Third, several needed updates were identified to extend to the entire powered descent phase. These included the use of multiple maps, addressing the high terrain relief typical of the South Pole, and being robust to higher altitudes where surface curvature affects performance. Demo+ addressed all of these.

3.4.2. Demo+

This secondary demonstration showed BlueNav-L with JPL's LVS operating during the entire powered descent to landing phase. The scenario began at 15km altitude and 500km range from the landing site. We used multiple reference maps for LVS TRN processing and LIDAR modeling with differing resolutions. These were actual South Pole maps for a representative trajectory. The BlueNav-L fused measurements from a higher-fidelity LIDAR model. The results showed adaptability to large horizontal translation while descending, demonstrated real-time map management, and showed robustness of the implementation to high terrain relief. The demonstration was successful and met the extended goals of the task.

3.5. **Conclusions and Recommendations**

3.5.1. Conclusions

The task met its objectives through the Demo and then expanded the maturity and capability under the Demo+. We infused JPL's LVS into Blue Origin's in-house navigation capability to achieve a system for precise lunar descent and landing. The Blue Origin scope was internally funded with NASA providing JPL software and technical support. The effort integrated high fidelity sensor models, a real-time navigation filter, reference map generation/management, and the NASA JPL Lander Vision System. We demonstrated feasibility of BlueNav-L in hardware-in-the-loop with the JPL LVS running on surrogate hardware and representative CONOPS. The final demonstration ran real-time for the full powered descent phase to landing and used representative map data from the lunar South Pole. The effort under this task achieved the goal for Technology Readiness Level (TRL) advancement for this capability to TRL 4 (validation in a laboratory environment).

3.5.2. Recommendations for Future Work

The final demonstration showed the maturity of the updated LVS and BlueNav-L for application to precise lunar landing. Work does remain on confirming the robustness and tuning key parameters for the lunar South Pole scenario. Assessing performance for other lunar landing scenarios is also forward work. The next major step is to combine the software and candidate hardware with the other elements of the system, specifically the camera, into a prototype for flight demonstration. That demonstration can take place either terrestrially or on an upcoming lunar mission to advance to TRL 6+ (system prototype demonstration in a relevant environment).

4. FLASH LIDAR TASK

4.1. Overview

The NASA/Blue Origin 2018 De-Orbit Descent and Landing (DDL) Tipping Point included a demonstration of Flash LiDAR with NASA's super-resolution (SR) software. The SR technology adds the capability to increase the spatial resolution of the native Flash LiDAR range images to a point where the sensor is viable for lunar hazard detection. Given the nearly instantaneous measurement of the Flash LiDAR technology, this could offer a fuel savings when landing on the Moon and improved customer payload capability. In addition, given the LiDAR technology does not need ambient light, this sensor is in the class that could enable safe landing even in permanently shadowed regions.

This task of the DDL Sensors Tipping point is a public-private partnership to demonstrate NASA and commercial hazard detection technology. Through this demonstration Blue Origin has gained valuable insight into the maturity of Flash LiDAR with super-resolution, and this will better inform the strategy for ensuring safe landing during future lunar landing missions.

The task consisted of calibration and characterization of the Flash LiDAR, characterization of the SR algorithm, implementation of the real-time SR algorithm on a high performance Graphics Processing Unit (GPU), assembly of the complete breadboard system, and dynamic tests of the completed breadboard system at the NASA Langley Research Center (LaRC) Landing and Impact Research Facility ("Gantry"). Blue Origin then received return shipment of the Flash LiDAR and GPU it had purchased with the compiled SR software installed. They then conducted ground testing in their facilities to cement the learnings and to better inform the future development strategy.

4.2. Key Results and Findings

Completion of this task was an example of the potential mutual benefits for public-private partnerships. Blue Origin provided the hardware required to complete the Flash LiDAR and super-resolution software maturation. NASA Langley provided the software development and testing experience. The combination and work completed provides a foundation for future collaboration.

The Blue Origin procured hardware consisted of items purchased from Advanced Scientific Concepts (ASC), LLC as well as AiTech, Inc. From ASC we purchased one integrated TigerCub camera and 1064 nm laser system, one camera body without laser, camera control systems (laptop computers) with ASC software installed, two optics kits (15 deg and 8.6 deg field of view), and all non-recurring engineering (NRE) associated with purchase of these items. From AiTech we purchased two A176 Cyclone ruggedized GPUs and one harness assembly to connect the Flash LiDAR, GPU, and camera controller laptop together.

These items were loaned to NASA Langley to perform the laboratory characterization and Gantry testing. The hardware was returned to Blue Origin by the end of the period of performance of the contract. The details of the testing performed at NASA Langley along with the key results and findings are provided in References 3 and 8.

After the Gantry test was completed, the hardware was returned to Blue Origin's facility in Kent, WA as was all of the digital data from the NASA test activities. A government software usage agreement (SUA) was also established between NASA and Blue Origin allowing use of the SR software during the contract period of performance. The purpose of this agreement is to allow Blue Origin to use the algorithm on-site for research purposes. Blue Origin was able to successfully set up the Flash LiDAR, control station, and GPU hosing the SR software in one of our Kent, WA laboratories. Basic operation of the software was verified at Blue Origin. An issue was encountered with the unit in the benchtop testing that required repairs to be performed by ASC. The root cause was due to overexposure of the receive detector photodiodes from unattenuated laser backscatter. We have since had ASC repair the unit and in parallel performed further analysis to verify hardware safety is always maintained in every operating environment (lab and field testing). Continued collaboration with LaRC and ASC have allowed us to enhance our LiDAR testing infrastructure by prescribing ND filter solutions as a function target range. These recommendations have now been included in our test procedures allowing execution of safe and repeatable lab testing for sensor characterization. We are also finalizing a modular test platform and target for use in our 7-DOF gantry facility to exercise Super Resolution in a short range (< 10 m) lab-controlled environment. The gantry testing is planned with preliminary results expected in early Dec 2021.

In parallel, we have also initiated the procurement of a heavy lift drone and gimbal platform that will hold the ASC Flash Lidar and accompanying computer enabling more flight representative testing. This airborne test platform will provide the ability to rapidly vary test variables such as slant range and incident angle while in-flight over our existing 100 m x 100 m hazard field facility at Launch Site One in West Texas. In preparation for the drone delivery in Q1 of 2022, we have also been coordinating the required FAA heavy lift drone certificate of authorization and incorporating additional safety requirements per ANSI Z136.6 - Standard for Safe Use of Lasers Outdoors into airborne test procedures. The end goal for this campaign is to validate our lunar hazard detection and avoidance simulations with anchored sensor models that allow us to trade lander and DDL mission variables like vehicle hazard tolerance and divert delta-V allocation. As this testing will take place outside of the program period of performance, we have initiated a software usage agreement for the Super Resolution software and user software. We will also explore other avenues for continued collaboration with NASA Langley experts during this Blue Origin led test campaign.

4.3. **Conclusions and Recommendations**

Overall Blue Origin considers this a successful collaboration with NASA. However due to the timing of this activity during the COVID-19 pandemic, several issues were encountered that impacted schedule and information exchange. The original scope of work included more in-person exchange between Blue Origin and NASA to help facilitate knowledge transfer from NASA technology experts to Blue Origin. After one early technical interchange meeting, the Blue Origin task lead was only able to attend one day of the first round of Gantry tests in person. While this access was greatly appreciated, it was insufficient to provide Blue with enough experience in operating the SR software to enable independent high-proficiency use. On-site work at Blue Origin was also severely limited in accordance with state and local health guidelines, and so only essential work on-site was performed to verify hardware and software functionality. Additional on-site work and information exchange is still needed between Blue Origin and NASA to complete transfer of proficiency to Blue Origin. While we consider the DDL Flash LiDAR Demonstration task complete, we plan to use internal Blue Origin resources to gain proficiency with the hardware and software going forward.

The capabilities of the Flash LiDAR with SR demonstrated by this task are impressive and are detailed in References 3 and 8. Through the separate but complementary Precision Landing Announcement of Collaboration Opportunity (ACO) contract with NASA, Blue Origin is leading a system study to further quantify the value of hazard detection sensor performance parameters. The Flash LiDAR with SR offers the fastest DEM generation time compared to alternative scanning LiDAR systems, and this may translate into fuel savings if the spatial resolution of the range images is sufficient. Further work is required to determine what is "sufficient" and to understand the configuration of the system that meets the hazard sensing requirements.

5. PROGRAM LEVEL CONCLUSIONS AND RECOMMENDATIONS

In this section of the report, we review and summarize the total program accomplishments from the perspective of providing value to the offeror for its investment and in the maturation of the technologies toward commercialization. We follow with recommendations for future Tipping Points.

5.1. **Conclusions**

Referring to Section 2.1, the primary program objectives were:

1. Demonstrate the performance of NASA-developed and contractor provided precision landing sensor and processing on the New Shepard Propulsion Module
2. Demonstrate a commercial navigation system for safe and accurate lunar landings using NASA-developed Terrain Relative Navigation (TRN) algorithms as part of a Hardware-in-the-Loop (HWIL) simulation environment
3. Develop and demonstrate a Flash LiDAR prototype for hazard detection derived from NASA-developed Flash LiDAR sensor design and image processing software

The task summaries provided in Sections 3, 4, and 5 have documented in detail that these objectives were all met by the program. We have also summarized in those sections the Blue Origin funded work, which exceeded 25% of the originally proposed total program cost, as required by the Tipping Point program.

The summaries of the combined work do not, however, provide a clear view of whether the high-level intent of infusing these technologies into commercial products has been met. To provide an integrated view of the accomplishments and a frank assessment against the high-level intent of the Tipping Point program, we summarize the accomplishments on a per technical capability – sensor, software, or hardware – against several key metrics. We have decomposed the capabilities into separable items that are of interest or have potential for further commercial development from the Blue Origin perspective. Table 1 lists and briefly describes the capabilities, identifies the task which provided the data for evaluation, and summarizes the accomplishments within the task. The scope is limited to testing performed as part of the DDL Tipping Point and documented in this final report. Three metrics were used to assess the maturity and readiness for commercial use per the objectives of the Tipping Point program. These are:

1. Extent of data gathered under the program that could be used to advance the technology readiness level. This metric measures the quality and quantity of data obtained and rated as: Yes, No, or Partial. We limit our evaluation to the data produced within the scope of this program.
2. Operational and integration maturity of the capability. This metric measures the complexity associated with incorporating the capability, is qualitative, and is defined by three levels: low, medium, and high. This represents the level of effort required to incorporate the capability as demonstrated by the effort required on the program.
3. Commercial availability of the capability. This metric is binary – either available or not – and is evaluated based on access, whether through a non-exclusive license, a software release, or commercial procurement.

These criteria are all subjective and only from the Blue Origin perspective based on the program experience. Table 2 provides the metrics for each of these and the justification.

Table 1: Summary of capabilities tested during DDL Tipping Point and major accomplishments.

Capability	Description	Task	Accomplishments
Flash LiDAR	Sensor procured from ASC as commercial item	Flash LIDAR Demonstration	Tested in lab setting and on gantry by NASA Langley as part of integrated system.
Super-resolution Software	Software provided by NASA Langley and deployed to the GPU	Flash LIDAR Demonstration	Tested in lab setting and gantry by NASA Langley as part of integrated system.
Map Relative Localization Software	JPL's MRL software as delivered in C-code and modified for run-time performance and lunar application	BlueNav-L Demonstration Sensors Demonstration	Updated and deployed to representative hardware, integrated into the real-time hardware in the loop, and demonstrated on representative lunar scenario. Replay of New Shepard recorded flight data compared with truth.
Visual Odometry Software	JPL's VO software as delivered in C-code	Sensors Demonstration	Replay by JPL of the New Shepard recorded flight data and comparison with truth.
Blue Origin Navigator Software	Navigation algorithms and software that interfaces with JPL's MRL and other sensors	BlueNav-L Demonstration	Developed and deployed to representative hardware, integrated into the real-time hardware in the loop, and demonstrated on representative lunar scenario.
Blue Origin Navigator Computer	Navigation computer that hosts JPL's MRL and separately Blue Origin's navigation software	BlueNav-L Demonstration	Hosted software, integrated into the real-time hardware in the loop, and demonstrated on representative lunar scenario.
New Shepard Propulsion Module	Platform for testing lunar landing sensors in representative environment	Sensors Demonstration	Successfully completed two flights with multiple sensors, validated environments and interfaces, and provided quality truth data to payloads.
Commercial Doppler LiDAR	Sensor procured from Optical Air Data Systems as commercial item	Sensors Demonstration	Sensor qualified, installed, and operated as expected for two flights. Robust to environments and data compared to truth.
DLC Camera and IMU	Sensors procured as commercial items by JSC.	Sensors Demonstration	Sensor qualified, installed, and operated generally as expected for two flights. Minor camera anomaly on Flight 1.
DLC Computer	Computer built by JSC and hosting core and application software.	Sensors Demonstration	Hardware qualified, installed, and operated as expected for two flights.
DLC Software – Core Software	Core software from JSC to manage sensor interfaces, logging, etc.	Sensors Demonstration	Software qualified and operated for two flights. Major timing and other anomalies on Flight 1 and minor anomalies but otherwise excellent performance on Flight 2 after updates.
DLC Software - Applications	Navigation, guidance, and TRN application software from JSC	Sensors Demonstration	Applications developed and exercised for two flights. Anomalies on Flight 1 and excellent performance on Flight 2 after updates
Navigation Doppler LiDAR	Doppler and ranging LiDAR from Langley.	Sensors Demonstration	Qualified, integrated, and operated for two flight. Major anomaly on Flight 1 with very limited valid data, major anomaly on Flight 2 with no valid data recorded.

Table 2: Blue Origin assessment of capabilities maturity based on testing during DDL Tipping Point.

Capability	Technology Readiness Data Gathered	Integration/ Operations Maturity	Commercial Availability	Justification
Flash LiDAR	Yes	Medium	Available	Tested in a ground environment. Sensor is commercial item procured from a supplier with necessary artifacts and support. Limited Blue Origin experience.
Super-resolution Software	Yes	Low	Not Available	Tested in a ground environment not representative of landing dynamics. Interfaces and operations not documented or validated. Software not available in the catalog without complicated licensing.
Map Relative Localization Software	Yes	Medium	Available	Tested in a representative environment inclusive of lunar landings and real-time data. Tuning and map building drive the integration complexity. Available in NASA software catalog and can be licensed.
Visual Odometry Software	Yes	N/A	Available	Not evaluated by Blue Origin during the program but was by JPL using New Shepard flight data. Code was delivered and is available in the NASA software catalog and can be licensed.
Blue Navigation Software	Yes	Medium	Available	Tested in a representative environment inclusive of lunar landings and real-time data. Tuning and required further maturation and qualified drive the integration complexity. Full commercial rights retained by Blue Origin.
Blue Navigation Computer	Yes	Medium	Available	Tested on the bench in hardware-in-the-loop. Continued maturation requires packaging and qualification along with interfaces to the sensors.
New Shepard Propulsion Module	Yes	High	Available	The PM payload spaces are now available for commercial use through the Flight Opportunities.
Commercial Doppler LiDAR	Yes	High	Available	Sensor completed qualification and was demonstrated on two flights up to or exceeding its published envelope. Integration and operations were straightforward. Remaining maturation is associated with flight build.
DLC Camera and IMU	Yes	High	Available	Sensors completed qualification and were demonstrated on two flights. Integration and operations were straightforward. Need to mature a flight build.
DLC Computer	Yes	High	Not Available	Computer completed qualification and was demonstrated on two flights. Integration was straightforward. Not commercially available and utilizes custom boards.
DLC Software – Core Software	Yes	Medium	Available	Core software completed qualification and was demonstrated on two flights. Integration encountered some issues. Software is available (older release).
DLC Software – Applications	Yes	Medium	Not Available	Applications completed qualification and were demonstrated on one flight. Some integration and operational complexity. Source code not available in NASA catalog.
Navigation Doppler LiDAR	Partial	Low	Available	Sensor was qualified, gathered data, but failed to operate on either flight. Environments were cited and remains to be resolved. Commercial units have not yet been built but can be purchased.

For the capabilities from the Flash LiDAR task, the maturation goal from the proposal was met. Challenges to commercial use, however, remain due to operation complexity, access to the software, and available licensing. Currently exclusive rights for the software are licensed to a third party that was not a participant in the Tipping Point. The developments under the program and the licensing will need to be resolved for further commercial development. In addition, there was limited opportunity for Blue Origin to work with the system and particularly the Super-Resolution software, which effected the operations maturity assessment. Custom NASA provided ground software, also subject to licenses, are required at this time.

For the capabilities associated with the BlueNav-L task, the maturation goals of the proposal were met or exceeded. This task was an excellent example of the public-private partnership potential. JPL's MRL software source code was provided to Blue Origin who then performed integration work and identified multiple improvements for its application to lunar landing. JPL delivered software updates based on these recommendations and the iterations led to two successful demonstrations. The delivery of the source code also allowed Blue Origin to shadow JPL in the post-flight analysis of the New Shepard flights and gain first-hand experience with it. Combined, these activities allowed Blue Origin to have a clear path of infusion onto a commercial product. A path to commercial license is clear if used on any government sponsored missions and a path for pure commercial use is also clear. The medium rating for complexity stems primarily from experience with the maps critical to the capability. The availability and certification of maps along with lighting challenges are critical differentiator between the lunar and high maturity Mars application (the Mars2020 LVS). Metrology, calibration, and tuning were also required to obtain the results shown in the reports and add to the operational complexity. The hardware used also still requires maturation, primarily in the areas of radiation tolerance and packaging into a flight unit. Blue Origin has been exploring alternative hardware with higher radiation tolerance, shown that all the software items run on the alternate hardware, and is working on packaging. This collaboration highlights the benefit of NASA providing software capabilities with industry providing the hardware for flight implementations.

For the capabilities associated with the sensors demonstration task, the maturation goals were met but not with the originally proposed sensors. The goal of maturing the New Shepard Propulsion Module for payloads was also fully met and payloads are being manifested now through NASA's Flight Opportunities Program. Refer to the left side of Figure 1 with its three sensors: the Lander Vision System (LVS), the Long Range Altimeter (LRA), and the Navigation Doppler Lidar (NDL). Only the NDL actually made it to flight as the COTS prototype LVS hardware was unable to be hardened to the environments and the LRA was no longer flight or even ground test ready. The NDL unfortunately encountered anomalies on both flights, each associated with environmental factors. Fortunately, two alternatives were included in the program after award: the DLC from NASA JSC and a commercial Doppler LiDAR from Optical Air Data Systems. The latter was included after the Critical Design Review once it became clear the LVS COTS prototype could not achieve flight worthiness. The DLC and commercial LiDAR operated successfully on both flights and provided two complete sets of data needed on precision landing sensors. Multiple capabilities, as indicated in Table 2, are ready for commercial use and are of high technical and integration maturity. One critical capability – the DLC application software – is very attractive to Blue Origin but is not available since the software is not available for licensing in NASA's catalog. The DLC hardware also offers a challenge since there is no commercially available supplier for it. As discussed on the other tasks, Blue Origin sees the best path as NASA releasing the source code to the software catalog where it can be licensed and included into integrated software and hardware for flight.

5.2. **Recommendations**

The DDL Tipping Point has been very successful in infusing and increasing the understanding of NASA's technical capabilities in precision landing into industry. The model of public-private partnership – either through the Tipping Point mechanism or the related Announcement of Collaborative Opportunity – are strongly recommended to be continued by NASA's STMD. Here we make a few recommendations that are the opinion of the Contractor, Blue Origin.

The discussion in Section 6.1 highlights a few recurring themes related to software. In each task, the availability of NASA funded software is cited. Going forward, we recommend that NASA ensure software items which it has funded be readily available in the software catalog for industry partners to obtain, extend, and incorporate into their products. For many of the software capabilities within this program that was not the case with the most notable exception being JPL's MRL. The software applications on the DLC, funded by NASA and demonstrated under this program, for instance should be candidates for release. We intend on future Tipping Points and ACOs, as we did only in the case of the MRL and VO in this program, to have source code be an explicit GFI or deliverable. This will allow for closer inspection and maturation of the software aspects. In the sensor demonstration, for instance, we encountered multiple cases of undocumented behavior of the NASA payloads that, if not resolved, will cause future qualification or operations challenges.

The discussion in Section 6.1 also highlights a few recurring themes related to hardware. When hardware is to be delivered, we plan in the future to include a commercial entity to build the units to achieve technology readiness levels above TRL 6. Engineering Development Units (EDUs) should be the last level of NASA led hardware build if there is an intended future transition to a commercial provider. Otherwise a gap may remain to achieve commercialization. For higher maturity, such as TRL 7 or Engineering Test Unit (ETU) level, NASA can provide oversight in the build but not be leading. At this state of maturity, a separate validation campaign may be needed to confirm build quality and performance once transitioned to commercial supplier. We consider a successful New Shepard flight and the steps leading up to it to achieve at least TRL 7. As such, there is lost opportunity when the sensors under test are not at that level of maturity.

A final common comment is on the use of Technology Readiness Levels as a metric. STMD should strive to include more than just pure TRL metric, adding the integration/operations and commercial availability as additional maturation metrics. For successful transition of technologies to industry, these aspects need to be brought in earlier.