New Shepard Flight Test Results from Blue Origin De-Orbit Descent and Landing Tipping Point

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Under the public-private Tipping Point partnership between NASA and Blue Origin, two suborbital flights were performed using New Shepard to gather data on precision landing sensors. The flights collected data from NASA provided landing sensors, a commercial landing sensor, and host vehicle truth data for comparison. The flights significantly expanded the operational envelope of the sensors, achieving altitudes exceeding 100 km, speeds exceeding 1000 m/s, and included a propulsive landing. In this paper we provide a summary of the flights, including overview of payloads, preparations, and execution. We review the performance of the host vehicle and the commercial LiDAR. These flights were the first uses of the New Shepard Propulsion Module as a testbed for payloads.

I. Nomenclature

ALHAT	Autonomous Landing and Hazard Avoidance
CC	Crew Capsule
COBALT	CoOperative Blending of Autonomous Landing Technologies
CON	Center of Navigation
DDL	De-orbit Descent and Landing
DEM	Digital Elevation Map
DLC	Descent and Landing Computer
LiDAR	Light Detection and Ranging
LRA	Long Range Altimeter
LVS	Lander Vision System
NDL	Navigation Doppler LiDAR
OADS	Optical Air Data Systems
OMPS	Optical Moon Proximity Sensor
PM	Propulsion Module
PPP	Precise Point Positioning
SPLICE	Safe & Precise Landing – Integrated Capabilities Evolution
TRN	Terrain Relative Navigation

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II. Introduction

The NASA/Blue Origin 2018 De-orbit Descent and Landing (DDL) Tipping Point Program is a public-private partnership that includes a task to flight demonstrate NASA and commercial precision lunar landing sensors on a representative and challenging flight trajectory. The integration of NASA developed technology into a state-of-the-art launch vehicle, New Shepard, provided opportunities to mature critical sensor technology and algorithms that enable precise and safe landing. Through this demonstration both parties gained valuable insight into the maturity of precision landing sensors to better inform their strategies for future precision landing missions. The program included two flights on the New Shepard launch vehicle with NASA and commercial sensor payloads. The results of those flights are the focus of this paper. The program is referred to as the Blue Origin De-orbit Descent and Landing Tipping Point (BODDL-TP).

The demonstration built on completed and ongoing NASA-led development efforts, including the Mars 2020 Lander Vision System (LVS), Autonomous Landing and Hazard Avoidance Technology (ALHAT), and CoOperative Blending of Autonomous Landing Technologies (COBALT). The ALHAT program [1] culminated with low altitude flight demonstrations on the Morpheus vehicle of the Long-Range Altimeter (LRA) [1,2] and the second-generation Navigation Doppler LiDAR (NDL) [1] both from NASA Langley. Other sensors and capabilities were also tested [1]. COBALT [3] followed on to ALHAT and continued the NDL maturation and incorporated the Lander Vision System (LVS) from JPL. The LVS is a Terrain Relative Navigation (TRN) capability [3]. Flight demonstrations of these sensors and other capabilities were accomplished in 2017 on the Masten Xodiac vehicle [3]. Altitudes of ~500 m and speeds of ~25 m/s were achieved. The sensors from these programs formed the basis for New Shepard flights under the Tipping Point: the LVS from JPL, and the LRA and NDL from NASA Langley. All three were proposed as environmentally hardened versions of sensors previously flown on ALHAT or COBALT. Figure 1 shows the flight profile of the New Shepard vehicle and the originally planned sensors. As shown in Figure 1, the flight profile for New Shepard begins from the ground, continues to approximately 100 km altitude, and then returns for a propulsive landing of the Propulsion Module (PM) and a parachute landing of the Crew Capsule (CC). The primary flight objective was to remove 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 a lunar landing by increasing attainable altitude from <1 km to ~100 km, increasing vertical velocity from ~25 m/s to ~1000 m/s and providing exposure to a representative launch and space environment. The tests were planned to expand the flight envelope and technical maturity beyond previous NASA airborne tests and capture or exceed the full range of operation for each DDL sensor.

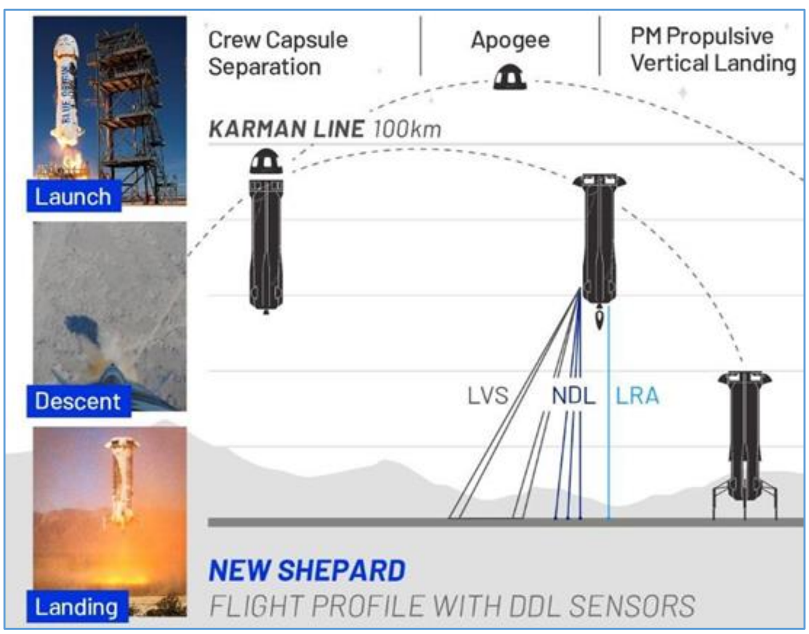

Figure 1: Proposed DDL Tipping Point Flight Demonstration on New Shepard.

The follow-on program to COBALT, the Safe & Precise Landing–Integrated Capabilities Evolution (SPLICE) program, continued to mature the NDL, an alternative TRN, and additional software and hardware for precise landing [4]. The NDL was an Engineering Test Unit packaged for the launch and space environments. The alternate TRN and other capabilities were hosted on NASA JSC's Descent and Landing Computer (DLC) in an Engineering Development Unit. To leverage these developments and realizing some of the sensors in their form factor from ALHAT or COBALT were not robust or mature enough to fly on New Shepard, the program focused on the latest SPLICE sensors for integration. Just after the Critical Design Review, however, it became clear the LVS hardware, which was a ruggedized version of an early LVS COTS hardware prototype, not the Mars 2020 LVS Vision Compute Element, was not able to be ready for flight and was removed from the manifest, freeing up a payload location. This provided the opportunity to integrate the Optical Moon Proximity Sensor (OMPS) [5] from Optical Air Data Systems (OADS). The OMPS is a commercial Doppler LiDAR providing range and Doppler speed measurements along 4 beams. All of the NASA provided sensors were in active development in parallel to the flight demonstration integration effort. This allowed the very latest NASA sensor developments to be tested under the program. Including the latest sensor improvements offered a substantial increase in the technology learning and partnership between Blue Origin and NASA.

In parallel to the sensor development, the New Shepard PM payload accommodation was matured. This paper does not describe the details of those accommodations which can be found in Reference 5. The objective was to provide equivalent maturity as payloads on the CC which are offered through NASA's Flight Opportunities program. New Shepard, prior to the two Tipping Point flights, had accomplished multiple CC payload missions and was an established provider of suborbital flights. Two additional successful CC payload flights and the two inaugural PM payload flights have been accomplished during this program.

The final set of PM payloads included the NDL from NASA Langley, the DLC from NASA JSC, and the OMPS procured from OADS and provided by Blue Origin. The host vehicle truth data was provided by the Blue Origin Navigator (BlueNav). While the LVS hardware had been removed from the manifest, the recorded camera and IMU data were replayed post-flight through JPL's LVS software to understand its performance [6]. Together these payloads provided insight on two approaches for TRN and two Doppler LiDAR systems. Details of the NDL and DLC performance can be found in Reference 5. The results of JPL re-processing the data through the LVS software are available in Reference 6. This paper provides information on the installation and operation of all the payloads and then review the host vehicle truth data and the OMPS data.

III. Sensor and Operations Description

A. Sensor Overview

The final set of sensors included the NDL from NASA Langley, the DLC from NASA JSC, and the OMPS procured from OADS. The NDL consists of an electronics box and laser connected by fiber optic cables to three telescopes [7] mounted at fixed angles within one of the transition tunnels, see Figure 2. The NDL sends near infrared (1550 nm wavelength) laser beams to the surface, and the reflected returns are detected to provide an estimate of the lander's velocity and range relative to the ground. The unit has been under development and completing low altitude testing for many years [2, 3].

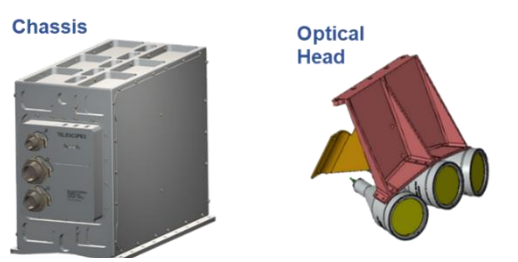

Figure 2: Navigation Doppler LiDAR from NASA Langley.

The DLC system includes a high-performance computer, camera, and an IMU for measuring attitude rates and lateral accelerations. The camera and IMU provide data to the TRN software running on the DLC. The output from the TRN on the DLC was provided to a navigation filter that estimates the vehicle's position, velocity, and attitude in real-time. The DLC also ran advanced guidance algorithms in a shadow mode [5, 8]. The recorded images and IMU data were post-processed through the LVS software from JPL, which was matured and used for Mars 2020 [6].

The OMPS, shown in Figure 3, has prior spaceflight heritage and consists of a small electronics box and four telescopes. The measurement principle, while still a LiDAR at 1550 nm wavelength, is different from the NDL and leverages OADS's years of development in terrestrial LiDARs for wind turbines, helicopters, and aircraft.

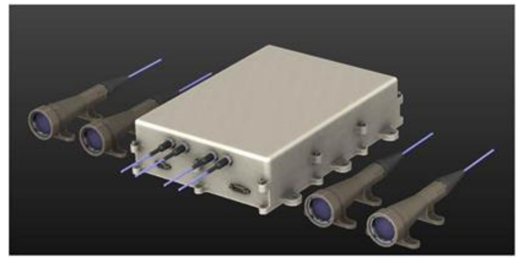

Figure 3: Optical Moon Proximity Sensor from Optical Air Data Systems.

B. Sensor Installation

As described previously, each unit consists of a chassis and a sensor head. The chassis were installed under the PM "table-top" and the sensor heads were installed in the transition tunnel and ring fin support to provide views to the ground during launch and descent. Figure 4 shows these installations in a CAD view and as installed. We installed the NDL telescopes just below the camera and IMU from the DLC. The OMPS telescopes were installed in a separate transition tunnel from the combined NDL and DLC sensor heads. Also shown in the CAD view is BlueNav, which provided the "truth" data and was the Center of Navigation (CON) to which all the flight data was referenced. The BlueNav was located above the NASA sensor head assemblies. The integration process included metrology of the as-installed sensor head assemblies, a camera calibration, and LiDAR beam finding which confirmed the seven line-of-sight vectors. These preparations ensured high accuracy knowledge of the installed sensors.

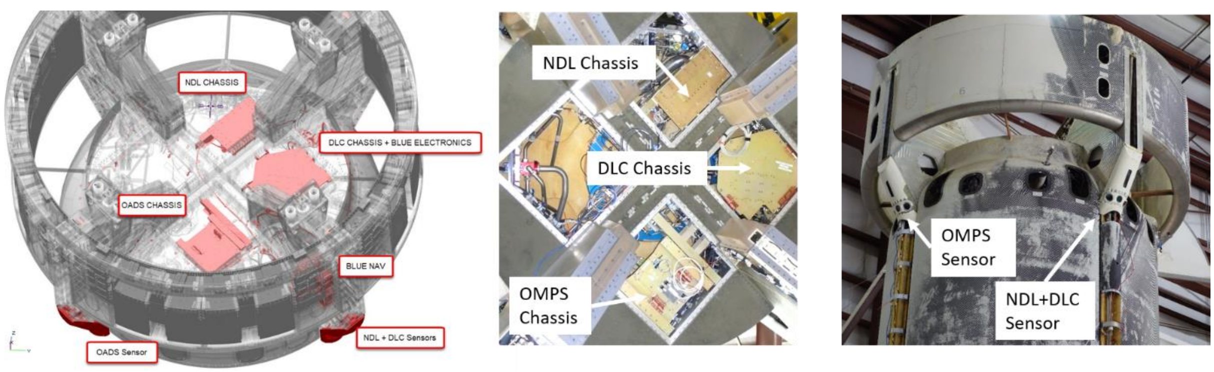

Figure 4: Installation of the DDL Sensor payload chassis and sensor heads on the New Shepard PM.

The sensor chassis and the supporting items such as batteries, payload controller, and switches were built-up in three separate assemblies, which are shown in Figure 5 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 for interface and functional verification as the flight versions and associated wire harnesses were being installed on the vehicle in parallel to the benchtop testing. The testing also exercised the operational procedures. The subassemblies and the sensor head assemblies were installed on the PM for the integrated system testing and for the two flights. After integration, pre-launch test activities were completed and the system was ready for test flights.

C. Operations

Each system was commanded and managed through the Blue Origin provided payload computer and power systems. Data and command interfaces were used to execute the launch operations. While the New Shepard host vehicle provided power to both the NDL and DLC, the data and command interface was solely with the DLC. This was by design as NASA wanted to demonstrate its integrated precision landing suite on New Shepard. We separately provided data and power to the OMPS. For these PM payloads, the NASA partners and Contracting Officer Representative were on-site supporting the launch operations in West Texas. Operations started at L-4 hr to cycle the payloads through their nominal operational sequence and complete hardware and software checks. We provisioned for some amount of troubleshooting if required. The NASA payloads were then shutdown awaiting the L-1 hr point. At that time, the payloads were booted and cycled through their planned second checkouts in preparation for flight. Between these sets of checks, cryogenics were loaded on the vehicle and numerous other launch activities were completed. Critical payload contingencies were executed at this stage, if required, in final preparations for launch. This ensured the primary mission objective of operating and recording the sensor data sets was met. It was not the responsibility of the DDL Tipping Point program to ensure successful operation of the NASA sensors. All the sensors began acquiring data while still on the launch pad. Data was recorded during ascent and descent to propulsive landing, and then distributed to the partners.

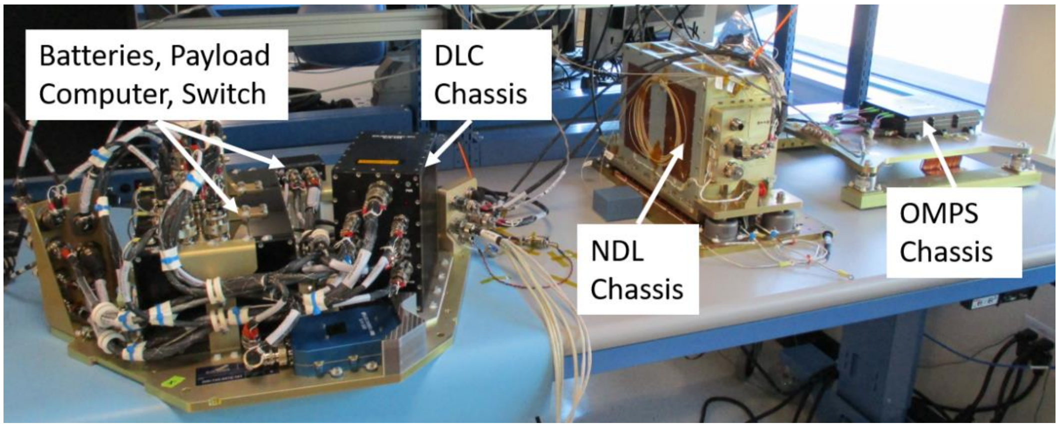

Figure 5: The DDL Sensor payload chassis and supporting payload services subassemblies.

D. Flight Summaries

Flight 1: 13-October-2020

The first flight was successfully completed on October 13, 2020 at Blue Origin facilities in West Texas. A first attempt was performed on September 24,2020 and the sensor payloads were operated through their first power cycle, but a scrub was called for reasons not related to the DDL payloads. This attempt, however, gave the team valuable practice in the launch operations, displays, and procedures. Between the first attempt and the successful first flight, no changes were made to the DDL payloads. 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 5. Blue Origin also provided the required interfaces and data needed to successfully operate the payloads throughout the flight. Based on analysis of the flight trajectory data, the PM met the mission requirements and performed as expected. The PM achieved the 100 km 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 calculated as better than ±0.25 m 1-sigma. Based on post-flight analyses of the interface data [5], 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 by the conditions, however the NDL did experience issues attributed to the temperatures. These are described in more detail in Reference 5. The maximum predicted vibration and shock were in family with some deviations at specific frequencies, notably for the NDL installation. A clear field of view for the DLC camera and LiDARs was provided during the flight based on the recorded images. Some dust was observed in both the ascent and descent recorded data for the OMPS. On ascent, lens flare was observed in the DLC camera images. The early morning low sun angle launch condition was a contributor along with other factors.

Flight 2: 26-August-2021

The second flight was successfully completed on August 26, 2021. In between the two flights significant updates and modifications were made to the NASA sensors to recover from anomalies or to enhance the quality and quantity of data obtained. No changes were made to the vehicle side installations or software. The NDL was returned to NASA Langley for extensive testing, minor hardware updates, and significant software updates [5]. The DLC software and firmware were updated [5] and loaded to the chassis in West Texas. During Flight 2, Blue Origin was once again responsible for providing the flight opportunity and delivering the associated trajectory truth data. These data again 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 5. Based on analysis of the flight trajectory data, the PM again met the mission requirements and performed as expected. The PM achieved the 100 km 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 ±1 m 1-sigma [5]. 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, resulting in fogging and icing of some of the sensor windows. 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 Reference 5. The power architecture was sufficient although adjustments had to be made operationally to handle the case of simultaneous operation of the NDL laser and the NDL heater. The maximum predicted vibration and shock were in family with similar deviations at specific frequencies as observed for Flight 1 for the NDL installation. Additional details on the interface data and findings can be found in Reference 5. For Flight 2, the DLC camera had a clear field of view through-out the flight based on the recorded images. The OMPS experienced icing and fogging on ascent which was likely due to the high humidity. The fogging cleared for descent.

IV. Host Vehicle Flight Data

In this section we describe the host vehicle data from the two successful missions. The first flight took place on 13-October-2020 and the second flight on 26-August-2021. These host vehicle flight data including trajectory data, timing and key events, and coordinate frames. These data have also been made available through data.nasa.gov [9].

A. Flight Trajectory

Based on analysis of the flight trajectory data, the PM met the mission requirements and performed as expected for both flights. The detailed trajectory time histories are shown in Figure 6 for Flights 1 and 2. In both cases, the PM successfully achieved the 100 km altitude objective and performed a propulsive landing. Table 1 lists the timeline of major events from the two missions along with the altitude and velocity at each event. The consistency and repeatability between the two fights is evident.

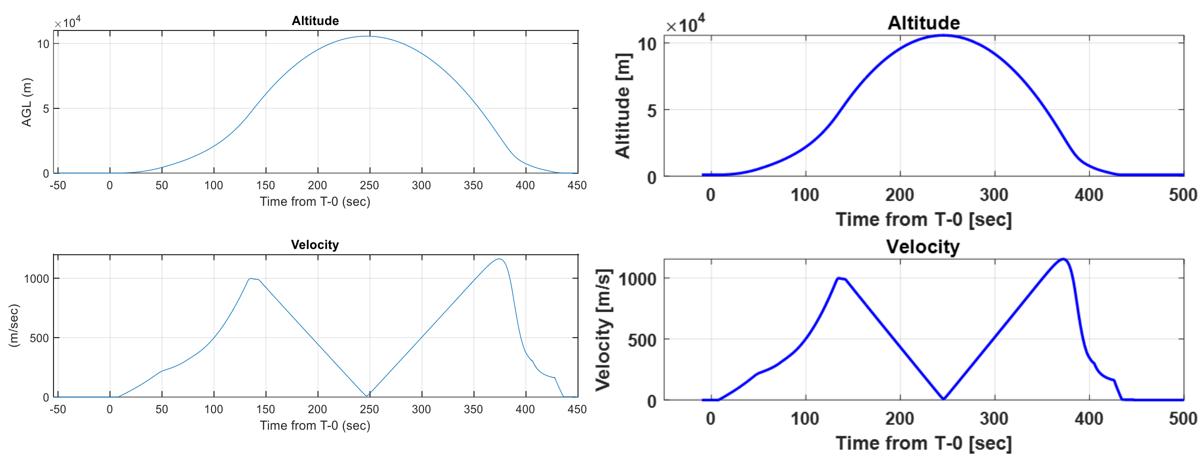

Figure 6: Vehicle altitude and velocity from Flight 1 (left) and Flight 2 (right).

The vehicle data was transmitted real-time and logged for detailed post-processing. Blue Origin re-processed the trajectory using precision GPS solutions post-flight. For Flight 1, to get the best truth trajectory Blue Origin processed both the PM and CC raw GPS data. Both the PM and the CC data were processed with Precise Point Positioning (PPP) which is typically more precise than a differential GPS method, but also has higher quality requirements on the raw data. There is a roughly 8 second outage in the truth position data after CC separation and prior to PM convergence. This outage occurs from 157 seconds to 165 seconds after T-0. During this time, the original onboard position state is used. The estimated errors in the position and velocity measurements for Flight 1 are less than 0.25 m, 1-sigma. All position data has been transformed into the CON frame and updated for the precision metrology. The surveyed PM position after landing was used to verify the reprocessed truth trajectory. For Flight 2, a higher number of GPS satellites were visible during the flight and the post flight reconstruction used only the PM observations. Unfortunately, we were not able to use PPP and instead used a differential GPS correction. This resulted in lower accuracy in the

Flight 2 truth, 1 m, 1-sigma. A post flight precision survey was once again used as a final check on the touchdown accuracy.

Table 1:Timeline of major events from Flight 1 and Flight 2 on New Shepard.

Event	Flight 1 Elapsed Time (s)	Flight 1 Altitude (m)	Flight 1 Velocity (m/s)	Flight 2 Elapsed Time (s)	Flight 2 Altitude (m)	Flight 2 Velocity (m/s)
Ignition	0	1118	0.0	0	1120	0.0
Liftoff	7.26	1118	0.0	7.27	1120	0.0
MECO	143.49	56281	982.5	142.36	55207	983.8
Separation	163.26	73823	792.2	163.22	73626	782.9
Apogee	246.6	106744	0.2	245.58	105776	0.1
Mach 1	403.83	6964	-321.9	401.93	7097	-323.9
Deploy brakes	406.34	6184	-302.0	404.86	6180	-302.2
Restart ignition	425.31	2201	-166.4	423.65	2207	-167.2
Throttle up	427.31	1870	-164.0	425.69	1868	-164.7
Constant velocity	436.6	1147	-3.0	434.82	1147	-3.0
Touchdown	447.83	1116	-2.4	446.42	1115	-2.4

All Blue Origin recorded and post-processed data are time tagged using the TAI (International Atomic Time) time standard which is currently 37 seconds ahead of UTC. Element timestamps are in nanoseconds since 1970-01-01. For Flight 1, the reference T-0 time was 1602596210210000000 nanoseconds which corresponds to 2020-10-13 13:36:13.21 UTC. For Flight 2, the reference T-0 time is 1629988317210000000 nanoseconds which corresponds to 2021-08-26 14:31:20.21 UTC. The T-0 time for both corresponds to the engine command start and occurs prior to thrust build-up or liftoff. The NASA payloads separately timestamp and log their data based on the Blue Origin provided GPS week, GPS seconds within the week, and pulse per second timing. The timelines of transmitted and received data were used to confirm the relative timing and any corrections performed to the final flight data [9].

B. Coordinate Frames

The truth trajectory data is provided in the vehicle Center of Navigation (CON) frame. All sensor installations and orientations are referenced to this frame. These were verified during a metrology campaign prior to the flights. The transformation between the FAB and CON frames is given by:

pos_CON_from_FAB_in_FAB = [20.7354, 1.0614, -1.4639] m

quat_CON2FAB = [0.6722, -0.2151, -0.6744, -0.2168]

V. Commercial LiDAR Data

The commercial LiDAR from OADS called the OMPS was integrated and flown on both flights. The sensor provides range and speed measurements using four telescopes. The data from the unit was recorded real-time by Blue Origin's systems. This section provides a summary of expected performance and then a summary of the flight data. Comparisons with recorded vehicle truth data is provided.

A. Expected Performance

The expected performance of the OMPS is shown in Figure 7. The specific flight unit had an expected speed measurement range of [-49, +26] m/s along each line-of-sight beam. Valid range measurements were expected for speeds between +/-50 m/s, as indicated by the table on the right in Figure 7. Expected range noise is 0.5 m (3σ) and expected Doppler speed noise is 0.5 m/s (3σ).

Laser Altimeter

Parameter	Specification
Measurement Altitudes	10 – 5,000 m*
Altitude Accuracy (3σ)	< 0.5 m
Max. Acceleration During Operation	3 m/s²
Max. Angular Rotation Rate	≤ 10°/ sec
Attitude Reporting	Optional **
Attitude Accuracy (3σ)	Better than 0.5°
Data Reporting Frequency	10 Hz

* Assumes 10% surface Albedo and no planetary atmospheric attenuation
Design can be scaled to accommodate longer ranges and atmosphere

** Spacecraft attitude relative to planetary surface derived from multiple non-collinear range measurements

Laser Velocimeter

Parameter	Requirement
Measurement Range	10 – 1,000 m *
Vertical Velocities Measured	0 – 50 m/s
Horizontal Velocities Measured	0 – 3 m/s
Vertical velocity Accuracy (3σ)	0.5 m/s
Horizontal velocity Accuracy (3σ)	0.2 m/s
Max. Acceleration During Operation	3 m/s²
Max. Angular Rotation Rate	≤ 10°/ sec
Data Reporting Frequency	10 Hz

* Assumes 10% surface Albedo and no planetary atmospheric attenuation
Design can be scaled to accommodate longer ranges and atmosphere

Figure 7: OMPS expected performance [5].

B. Sensor Frame

The OMPS sensor location and orientation have been refined using metrology collected prior to flight. Precision measurements were made at locations on the sensor heads as well as at ground intersection points to compute the beam origins and line-of-sight vectors. The location of the sensor head is given by:

pos_OMPS_from_CON_in_FAB = [0.16, -3.13, -1.22] m

This is the location of the sensor frame relative to the location of CON (in the FAB frame). The orientation for each of the beams is given by:

los_OMPS_1_from_CON_in_CON = [-0.2975, -0.3961, -0.8686]
los_OMPS_2_from_CON_in_CON = [0.0802, -0.4897, -0.8681]
los_OMPS_3_from_CON_in_CON = [0.1239, -0.7275, -0.6749]
los_OMPS_4_from_CON_in_CON = [0.4173, -0.2673, -0.8686]

These line-of-sight vectors are defined in the CON frame and are arranged as shown in Figure 8. Notionally, beams 1, 2, and 4 are mounted with a depression angle of 60° and beam 3 is mounted with a shallower depression angle of 42°. Additionally, beams 1 and 4 are spread ±45° in azimuth from the sensor center. Minor inconsistencies were resolved in the metrology data to derive the beam orientations listed. Overall, the orientation information from metrology produced more accurate predictions than the orientation information given by CAD.

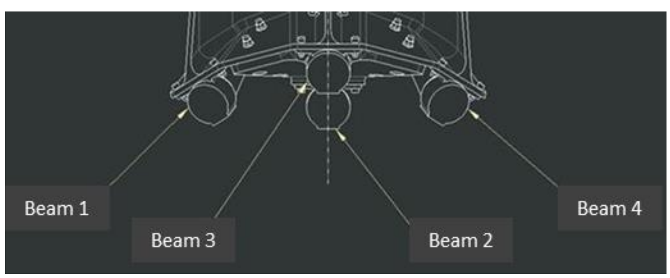

Figure 8: OMPS telescope naming convention and orientation.

C. Measured Flight Data

The recorded data consists of the valid real-time reported range and Doppler speed for each line of sight at the 10 Hz data rate. For Flight 1 during ascent, data is available from roughly T-0 to 45 seconds after T-0. During descent, data is available from roughly 430 seconds to 450 seconds after T-0. Roughly one minute of valid LiDAR data was collected in total on Flight 1. For Flight 2 during ascent, range data from two beams is available from roughly 20 seconds to 45 seconds after T-0. During descent, range and Doppler speed data is available from roughly 430 seconds to 450 seconds after T-0. Roughly one minute of valid LiDAR data was collected on Flight 2 as well.

The ascent and landing regions of LiDAR data can be seen relative to the West Texas Launch Site (WTLS) terrain in Figure 9 for Flight 1. Note that significantly less terrain is traversed during landing and the sensor is oriented north instead of southwest as it was during ascent.

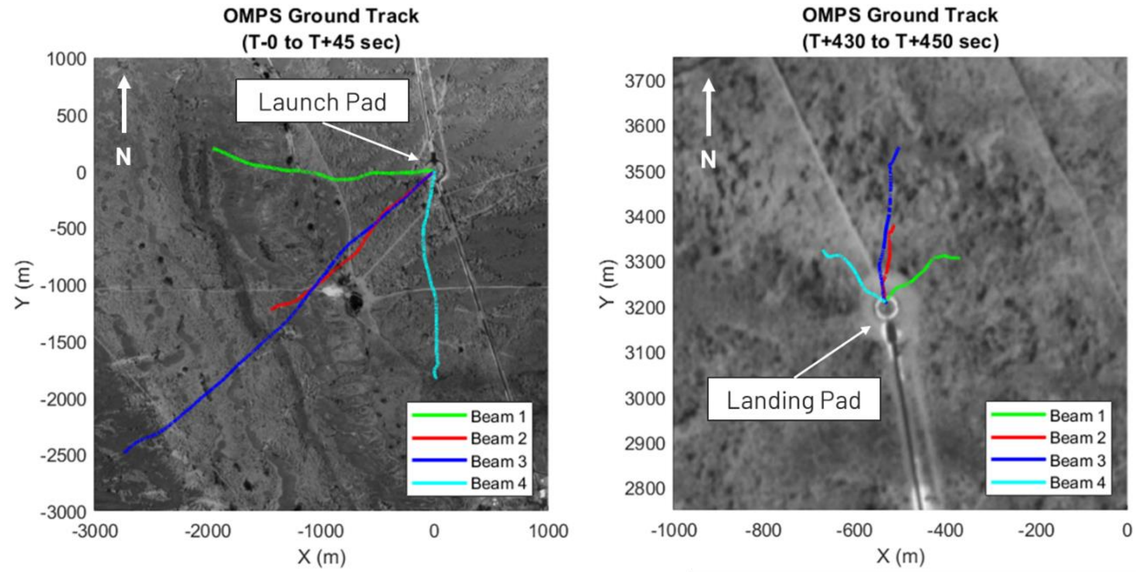

Figure 9: OMPS ground track during ascent and landing for Flight 1.

Figure 10 and 11 show plots of the recorded data. The data indicates the system operated as expected or exceeded expectations. For instance, the range on ascent was available for speeds much higher than 50 m/s, which occurred by 30 sec relative to T-0 on both flights. There was clear evidence of the effects of the dust plumes in the data for Flight 1. This is evidenced by higher noise levels in the Doppler speed and biases in the range. For ascent on Flight 1, beam 1 was confirmed to be oriented into the dust plume. For descent, beam 3, which is inclined at a different angle than the others and showed indications of observing the dust. These were confirmed by witness camera footage, as shown in Figure 12. Beam 1 is seen to be oriented directly into the dust and exhaust plume on ascent. On descent the higher elevation angle of beam 3 oriented it into the dust plume. The effects of dust were not evident in the Flight 2 data.

A LiDAR model was used to predict expected ranges and velocity values for the OMPS during Flight 2. These predictions were calculated using a processed trajectory comprised of position, velocity, and attitude as well as the Digital Elevation Map (DEM) shown in Figure 13. The DEM was generated by obtaining reference maps at high resolution and for a larger extent from the United States Geological Survey (USGS). The DEM used for the analysis (shown in Figure 13) has a resolution of approximately 8.8 m per pixel. It has an extent of 1° in the north-south direction and 2° in the east-west direction and covers the entirety of Blue Origin's Launch Site One in West Texas. The importance of the DEM in the comparisons is evident from Figure 14 which was performed using a flat terrain assumption. Variations from predicted to measured range of [-20,+10] meters are calculated. The measurements and predictions were compared for two portions of the flight: for about 40 seconds after launch, and for about 15 seconds prior to touchdown for both Flight 1 and Flight 2. These comparisons are shown in Figure 15 through Figure 18. Overall, for the data that was successfully captured for both flights, there is good agreement between the measurements and predictions.

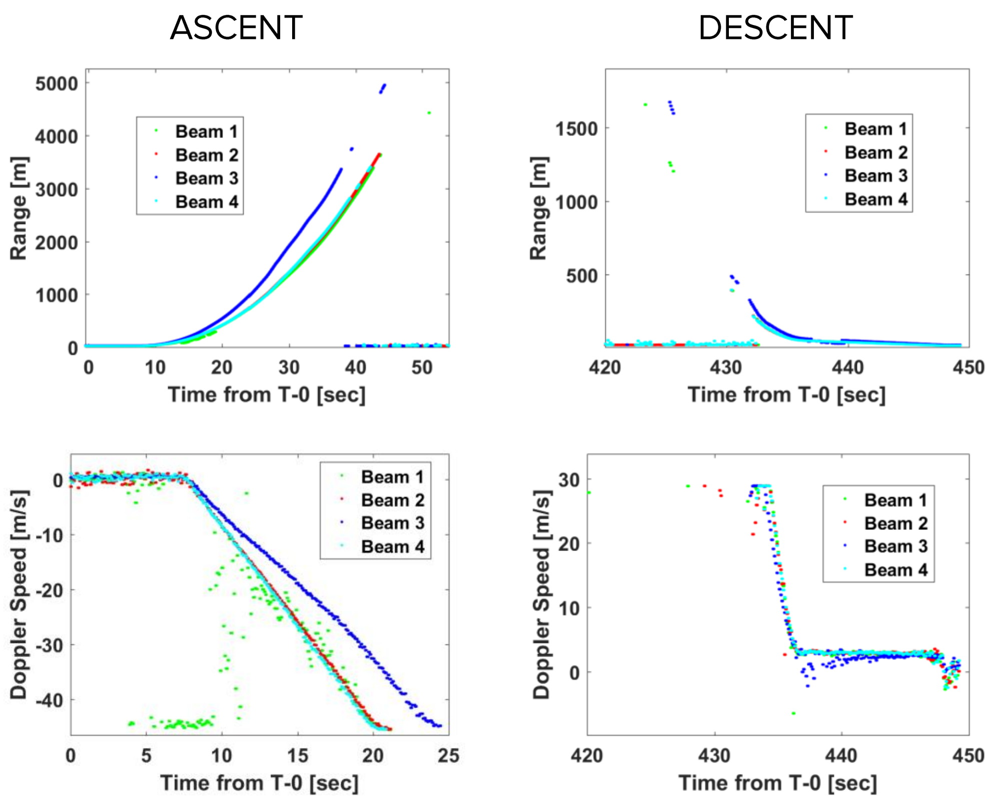

Figure 10: Recorded valid data from OMPS during ascent (left) and descent (right) for Flight 1.

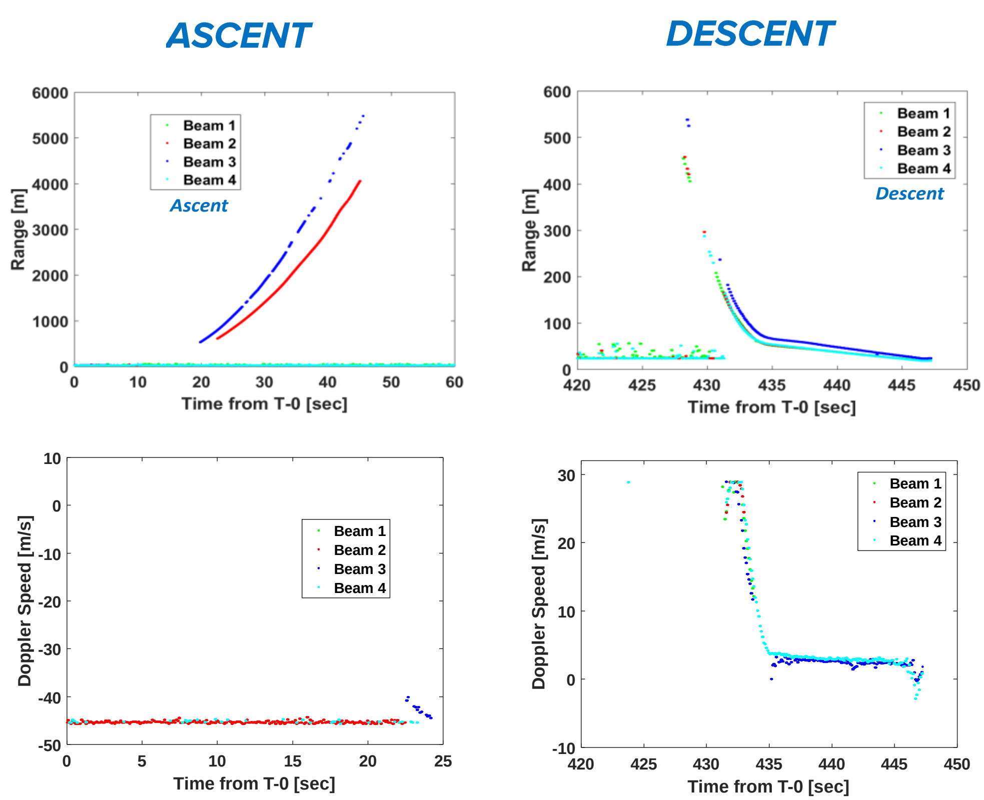

Figure 11: Recorded valid data from OMPS during ascent (left) and descent (right) for Flight 2.

Figure 12: Dust plumes for Flight 1 at liftoff (left) and landing (right) confirming dust affecting recorded data.

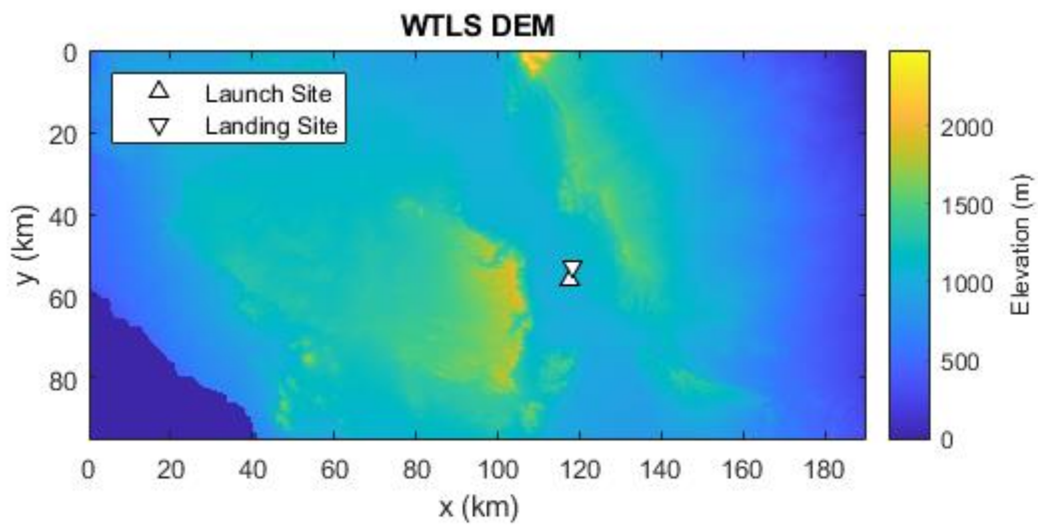

Figure 13: WTLS elevation data used for predicting LIDAR ranges.

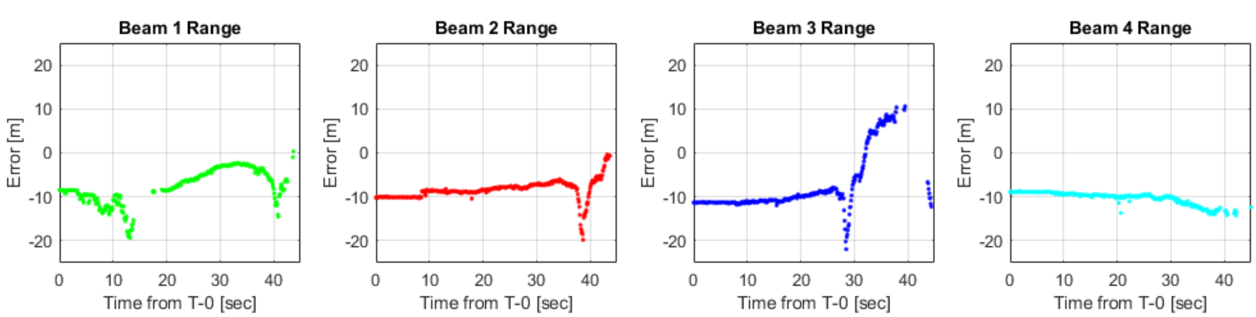

Figure 14: Difference between measured OMPS data and predictions during ascent of Flight 1 without correcting for the local elevtion variations using the West Texas Digital Elevation Map.

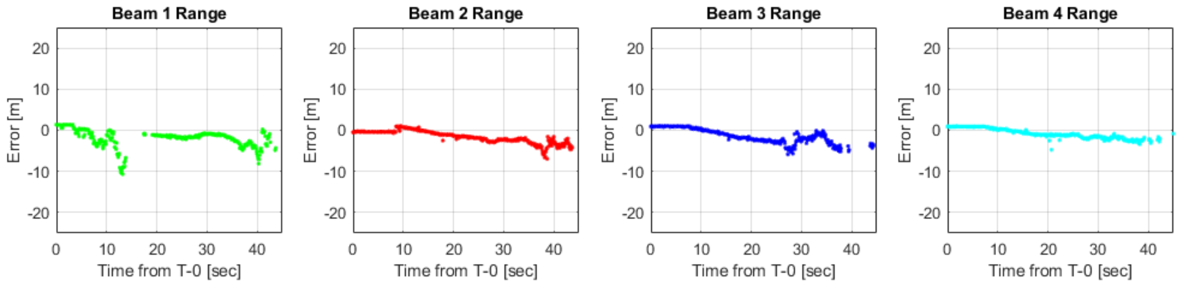

Figure 15: Difference between measured OMPS data and predictions during ascent of Flight 1.

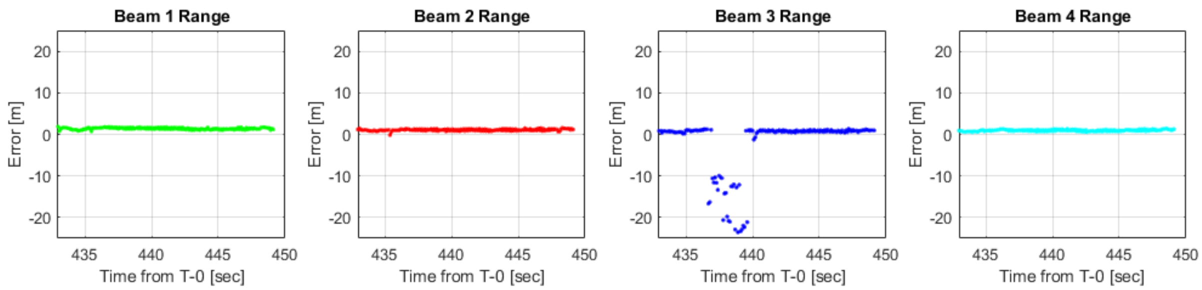

Figure 16: Difference between measured OMPS data and predictions during descent of Flight 1.

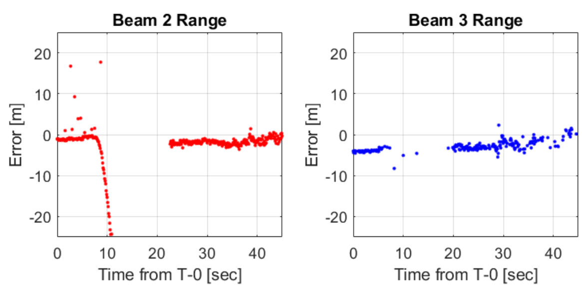

Figure 17: Difference between measured OMPS data and predictions during ascent of Flight 2.

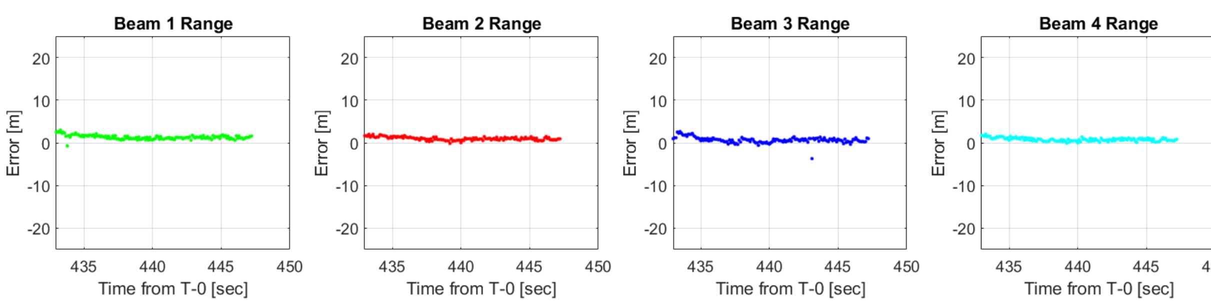

Figure 18: Difference between measured OMPS data and predictions during descent of Flight 2.

VI. Conclusion

Blue Origin completed two flights using New Shepard to gather data on multiple precision landing sensors and expand their operational envelope and maturity. Altitudes exceeding 100 km and speeds exceeding 1000 m/s expanded the flight envelope of the sensors along with exposing them to the launch and space environment. These two flights were the first use of the New Shepard PM for payloads and demonstrated its utility. The flights were performed through a public-private partnership entitled the Blue Origin De-orbit Descent and Landing Tipping Point. This paper summarized the payloads, their installation, and operations during the flight tests. Data from the host vehicle, representing the truth trajectory, along with data from a commercial LiDAR sensor were reviewed for both flights.

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