An open-loop flight test campaign of the NASA COBALT (CoOperative Blending of Autonomous Landing Technologies) payload was conducted onboard the Masten Xodiac suborbital rocket testbed. The payload integrates two complementary sensor technologies that together provide a spacecraft with knowledge during planetary descent and landing to precisely navigate and softly touchdown in close proximity to targeted surface locations. The two technologies are the Navigation Doppler Lidar (NDL), for high-precision velocity and range measurements, and the Lander Vision System (LVS) for map-relative state estimates. A specialized navigation filter running onboard COBALT fuses the NDL and LVS data in real time to produce a very precise Terrain Relative Navigation (TRN) solution that is suitable for future, autonomous planetary landing systems that require precise and soft landing capabilities. During the open-loop flight campaign, the COBALT payload acquired measurements and generated a precise navigation solution, but the Xodiac vehicle planned and executed its maneuvers based on an independent, GPS-based navigation solution. This minimized the risk to the vehicle during the integration and testing of the new navigation sensing technologies within the COBALT payload.

I. Introduction

The COBALT Project\textsuperscript{1,2} was initiated in July 2015 to integrate and flight test two NASA sensor technologies that, when combined, provide a spacecraft with knowledge during descent and landing that can be used for precise navigation and soft touchdown in close proximity to a targeted surface location. Integration and ground testing of the COBALT payload was completed in early 2017, and an open-loop (OL) flight test campaign was conducted onboard the Masten Space Systems (MSS) Xodiac suborbital rocket vehicle in Mojave, CA between March 13, 2017 and April 12, 2017. The flight campaign was extremely successful, providing valuable data on the performance of the COBALT sensors and algorithms, as well as insight into revisions required for future campaigns. This paper provides an overview of the OL flight testing, including the campaign objectives, overview of the payload architecture, the flight operations concept, and the initial OL data analysis.

The two NASA sensing technologies within COBALT include the LaRC Navigation Doppler Lidar (NDL)\textsuperscript{3–6} for velocity and range measurements, and the JPL Lander Vision System (LVS)\textsuperscript{7–9} for map
relative navigation. A specialized COBALT navigation algorithm fuses the NDL measurements with the LVS data to produce a precise Terrain Relative Navigation (TRN) solution that can be used for vehicle maneuver planning and execution to achieve a precise landing. During this OL flight campaign, Xodiac does not rely on the COBALT measurements and, instead, utilizes an MSS-developed navigation solution that relies on Global Positioning System (GPS) measurements. This testing approach minimizes the risk to the vehicle and payload during initial flights and revisions of the new navigation technologies.

The COBALT project goals are to mature NDL technology toward spaceflight readiness and to flight-demonstrate precise navigation with the integrated NDL and LVS technologies. These goals are consistent with the NASA Entry, Descent, and Landing (EDL) technology roadmaps for Precision Landing and Hazard Avoidance (PL&HA) technologies, which have been identified by both NASA and the National Research Council (NRC) as high-priority capabilities for future robotic and human landing missions to many solar system destinations. The technologies within COBALT are continuing development initiated within prior agency projects, such as the the NASA multi-center ALHAT (Autonomous precision Landing and Hazard Avoidance Technology) project and the JPL ADAPT (Autonomous Descent and Ascent Powered-Flight Testbed) project. COBALT is also leveraging ongoing agency efforts toward infusion of LVS onto the Mars 2020 mission.

I.A. Objectives of Open-Loop Flight Campaign

The purpose of OL testing is to mitigate risk to a host vehicle during the development and testing of new Guidance, Navigation and Control (GN&C) technologies prior to actively utilizing the technologies within the vehicle GN&C subsystem. During OL flights, the host vehicle actively utilizes proven GN&C capabilities, while newer, onboard technologies generate performance data for post-flight analysis and maturation. The riskier process of closed-loop testing then actively utilizes the new technologies within the host vehicle GN&C subsystem, with prior capabilities initially operating in the background as monitors and backups.

For the COBALT OL campaign, this GN&C test approach minimizes risk to the payload and the Xodiac vehicle while facilitating the collection and processing of simultaneous, time-synchronized, and dynamically-consistent measurements from all COBALT sensors. The Xodiac vehicle uses its own GPS-based navigation to actively plan guidance profiles and execute thruster-control maneuvers. The OL campaign was designed to address several key project objectives:

- Flight test the NDL in a propulsive-descent trajectory profile that is dynamically relevant for future NDL spaceflight applications.
- Collect a rich data set for use in post-flight analysis of COBALT sensor and avionics performance, payload/vehicle time synchronization, and COBALT software and navigation filter revisions.
- Prepare and mature the collaborative NASA and MSS teams for integrated operations during both the current flight campaign and for future joint campaigns.
- Provide MSS with data from both Xodiac and COBALT navigation filters during the same flight, which MSS can use to define thresholds for an acceptable navigation uncertainty corridor to autonomously monitor COBALT navigation onboard and in real time during a future, closed-loop flight campaign.

I.B. Payload Hardware

The COBALT payload (Figure 1) consists of a sensor assembly, a custom Compute Element (CE) and communication system, a power unit, an Electro-Magnetic Interference (EMI) shroud, and a payload frame. The payload frame was designed to interface with the MSS Xodiac vehicle. The sensor assembly attaches to the side of the payload frame and consists of the NDL optical head, the LVS camera, and an LN-200 Inertial Measurement Unit (IMU) mounted inside of a stiffened structure, which maintains the relative sensor alignments critical for COBALT precision navigation. The COBALT hardware configuration leverages components from the prior ADAPT project, as well as the SURROGATE and RoboSimian mobile robot programs. The payload volume is 0.127 m$^3$ and mass is 44.3 kg.

The NDL uses collimated laser light, split into three beams, to generate ultra-precise and direct Line-of-Site (LOS) velocity measurements. A custom laser waveform enables the sensor to also measure per-beam
LOS range. The NDL sensor within the COBALT payload is a third-generation (GEN3) unit (Figure 2) that has reduced the size and mass of the electronics unit by 50% from the prototype NDL tested during the ALHAT project. The new NDL also increases the dynamic performance envelope to velocities and ranges in excess of 200 m/s and 4 km, respectively, compared to the prototype unit performance envelope of 75 m/s and 2.5 km. For COBALT, the NDL beams are pointed 25° off nadir, and the optical head is mounted to the port side of the payload, which configures the three NDL beams to have a side-swept (Beam A), forward-swept (Beam B), and aft-swept (Beam C) configuration.

The COBALT command and data interfaces to the vehicle include an Ethernet connection and an RS422 Pulse-Per-Second (PPS) signal. The Ethernet connection is used for transmitting the COBALT navigation state to the vehicle and for receiving up-to-date GPS time information from the vehicle, which corresponds to the RS422 PPS signal. The timing data assists in reducing timing offsets between the payload and vehicle times, which is necessary for post-flight performance comparisons and critical for potential closed-loop testing. Figure 3 shows the COBALT payload integrated onto Xodiac.

I.C. Flight Test Concept of Operations

The COBALT Concept of Operations (ConOps) was developed to provide a trajectory test envelope (Figure 4) that expanded on prior NASA precision landing technology testing in 2014 during the ALHAT and ADAPT projects, which flew on the NASA Morpheus and MSS Xombie vehicles, respectively. The ConOps targeted higher altitudes and velocities than attained in either previous project. Additionally, the flight profile was designed to maximize the timeline for collecting and blending NDL and LVS measurements within the navigation filter. The profile of the finalized COBALT ConOps is similar to the ADAPT ConOps,\(^\text{16}\) with similar velocity but much higher altitude, which is enabled by the Xodiac vehicle performance capabilities. The COBALT altitude and velocity are also roughly double what was attained for ALHAT testing onboard the Morpheus vehicle.\(^\text{15}\)

The Xodiac vehicle made its first free flight in 2016, and subsequent MSS envelope expansion flights
proved the vehicle capable of flying the ConOps with a COBALT-representative payload mass. The flight profile provides a nominal flight time of 68 seconds from launch until the final 20 m altitude target above the landing pad. On takeoff, the vehicle performs a vertical ascent to reach the peak 500-m altitude, followed by a vertical descent with reduced engine thrust to achieve a 25 m/s downward velocity. At maximum downward velocity, a 300 meter lateral divert maneuver is planned onboard and executed to target a pre-determined, down-range landing location.

NDL velocity and range measurements nominally become available above a 5-10 meter altitude during ascent, and LVS measurements nominally become available above 75-100 meters during ascent. The COBALT navigation solution is initialized on the ground prior to launch by using the Pose Initialization and Propagation (PIP) system developed for the ADAPT project. The PIP system uses the onboard LVS camera to image GPS-surveyed ground targets and compute the pre-launch vehicle pose. After liftoff, the COBALT navigation filter propagates on the COBALT IMU. Once NDL and LVS measurements become available and satisfy data validity checks, the COBALT navigation filter blends the measurements to estimate the vehicle pose.
II. Open-Loop COBALT Performance

The OL flight test campaign included ground integration and testing, followed by three tether tests and two free flights. The three tether tests provide low-risk vetting of the integrated payload and vehicle functionality under the constraints of engine thrust and remote flight operations. During these tests, the vehicle performs a low-altitude hover and is tied to a crane with a tether line to ensure minimal risk to vehicle and payload if a test anomaly causes a hard engine shutdown. The free flights are conducted after joint team assessments of tether performance and concurrence on OL flight test readiness.

The campaign provided excellent data for assessing COBALT sensor and navigation performance. Both the NDL and LVS functioned extremely well during the flight testing. Analysis is still ongoing, so this section provides an initial assessment of the NDL sensor and the COBALT navigation filter. Further results will be forthcoming in future publications.

II.A. NDL Performance

NDL measurement data indicated excellent performance within the intended NDL flight regime of propulsive descent. Per-beam NDL LOS velocity data for Free Flight 02 (FF02) is provided in Figure 5, with Beams A, B and C corresponding to side-swept, forward-swept, and aft-swept telescopes, respectively (See Figures 1 and 2). The Beam A range data from Free Flight 01 (FF01) and FF02 is provided in Figure 6.

![Figure 5. NDL line-of-site velocities for Free Flight 02](image)

NDL signal losses were observed in the velocities and ranges following vehicle pitch-over at peak altitude at around 60 seconds (See Figures 5 and 6). The likely cause for the signal loss is interference from the moving column of heated air produced from the engine plume during ascent; this same phenomenon was observed during ALHAT flight testing on the Morpheus vehicle. This phenomenon would not be present when landing on the Moon or other airless bodies, and it is probably not an issue on Mars or in other thin
atmospheres. The interference was primarily observed on the aft-swept NDL beam (Beam C), but some interference was also seen in the side-swept (Beam A) and forward-swept (Beam B) beams, as well, just after vehicle pitch over. Mitigation options for reducing or eliminated the plume interference issue will be considered for future flight campaigns. One potential option is to modify the NDL optics to increase the off-nadir telescope angles or reorient them to point the beams further away from the likely regions of the heated air column. Another option is the utilize a wind placard on the flight test conditions. Both of these options were successfully implemented during ALHAT flight testing on the Morpheus vehicle.

Some anticipated measurement outliers were also observed in the NDL data during takeoff and landing, as seen in Figure 6, for both flight tests. This is a region of short ranges and low velocities, which are outside of the intended regime for NDL operation. The NDL is expected to produce outliers in this region. Additionally, interactions between the engine plume and concrete takeoff/landing pads generates dust and other ejecta that can trigger NDL measurements. Detection and elimination of these outliers within the sensor poses a significant challenge, but the vehicle navigation filter can utilize its vehicle position and velocity estimates, plus NDL calibration-based knowledge of the outlier regions, to avoid processing the NDL measurement outliers.

II.B. Preliminary COBALT and Xodiac Navigation Filter Comparisons for Free Flight 02

Initial analysis of the COBALT navigation solution relative to the Masten GPS-based navigation solution shows good overall agreement. Figure 7 shows an overlay of the position estimates relative to a surface-fixed frame at the launch pad that is aligned to East-North-Up (ENU). The ConOps profile is evident from the navigation data. The navigation data is only shown for FF02 for reasons discussed in the closing remarks of Section III. Additionally, the COBALT navigation solution provided in these plots is from post-flight reprocessing of the data that is leveraging refinements to the navigation filter, as well as including all COBALT sensor measurements from the flight. A 10 meter minimum altitude threshold is used in the filter to prevent the processing of NDL measurements on takeoff and landing, which avoids the anticipated outliers.

Figure 7. Overlay of COBALT and Masten navigation solutions from Free Flight 02

Figure 8 provides difference plots of position (left) and velocity (right) components, in the launch-site ENU frame, between the COBALT and Masten navigation solutions. Independent truth telemetry was not
available with the flight tests, so the comparison plots are not error plots, but rather difference plots between two independent navigation solutions. The step in position difference at \( \sim 40 \text{ sec} \) occurs at the first LVS measurement update as map relative localization data becomes available. This step is anticipated, reflecting a correction to the filter state that compensates for IMU propagation errors that have accumulated since launch. Sources for the differences observed in the data are being studied in post-campaign data analysis. Some initialization differences have been identified between COBALT and Masten navigation, and some other error sources with terrain modeling have been identified that are believed to cause errors on the order of 2 meters.

![Figure 8. Position (left) and Velocity (right) difference between COBALT and Masten navigation (Free Flight 02 data)](image)

III. Closing Remarks and Next-Steps

The open-loop campaign accomplished the objectives planned for the ground, tether, and free flights, although some new engineering challenges have been revealed. The campaign demonstrated the COBALT ConOps with the two successful Xodiac flights along the planned trajectory profiles. The campaign also prepared the joint team for integrated operations and improved the cadence of test procedures execution. Both flights generated excellent performance data for the new NDL sensor and demonstrated it in a dynamically-relevant flight trajectory, which is a key step in the COBALT project plan to achieve a Technology Readiness Level (TRL) of 5 for the sensor. The campaign provided the first COBALT dataset that has simultaneous, time-synchronous, dynamically-consistent IMU, LVS and NDL measurements.

The campaign was not without challenges. During Free Flight 01, an unanticipated overloading of the COBALT avionics processor was revealed, which resulted in data logging errors, partial IMU data loss, and limited LVS image acquisition. To overcome this challenge for Free Flight 02, the in-flight processing of COBALT data was limited to IMU and LVS measurements. The NDL data was recorded for post-flight reprocessing of COBALT navigation with all measurement types. Resolving the processor overloading is essential for future closed-loop flights, and the solution requires an upgrade to the COBALT avionics processor. Data rate throttling has been investigated but does not provide sufficient processing margin.

The existing open-loop flight data will be used for further analysis and revision of simulations and navigation algorithms to prepare them for future flight test campaigns and toward infusion into spaceflight missions. A follow-on effort has been defined to upgrade the COBALT avionics, and future flight campaigns will include an open-loop flight to verify updates to the COBALT avionics and the navigation filter prior to conducting closed-loop flights.
Acknowledgments

We want to acknowledge the large COBALT team, which consists of individuals across NASA and at MSS, that has supported the development, implementation, testing, analysis and dissemination of this project. We additionally want to acknowledge the team at MSS that worked diligently to prepare the Xodiac vehicle for the COBALT open-loop flight campaign. Additionally, the authors acknowledge the prior NASA ALHAT project team and the JPL ADAPT project team whose work the COBALT team has built upon. The COBALT project derives funding and support from multiple NASA directorates and programs, including the Human Exploration and Operations Mission Directorate (HEOMD) Advanced Exploration Systems (AES) Program (through the Lander Technologies Project), the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program, and the STMD Flight Opportunities (FO) Program. The project is also leveraging the products of the ongoing Science Mission Directorate (SMD) and STMD co-investments into the LVS development and maturation. The project is also utilizing the flight test capabilities of the U.S. commercial spaceflight industry through the STMD FO Program funding provided to MSS for the COBALT flight testing onboard the Xodiac vehicle. The work described herein involved contributions from NASA JSC, JPL, LaRC, and AFRC (Armstrong Flight Research Center), along with MSS. The COBALT work at the Jet Propulsion Laboratory, California Institute of Technology, was performed under contract with the National Aeronautics and Space Administration (Government sponsorship acknowledged).

References


