Morpheus Vertical Test Bed Flight Testing

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***Abstract* — NASA's Morpheus Project has developed and tested a prototype planetary lander capable of vertical takeoff and landing, that is designed to serve as a testbed for advanced spacecraft technologies. The lander vehicle, propelled by a Liquid Oxygen/Methane engine and sized to carry a 500 kg payload to the lunar surface, provides a platform for bringing technologies from the laboratory into an integrated flight system at relatively low cost.**

Morpheus onboard software is autonomous from ignition through landing, and is designed to be capable of executing a variety of flight trajectories, with onboard fault checks and automatic contingency responses. The Morpheus 1.5A vehicle performed 26 integrated vehicle test flights including hot-fire tests, tethered tests, and two attempted free-flights between April 2011 and August 2012. The final flight of Morpheus 1.5A resulted in a loss of the vehicle. In September 2012, development began on the Morpheus 1.5B vehicle, which followed a similar test campaign culminating in free-flights at a simulated planetary landscape built at Kennedy Space Center's Shuttle Landing Facility.

This paper describes the integrated test campaign, including successes and setbacks, and how the system design evolved over the course of the project.

TABLE OF CONTENTS

1. INTRODUCTION

The Morpheus Project provides an integrated vertical test bed (VTB) platform for advancing multiple subsystem technologies. While technologies offer promise, capabilities offer potential solutions for future human exploration beyond Low Earth Orbit (LEO). Morpheus provides a bridge for evolving these technologies into capable systems that can be demonstrated and tested. This paper describes the vehicle test campaign conducted on the Morpheus 1.5 'Bravo' (1.5B) vehicle.

There are two key technologies that Morpheus is designed to integrate and demonstrate. The first is a liquid oxygen (LOX) / liquid methane propulsion system. The Morpheus LOX/methane propulsion system can provide a specific impulse during space flight of up to 321 seconds; it is clean-burning, non-toxic, and cryogenic, but space-storable. Additionally, for future space missions the methane could be produced in-situ on Mars, and the oxygen is compatible on-board with life support systems and power generation. These attributes make LOX/methane an attractive propulsion technology for a lander of this scale.

The second technology is autonomous landing and hazard avoidance. When landing on any planetary or other surface, the vehicle must be able to autonomously (i.e. without ground communication) determine a safe landing site that is free of large boulders, rocks, craters, or highly sloping surfaces. Morpheus is designed to carry sensors developed as part of the Autonomous Landing and Hazard Avoidance (ALHAT) project. The ALHAT senor suite includes a hazard detection system, doppler lidar, and laser altimeter. These sensors and associated software, when integrated with the Morpheus vehicle, will demonstrate an integrated capability to perform closed-loop hazard detection and autonomous landing.

The Morpheus vehicle is a "quad" lander design with four tanks, a single gimbaled engine and LOX/Methane Roll control thrusters. The Morpheus Project also includes the operations center and all ground systems and ground support equipment (GSE) for testing on-site at both NASA's Johnson Space Center (JSC) and Kennedy Space Center (KSC).

Morpheus design and development began in June 2010, primarily by an in-house team of NASA engineers at JSC. Following successful free-flight the Pixel Lander, Morpheus' prototype, the NASA team completed the construction and testing of the 1.0 and 1.5A versions of the Morpheus vehicle (REF XX). Unfortunately, the 1.5 'Alpha' (1.5A) vehicle was lost during early free-flight testing in August 2012.

The loss of Morpheus 1.5A resulted in a rebuild effort to return to testing. Over seventy upgrades were approved for

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incorporation into the 'Bravo' vehicle, as well as GSE, operations and test facilities. Rebuild efforts began in earnest in October 2012 with the first integrated hot-fire test completed six months later.

The knowledge gained in testing the 'Alpha' vehicle significantly improved the performance characterization of the 'Bravo' vehicle once its testing began. However, there were a number of differences that needed attention. For example, 'Bravo' is 200 pounds heavier than the 1.5A vehicle and its engine produces 800 pounds more thrust than its predecessor. The change in mass properties, combined with some feed system implementation changes, initially led to an unacceptable susceptibility to propellant imbalance that caused a number of automatic soft aborts during early tether testing. The soft abort box only allows 4 meters (4 m) of lateral excursion for tether testing, to prevent tether interaction and ensure crane protection. Tuning of guidance and control parameters eventually overcame the problem, allowing tether testing to proceed unhindered.

Improvements for 'Bravo' vehicle operations also included significantly enhanced flight simulation capabilities. Reliable simulation tools afforded the project the opportunity to predict vehicle performance under more risky tether flight profiles. Planned testing progressed from simple vertical hovers (all that was accomplished with 1.5A in 2012) to multi-level vertical ascent profiles with lateral translations of up to 3 m. This expanded capability enabled the testing of different versions of gain scheduling through all phases of flight, which allowed the project to employ a 'test like you fly' approach in preparation for future free flights at KSC.

Integration with the ALHAT instruments was repeated with the 'Bravo' vehicle during tether testing at JSC. Integrated performance was significantly improved from 2012, with nearly all discrepancies resolved and demonstrated Hazard Detection System (HDS) pointing accuracy within 0.15 degrees. Additionally, the project collaborated with the Mars 2020 Program from the Jet Propulsion Laboratory by incorporating a plume impingement study using Mars soil simulant on the ground during a tethered test.

The final phase of 1.5B testing is being conducted at KSC, which includes vehicle free-flight over an increasingly difficult set of trajectories. The culmination of this testing will be closed-loop use of the ALHAT HDS to identify and guide the vehicle safely to landing within a simulated planetary terrain.

2. DESCRIPTION OF JSC TEST TYPES

Morpheus testing includes three major types of integrated tests: hot-fire, tether, and free-flight. Each of these tests has increasing scope and demonstrates additional vehicle capabilities. Hot-fire testing focuses on the engine igniter, main engine, and Reaction Control System (RCS) performance using a constrained test configuration. Once engine-testing reaches a certain point, tether tests are conducted to evaluate the integrated engine and Guidance, Navigation, and Control (GN&C) performance. A subset of the tether tests also includes ALHAT sensors to demonstrate the integrated performance of the Morpheus/ALHAT system. The culmination of the testing at JSC is a tethered Ground Take-off And Landing (GTAL) test used to confirm launch and landing dynamics. Following this series of tests the team and vehicle depart for KSC for free-flight testing.

These tests are similar to the integrated test conducted with the 1.0 and 1.5A versions of the Morpheus vehicle. This section summarizes these tests with a focus on the key differences and improvements for the 1.5B vehicle.

Hot-Fire Testing

During hot-fire testing the vehicle is completely restrained from movement where the primary focus is to test the LOX/methane propulsion system. In this configuration a crane is used to suspend the vehicle above the ground to provide clearance for the vehicle exhaust plume. The vehicle is also constrained from below using straps anchored to the ground that prevent vertical and lateral vehicle motion.

Figure 1 shows the vehicle during test in the hot-fire configuration. This figure represents the final configuration during test firing. For initial power-up, checkout, and propellant loading the vehicle remains on the ground. The final lift is completed just prior to helium pressurization and test firing. The vehicle is suspended approximately 20' above a concrete pad by a crane outfitted with shielding to prevent damage from flames or debris during the test firing. Additional restraints are attached below the vehicle consisting of chains, metal turnbuckles, and U-rings anchored to the concrete (a design improvement over the nylon straps with insulation used in 1.5A testing). The lower straps are tensioned using the metal turnbuckles that are then anchored into the concrete pad.

The objectives for hot-fire tests include demonstration of the igniter, engine ignition, performance at varied throttle settings and burn duration tests. The Morpheus Project test approach limits testing on a dedicated engine test stand and emphasizes a quick transition to integrated vehicle tests. Testing on the vehicle promotes optimization of engine performance for the actual vehicle propulsion feed system instead of the test stand system. It also allows gimbal sweeps to evaluate the integrated performance of the actuators under load. The majority of engine characterization is conducted on the vehicle, essentially making the hot-fire configuration the primary engine test stand for the Morpheus Project.

Some additional upgrades for the 1.5B testing were access to Developmental Flight Instrumentation (DFI) and helium pressurization during testing. The DFI data provided insight into the engine stability (via dynamic pressure transducers), which allowed the team to assess if start conditions were instability-free without having to stand down during the test.

This DFI was accessed by running a thermally-insulated ethernet line directly to the vehicle flight computer (Avionics and Power Unit, APU). A helium line was also run to the vehicle in this flight configuration allowing re-pressurization and finer control of the engine starting pressures. Both of these changes were critical to the efficiency of 1.5B testing hot-fire testing since each test day included numerous engine ignitions to characterize the performance differences between the test-stand at Stennis Space Center and the Morpheus vehicle.

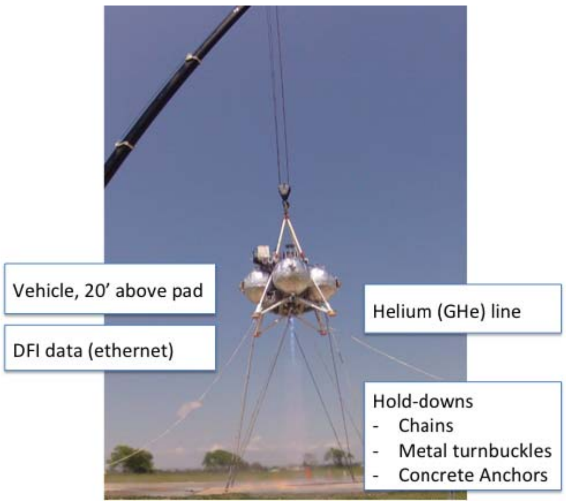


Figure 1 – Morpheus 1.5B in Hot-Fire Test Configuration

A second configuration, Ground Hot-Fire, was also used to test the engine performance and well as the thermal and vibroacoustic environments at liftoff. This was particularly important for the 1.5B testing to evaluate the new flame trench (Figure 2), which was added to divert vibroacoustic energy away from the vehicle during liftoff. In this case, the vehicle remains static on the ground, chained to the launch pad and the engine is only run for up to a few seconds at maximum thrust to envelope any environments expected on an actual launch attempt. With the addition of the flame trench the worst-case vibration might not be at ground level so an additional low-altitude test (1 meter height) was conducted to characterize the vibration environment.

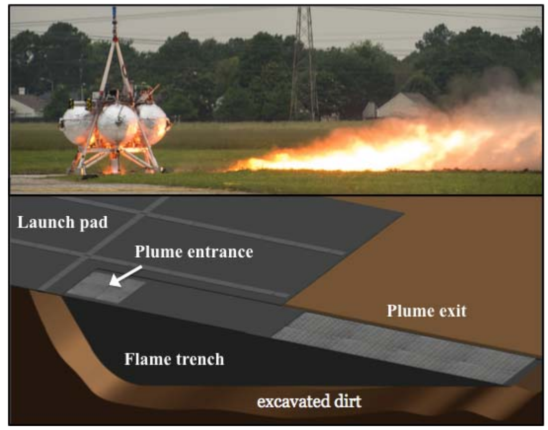


Figure 2 – Morpheus 1.5B Flame Trench

Tether Testing

For tether tests the vehicle is suspended from a crane as shown in Figure 3 to enable testing of the propulsion and integrated GN&C without the risk of a vehicle departure or crash. The goal of these tests is to demonstrate vertical translation, horizontal translation, and vehicle hover. During the 1.5B testing the size and complexity of the tether profiles were expanded beyond the simple vertical translations and hovers completed in the 1.0 and 1.5A testing. Upon successful completion of the tether test profile the vehicle descends and "lands" at the end of the tether.

Tether testing provides the first opportunity to perform integrated testing of the Morpheus vehicle with closed-loop GN&C. The primary objective of tether testing is to demonstrate 6 degree-of-freedom (DOF) GN&C for translation, hover, and simulated landing operations. An additional objective is to understand the integrated performance of avionics, propulsion, and GN&C. Tether testing allows rapid refinement of this integrated performance without risk of a vehicle crash.

Due to the potential dynamic loads during tethered flight, a substantially larger 120-ton crane is used for this testing than used in hot-fire testing (Figure 3). An energy absorber was placed in-line with the crane boom and vehicle to reduce the loads on both the crane and Morpheus vehicle and help prevent damage to either asset. The energy absorber consists of a metal tube filled with sections of aluminum with a honeycomb cross-section (an upgrade for the weather and humidity sensitive cardboard material used in 1.5A testing). The aluminum sections dissipate dynamic loads when crushed and have specifically designed cut-outs to provide the desired load attenuation characteristics. Below the energy absorber is a length of tether sufficiently long to allow approximately 3 meters of vertical translation with margin for overshoot and altitude uncertainty. This tether is outfitted with a bungee cord to bunch the tether when slack and prevent it from draping and snagging on the vehicle. Suspending the vehicle 15'- 20' above the pad prevents the vehicle from impacting the ground if a contingency engine shutdown is required. Finally, when the vehicle is lifted before testing it is held in place by a light-weight nylon hold-down cord to prevent motion prior to ignition. The rocket plume quickly melts the hold-down cord, allowing the vehicle to translate.

Additional tether test objectives were added for the 1.5B vehicle to evaluate the design upgrades. This included a tether test with the backup Inertial Measurement Unit (IMU), a commanded switch from the primary to backup IMU during flight, and a commanded switch from the primary (LOX/Methane) to the backup (helium) RCS system during flight.

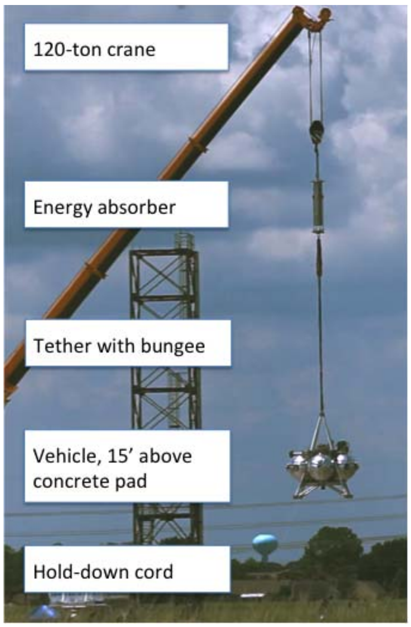


Figure 3 – Morpheus 1.5B in Tether Test Configuration

An additional tether test configuration was added for the 1.5B JSC test campaign that allowed for up to 5 meters of vertical translation and to test the rigging setup planned for the GTAL test configuration explained in the following section. Specifics of the tether test profiles, objectives and results are included in Section 4, JSC Test Campaign Summary.

Ground Take-off And Landing (GTAL) Testing

The GTAL test, while still constrained via tether, was designed to buy down risk by demonstrating liftoff over a flame trench followed by a nominal translation, descent and landing back on the ground. The tether only provided range safety and helped to minimize potential for any damage if there is a problem during the test. This was the last test planned at JSC before the vehicle was moved to KSC for testing at the Shuttle Landing Facility (SLF).

Figure 4 shows the vehicle and crane configuration for GTAL. One of the key objectives of GTAL is to test the launch environment of the vehicle including the flame trench (shown in Figure 2) and the launch stands (shown in the inset of Figure 4). Prior to liftoff the launch stands provide a level platform for propellant loading and balancing and an interface with load cells on the Morpheus vehicle to provide live weight and Center of Gravity (CG) information. This solves two Morpheus 1.5A challenges – leveling the vehicle to maintain a zero CG for the fueled vehicle and providing a precise CG location prior to liftoff.

Similar to the tether test configuration a 120-ton crane is used to accommodate the vehicle loads in the event of an abort. However, in this test configuration the vehicle is not prevented from impacting the ground to accommodate landing, as intended, on the ground at an adjacent pad. Other differences are the addition of two 20' sections of rigging offloaded during the flight via a weight and pulley assembly (pictured in Figure 4). This setup is similar to what was testing in the final 3 tether tests, which were intended to prepare for GTAL.

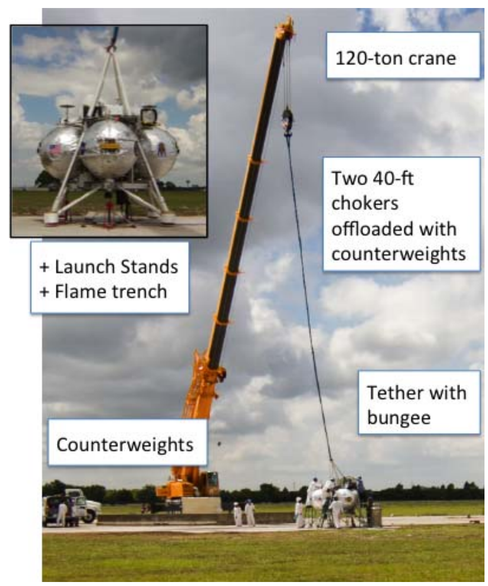


Figure 4 – Ground Take-off And Landing (GTAL) Test Configuration

When completed, the GTAL test demonstrated the complete integrated Morpheus vehicle throughout launch, flight, and landing. The GTAL flight profile is shown in Figure 5, which included a 7-meter ascent, 10-second hover, 30-deg slant profile ("Quad"), descent, and terminal descent (during which landing logic is active). The profile is sized based on the available range of vehicle motion with the crane and tether arrangement. This flight was essentially a free-flight test with the added complexity of the rigging and the resulting forces imparted on the vehicle. Successful demonstration of this test completed the testing at JSC and represented completion of all of the necessary subsystem and vehicle-level testing necessary to conduct free-flights at KSC.

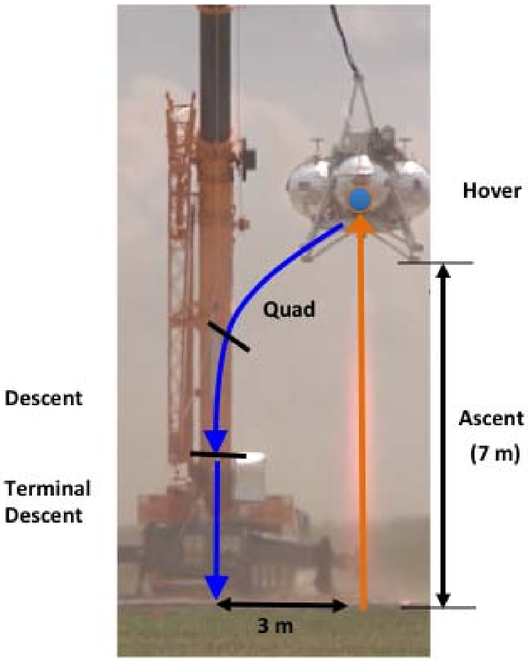


Figure 5 – Ground Take-off And Landing (GTAL) Profile

3. DESCRIPTION OF KSC TEST TYPES

The focus of KSC testing is vehicle "free-flights" of increasingly challenging flight profiles. The primary reasons for conducting free-flights at KSC (as opposed to JSC) are a much larger and non-residential test area, and the construction of a 100 meter by 100 meter "hazard field" of simulated planetary terrain located at the north end of the SLF, pictured in Figure 6.

A variety of free-flight trajectories will be flown to incrementally build up to the "Hazard Detection Phase" (HDP) trajectory needed for ALHAT landing detection scanning. Following the demonstration of this trajectory the full suite of ALHAT sensors will be integrated with the Morpheus vehicle. During KSC testing the Morpheus system is without the safeguards provided by the tether. The vehicle safeguards still include automatic on-board aborts, remotely commanded aborts, as well as a redundant and independent flight termination system using spotters to visually determine trajectory deviations. Since this is the first opportunity to fly these profiles the ALHAT sensors will not be flown until Morpheus has demonstrated the complete suite of flight profiles up to and including the HDP. This will prevent the loss of the ALHAT hardware in the event of a Morpheus problem during early test flights. In place of the ALHAT components are a set of low-fidelity simulators to provide the equivalent weight and CG of the ALHAT components.

Figure 6 – Morpheus Test Area at the Shuttle Landing Facility (SLF)

The KSC test campaign is broken into 4 smaller test campaigns to provide downtime for vehicle maintenance and data analysis. The four campaigns have been designated as Campaigns 0-3 and are described in detail below.

Campaign 0, Initial Free-Flight Capability

During this campaign the team transfers all operations from JSC to KSC including vehicle systems, ground systems, and operations. The first test conducted is a tether test to demonstrate the vehicle system health and performance following shipping. It also demonstrates the end-to-end logistics required for Morpheus testing (transportation logistics at the SLF, propellant loading, vehicle communication and Electromagnetic Interference (EMI) environments, etc.). The majority of these capabilities are confirmed via a series of dry- and wet-runs during the first week of Campaign 0. At the end of the first week of KSC operations the team conducted a tether test.

The first Morpheus Free-Flight test is a "micro-slant" from the new portable launch pad with integrated flame trench and launch stands to the location of the 1.5A launch pad. This trajectory consists of a 15 meter ascent to hover followed by a 7 meter translation to above the landing pad and concludes with descent and landing. This profile is similar to the GTAL profile with double the ascent and lateral distances flown.

Upon successful completion of the "micro-slant" the team will conduct a slant hop trajectory from the Campaign 0 Launch Area (shown in Figure 6) to the landing area in the bottom right corner of the Hazard Field (LS1). This trajectory will be 50 meters in height and cover a downrange distance of 47 meters. This profile will include a hover at 25 meters into the ascent. This hover will allow the vehicle to have a reduced ascent rate and trim to any vehicle dispersions (such as CG, engine misalignment, etc.). The completion of these tests confirms the baseline capability of the vehicle to conduct free-flights of varied profiles.

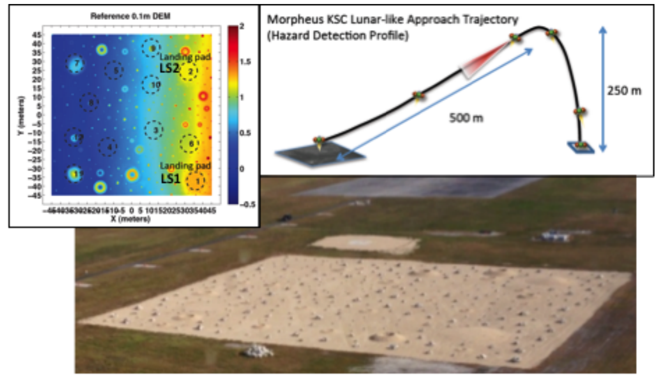


Figure 7 – HDP Trajectory and Hazard Field Overview

Campaign 1, Free-Flight Envelope Expansion

The purpose of this test campaign is to demonstrate vehicle capability that incrementally builds up to the translational position and velocities required for the HDP trajectory. The initial two flights will be from the same launch location as Campaign 0. Pending the success of those flights, the launch pad/flame trench will be moved to an intermediate location for two additional flights.

The specific objectives will be to increase the vertical ascent and horizontal translation. Each case will increase the distance traversed and the velocities flown. Following the completion of the Campaign 1 trajectories the vehicle will be postured to complete the full HDP trajectory.

The Morpheus/ALHAT team will then integrate the ALHAT HDS system with the vehicle following successful completion of Campaign 1 in preparation for test flights demonstrating the full ALHAT HDP trajectory and scan. The integrated Morpheus/ALHAT system will be tested via a tether test as the first flight of Campaign 2.

Campaign 2, HDP Flight Capability

During this test campaign the vehicle will complete the full HDP flight profile. Figure 7 shows an overview of the HDP trajectory, a reference Digital Elevation Map (DEM) of the Hazard Field (showing the landing sites) and an aerial photo of the hazard field. The HDP trajectory will be approximately 250 meters in altitude and 500 meters downrange. This is sized to provide the appropriate slant-range and downrange distance to the hazard field to allow the ALHAT sensors to scan correctly.

The first HDP trajectory flight will be a flight directly to Landing Site 1 (indicated at "LS1" in Figures 6 and 7). For the second flight during this campaign the vehicle will first fly toward the center of the HDS scan area, then execute a divert about halfway through the slant portion of the trajectory. This second trajectory will simulate the vehicle flight profile that would be flown to a hazardous area without prior knowledge of the "safe" landing sites.

The concept of operations is that the vehicle initially targets the Intended Landing Point (ILP), which will be the center of the HDS scan area. Then, the HDS will return a safe area within the scan capability (planned for 60 x 60 meters) and the vehicle will divert to the safe site. This will be simulated with the vehicle by flying to the ILP until diverting to the preplanned landing site (typically Landing Site 1, although Landing Point 2 could also be used).

The Morpheus/ALHAT team will then integrate the ALHAT HDS system with the vehicle and conduct two open-loop test flights demonstrating the full HDP trajectory and scan. Once this data is collected and processed, the team will assess the readiness of the integrated Morpheus/ALHAT system to demonstrate the HDP trajectory using closed-loop HDS data.

Campaign 3, HDP Flight Capability with ALHAT

The final planned KSC campaign will demonstrate the full HDP trajectory and scanning closed-loop. This campaign will be two flights of the Morpheus/ALHAT system and use the ALHAT navigation information to land the vehicle at the intending landing site (as deemed "safe" by the HDS system).

There are two safeguards to help ensure that the vehicle will land in the correct area. The first is the construction of the hazard field itself, which was design by using the HDS site selection algorithms. The location of the rocks and craters was specifically selected to result in the desired landing location (Landing Site 1) as the "safest" site according to the algorithms. The second safeguard is that the Morpheus Autonomous Flight Manager (AFM) is programmed with the location of Landing Site 1 and compares the results of the HDS landing site selection to confirm it is correct within the required tolerance.

By demonstrating this trajectory twice, the Morpheus/ALHAT team will confirm the ability of the system to operate closed-loop and demonstrate repeated success of the end-to-end flight system and sensor performance.

4. JSC TEST CAMPAIGN SUMMARY

Between April and November 2013, the Morpheus team completed 5 hot-fire tests, 13 tether tests, and the GTAL test. The following sections summarize the JSC testing campaign including objectives, issues, modifications and results.

The JSC test campaign, despite being similar to previous testing during 1.0 and 1.5A testing, was critical to verifying the integrated 1.5B vehicle including the large number of design upgrades. The tests described below occurred after an extensive period of vehicle construction and subsystem testing, although the integrated verifications were primarily completed during the test campaign outlined here. In addition to the vehicle test types mentioned above and summarized below there were several key test efforts between September 2012 and March 2013, including main engine test firings at Stennis Space Center (SSC), helicopter testing of the integrated Morpheus and ALHAT system, and a liquid nitrogen loading test to expose the system to cryogenic temperatures and qualify the landing gear for flight. The first engine test firing was conducted on April 23rd following completion of the vehicle buildup and initial testing.

Hot-Fire 7 (HF7) and Hot-Fire 8 (HF8)

These two tests were both conducted in the "hot-fire" configuration show in Figure 1 and were intended to test main engine ignition. Since the 1.5B vehicle also includes LOX/Methane RCS thrusters the tests had the added complexity of conditioning the system for ignition of both the main engine and methane RCS simultaneously. Similar to previous HF tests the tests were executed via an open-loop command scripts.

During HF7, conducted on April 23rd 2013, three ignition tests were successfully executed as well as separate tests of the methane RCS system. The durations were purposely limited to 200 ms, 600 ms, and 600 ms respectively to limit the likelihood of engine instabilities causing issues. This was also the first test of the new engine instability instrumentation, which would command an engine shutdown if an instability was detected (via a sufficiently high signal from dynamic pressure transducers). This test also exercised the LOX/methane RCS system, which performed well over a range of propellant conditions.

The following test, Hot-Fire 8, was conducted one week later and expanded demonstrated 1.5B vehicle capability to include longer duration main engine firings (up to 50 seconds duration), simultaneous main engine and RCS firing, and engine gimballing during firing. One anomaly that occurred during this test was a scripting conflict between main engine and RCS commanding. The two scripts, one commanding each subsystem, were being run simultaneously and occasionally the commands were in conflict causing only one command to get through to the vehicle. The result of this commanding conflict was a delay in the engine gimbal motion and a delayed shutdown (resulting in a 10 seconds of additional burn time). The solution to this issue for future tests was to combine all commands into a single script to prevent script execution conflicts. Fortunately the necessary test objectives were completed despite this commanding issue.

Hot-Fire 9 (HF9), Ground and Low-Altitude Hot-Fire

Once the initial hot-fire tests were completed, the next objective was to evaluate the newly constructed flame trench to confirm the desired reduction in vehicle vibroacoutics during lift-off and at low-altitudes. The initial plan for this test included three test firings with one at each ground-level, 1-meter altitude, and 2-meter altitude. However, during the initial test-firing at ground altitude an engine instability occurred and the test day could not accommodate the 2-meter test firing.

Following the initial instability the team quickly de-pressurized and inspected the vehicle. No major issues were found and the vehicle was re-pressurized for a second ground test-firing attempt with different ignition conditions. This time the vehicle started up and completed a 5-second burn (shown in Figure 8a).

The vehicle was again depressurized and inspected in preparation for the low-altitude test firing shown in Figure 8b. This test configuration included the addition of adjustable chains to provide the correct altitude of 1-meter by tensioning from above using a crane. This test firing was successfully executed with a similar duration and throttle profile as the ground test firing.

The primary result of this testing was the vibration data at each altitude, which was compared to vibration data from the 1.5A vehicle. Of particular interest was the data and health of the primary and backup IMU, one of which failed causing the loss of the 1.5A vehicle. Results of this testing confirmed that the flame trench has the desired effect of reducing the vibration at lift-off, and that both the primary and backup IMU's were within their vibration specification and operated as expected.

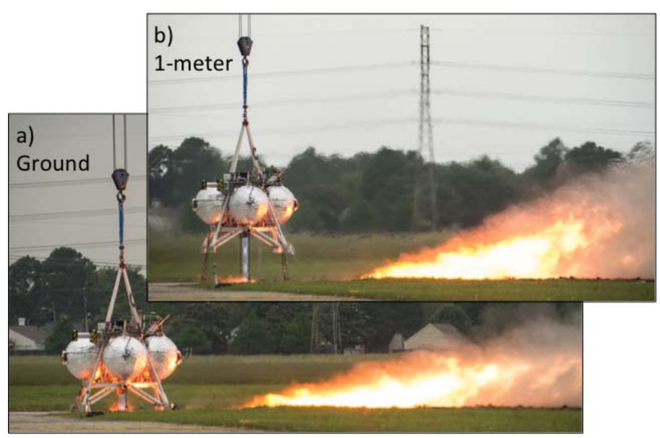


Figure 8 – Morpheus Hot-Fire 9 (HF9) Test Firings

a) Ground Hot-Fire b) Low-Altitude Hot-Fire

Tether Tests 21-26 (TT21 – TT26)

Following hot-fire testing the tether test campaign could begin. The primary purpose of these tests was to verify integrated GN&C performance for both primary and backup systems. The first tether test of the 1.5B vehicle, TT21 was conducted on May 24th 2013. Tether tests 21-26 had a similar flight profile to the 1.0 and 1.5A tether tests that included a 1.5 meter vertical translation, hover, and descent to simulated landing at the end of the tether (the vehicle in hover during TT26 is shown in Figure 9).

During Tether Test 21 (TT21) the vehicle ascended, but then violated the lateral position constraint and a soft-abort command was issued causing the vehicle to descend and land at the end of its tether. There are several reasons that a lack of lateral control could have occurred including CG imbalance of the loaded vehicle, engine misalignment, and inadequate GN&C performance. Similar issues occurred on some of the 1.5B tests due to a loaded vehicle CG issue so the team worked to improve that (i.e. better zero the loaded vehicle CG) for the following test.

The following test, Tether Test 22, successfully executed the planned flight profile and entire 60-second test duration resulting in a nominal shutdown with no major vehicle issues. At this time the presumption was that the system was performing well and that the loaded CG was better balanced than in TT21, resulting in the different outcome.

Figure 9 – Morpheus Tether Test 26 (TT26)

The objective of TT23 was to conduct a tether profile using the backup (IMU), the Systron Donner 500 (SDI-500). The test flight started nominally, completing ascent and hover, when vehicle telemetry was lost. Since the vehicle flight profile is autonomously executed onboard the vehicle the test was proceeding nominally, however, the Test Conductor (TC) decided to issue a soft-abort command to end the test flight. The abort proceeded without issue and fortunately the test flight duration was sufficient to verify acceptable performance of the SDI-500 IMU.

The evaluation of the backup IMU continued in TT24, which included a planned switch during flight from the primary IMU (Honeywell Space Integrated GPS/INS (SIGI)) to the backup IMU. An additional test objective was to command a downmode from the primary RCS (LOX/methane) to the backup RCS (cold gas helium vents). During the transition from ascent to hover the vehicle violated a soft abort limit (similar to TT21) and soft-aborted without accomplishing the test objectives. This excursion was due to the inability of the vehicle to handle a large propellant imbalance causing a non-zero CG (confirmed by the consistency with the direction of the lateral violation). The team was able to depressurize, shorten the flight profile for the remaining fuel, and adjusted to the vehicle rigging to better balance the CG. The second test firing (TT24b) was successfully completed including a commanded handover from primary to backup IMU during hover, satisfying that test objective. However, the shortened test duration was insufficient to also test the downmode to the backup RCS so that objective would have to be completed at a later date.

For the next tether test, TT25, the team added adjustable turnbuckles to the rigging configuration for the tether in response to the continued loaded vehicle CG issues. The concept was to allow adjustment in response to uneven loading or the vehicle hanging at a non-level angle (which causes uneven propellant distribution). Vehicle level sensors measuring the propellant in each tank, and the IMU providing vehicle attitude provide the CG and vehicle level, respectively. Both of these would be used to evaluate and adjust the loaded vehicle CG.

Tether Test 25 also included the integration of the ALHAT sensor suite for the first time with the 1.5B vehicle and a dual ascent and hover profile (first to 1.5 meters, hover, and then to 2.5 meters). This test was conducted on July 11th, 2013 and followed a series of integrated vehicle tests with the ALHAT components both in the Morpheus hangar and at the JSC test area. Unfortunately, this test again resulted in a soft-abort due to lateral position violation despite the best efforts of the team to properly level the vehicle. It became clear at this point that additional vehicle performance from the GN&C system was needed.

The team spent the next two weeks evaluating the vehicle guidance and control gains and parameters (referred to as "i-loads"). One discovery was an i-load specifying the maximum amount of vehicle tilt (non-zero attitude) that could be commanded was limiting the vehicle response to the initial vehicle motion. This limitation was preventing sufficient the vehicle response and was expanded to a more appropriate value for the Morpheus flight profiles. The guidance and control gains were also increased to help improve vehicle performance in lateral position (which is a particular concern during tether when operating in proximity of the crane). A new model of the engine performance for the 1.5B vehicle was also added and included in the analysis leading up to TT26.

Tether Test 26 was conducted on July 23rd 2013 and successfully completed all planned test objectives including evaluation of the new gains, ALHAT sensor integration and scanning, and the downmode from primary to backup RCS during flight.

Tether Test 27 (TT27)

Tether Test 27 had the same ALHAT test objectives as TT26, but also added planned lateral motion during the ALHAT HDS scanning. The flight profile for this test was a dual-hover similar to TT25 and TT26, this time with a 1-meter lateral translation to and from the first to second hover flight. During the lateral translations the vehicle was using, for the first time, a quadratic acceleration guidance profile, which was required for future KSC flight profiles.

During TT27 the vehicle completed the entire flight profile, but demonstrated unstable oscillatory motion at the end of the newly included quadratic acceleration segment. The vehicle attitude oscillated with rates up to 10 degrees per second when the guidance gains (which increase as the time remaining in the segment goes towards zero) increased beyond the range of stable values. The team had set a limit on the time-to-go (Tgo) to help limit the gain increase to 3.0 seconds, however, there were some incorrect assumptions made in the stability analysis and this value allowed the guidance gains to increase too much. Fortunately, when the segment changed to the hover segment, that followed each quadratic segment, the gains returned to a lower value and the vehicle motion quickly damped.

Following this test the team also reviewed the stability analysis assumptions, confirmed that the gains for Tgo of 3.0 seconds were unstable, and selected a new Tgo minimum value of 6.0 seconds for all future flights.

Despite the oscillatory motion the ALHAT objectives were successfully completed. This success allowed the team to de-integrate the ALHAT components and focus on Morpheus flight profiles in preparation for the GTAL test and future KSC testing.

Tether Test 28 – 29 (TT28, 29)

Tether Tests 28 and 29 focused on GN&C refinement and included an expanded flight envelope to emulate segments of the GTAL flight profile. Figure 10 shows the flight profile of TT28 and 29, which shares the same quadratic (Quad2) transitioning to descent as the GTAL profile (shown in Figure 5). This allowed the team to gain confidence that the system performs those components of the GTAL flight profile.

The primary change from TT27 to TT28 was the corrected Tgo limit to provide stable flight. There was a non-Morpheus objective of testing a Mars soil simulant in the presence of an engine plume for the Mars 2020 program. TT28 was very successful and demonstrated stable flight for the largest lateral motion (3 meters) and also the longest flight duration to-date of almost 80 seconds.

TT29 included addition improvements to the GN&C system including modified gains for improved stability margin, improved attitude rate filtering, and the addition of a "delta-velocity" landing trigger based on results from landing tests. This test had a shorter flight duration to match the GTAL plan for loading and segment durations. The test was highly successful and met all test objectives demonstrating the GN&C improvements during flight.

Tether Test 30 (TT30)

Tether Test 30 also increased the flight envelope in preparation for the GTAL test. This also allowed the team to prototype the rigging assembly needed for the higher ascent needed for GTAL. The flight profile (shown in Figure 11) included a 5 meter ascent which allowed an increase of the ascent rate by 3 times (from 0.4 m/s in previous tether tests to 1.2 m/s in TT30).

This test was highly successful and met the test objectives. The only minor issues were with the rigging setup, which identified areas of future improvement. With the successful completion of TT30 the team was now ready to complete the GTAL test.

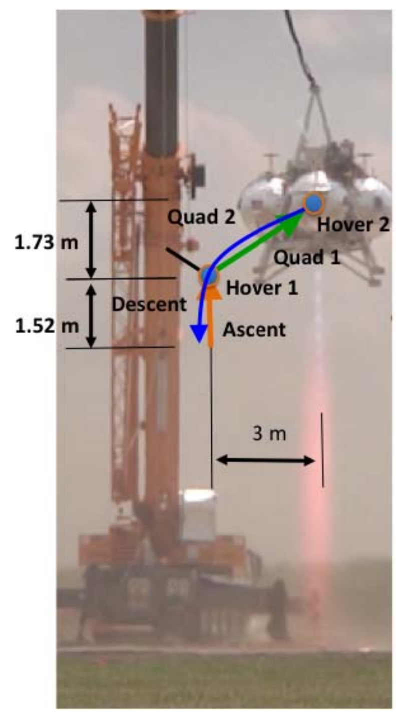


Figure 10 – Tether Test 28 and 29 Profile

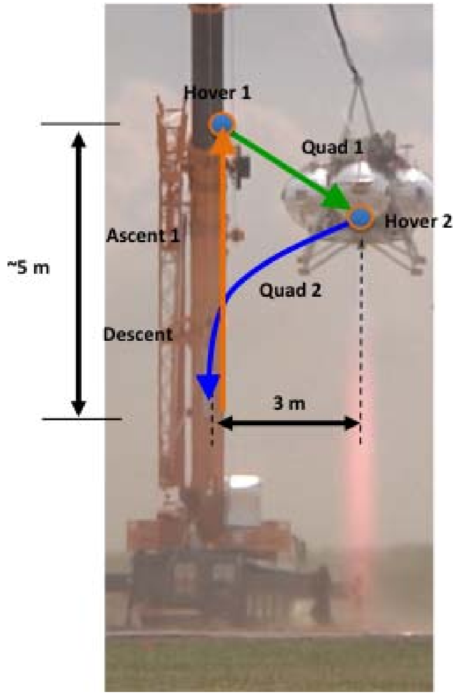


Figure 11 –Tether Test 30, 31, and 32 Profile

GTAL Attempt 1, Tether Test 31 (TT31), GTAL Attempt 2

On September 5th, 2013 the Morpheus team set out to conduct the first ground take-off and landing test with the Morpheus 1.5B vehicle. Early in the test day during the pre-fueling vehicle functional checks it was noticed that the backup IMU was exhibiting intermittent failure flags. Unfortunately, this required the team to scrub for the day to investigate since this hardware was required for flight (despite being used only in the event of a primary IMU failure).

The backup IMU issue was actually part of a larger vehicle electrical grounding problem, which was addressed by revisiting and confirming the grounding of the entire vehicle. During this time the GN&C team also worked improvements to the bias filter used for guidance acceleration commands, modified the gains for terminal descent and added the capability to detect a Global Positioning System (GPS) failure. These improvements were in-work, but not ready in time for the initial attempt and were awaiting the next opportunity to test during a tether test.

TT31 followed the resolution of the GTAL attempt 1 grounding issues and was used to verify the changes during a flight test prior to GTAL. It also allowed the team to test some improvements to the rigging setup learned during the TT30 but not fully tested prior to GTAL attempt 1. This test was successfully completed without issue with results virtually identical to TT30.

The second attempt of GTAL was conducted following the resolution and verification of modifications mentioned above. This test attempt proceeded nominally up through the execution of main engine ignition. However, the flight test was terminated 0.2 seconds into the main engine firing due to a burn-through indication. This indication was later determined to be false, but the flight would have been terminated regardless due to an engine instability that initiated during startup. Analysis of the ignition indicated an interaction between the ground and the stability of engine startup, which would require additional investigation via hot-fire testing at ground level above the flame trench.

Hot-Fire 10 (HF10), Hot-Fire 11 (HF11), and TT32

Hot-Fire 10 shortly followed GTAL attempt 2 and was intended to redefine the instability conditions seen during that test. It was also intended to define the range of engine start conditions that provide stable ignition (initial LOX and methane temperature and pressure combination). This testing successfully generated useful data characterizing engine stability in proximity to the ground and flame trench. However, the combination of this and previous testing resulted in injector face cracks requiring weld repairs prior to additional testing.

The Morpheus team was then forced to take an unexpected break in testing due to the lapse in government funding that occurred starting October 1st 2013. The combination of the shutdown and the required weld repairs resulted in a month delay between HF10 and HF11.

HF11 was successfully executed on October 29th, 2013 and included 11 test firings including 1-second at main stage. This testing confirmed the approach of an increased initial throttle command to provide stable startup of the Morpheus HD4-LT engine use for vehicle 1.5B testing.

An additional tether test, TT32, was now necessary due to the changes in start conditions and a required recalibration of the engine pointing following injector weld repairs. The team also took the opportunity to further refine the guidance and control gains. The test profile test profile and duration for TT32 was a repeat of Tether Tests 30 and 31. TT32 confirmed that the vehicle and team were now ready for GTAL.

Ground Take-off And Landing (GTAL)

GTAL, shown in Figure 13, was conducted on November 7th 2013 and represented the first successful Morpheus test flight to take-off, complete its flight profile, and safely land on the ground. Despite dealing with somewhat high winds and interaction with the tether rigging assembly the vehicle performed its flight profile extremely well and landed within inches of the intended landing target. The only issue of note was some minor damage to the altimeter due to debris from spalling concrete during landing.

Figure 13 – Ground Take-off And Landing (GTAL)

Successful execution of GTAL concluded the testing of the Morpheus 1.5B vehicle at JSC. The JSC testing campaign demonstrated all of the necessary vehicle capabilities including, primary, backup, and ALHAT objectives required for free-flight testing at KSC.

5. KSC TEST CAMPAIGN SUMMARY

This section discusses the Morpheus Free-Flight testing completed at KSC at the time this paper was written. Currently the team has completed the flights necessary to demonstrate the Morpheus 1.5B vehicle as a vertical testbed via free-flight testing conducted in Campaign 0.

Campaign 0 Test Results, Initial Free-Flight Capability

The first flight test of Campaign 0, TT33, was conducted on December 6th, 2013 and was a repeat of the flight profile flown during Tether Tests 28 and 29. Flying the TT28/29 profile allowed for more simplified crane rigging than that of the TT30-32 profiles flown in preparation for GTAL. This flight was completed successfully and confirmed that the vehicle, GSE, and team were ready to proceed with free-flight testing at KSC.

Free-Flight 3 (FF3) was the first attempted untethered flight of the Morpheus 1.5B and was successfully completed on December 10th, 2013. The vehicle completed a 54-second flight profile similar to GTAL with an increased ascent distance (15 meter) and downrange distance (7 meter). At approximately 20 seconds remaining in the flight GPS data was lost and did not recover. The vehicle was able to continue on its flight profile on IMU and altimeter data alone. Despite the loss of GPS the vehicle was still able to land safely within 0.15 meters (6 inches) of the intended landing target.

Following the completion of FF3 the team worked to determine the cause of the GPS data loss. Reviewing the data revealed that the GPS solution was slowly degrading during the course of the flight. Troubleshooting of the GPS box and antenna did not indicate any problems with that vehicle hardware. However, it was discovered that the Command and Telemetry (C&T) radio was malfunctioning and broadcasting outside of its frequency range. This resulted in blockage of the GPS frequencies preventing the Morpheus GPS from receiving those signals and producing a solution. This vehicle C&T hardware was removed, replaced, and tested on the vehicle. The new radio was also provided with additional vibration protection to help prevent a similar hardware failure in the future.

Free-Flight 4 (FF4) was conducted 1-week after FF3 and represented a significant expansion of the flight envelope. Figure 14 shows a composite set of images taken to show the profile view of the trajectory. This flight was again a similar profile to GTAL and FF3, but traversed much larger altitude (50 meters) and downrange (47 meters) distances. This flight was also the first flight to land in the hazard field (at LS1). FF4 was extremely successful with the vehicle flying its flight profile flawlessly and landing within 0.09 meters (3.5 inches) if the intended landing target. The successful completion of FF3 brought Campaign 0 and 2013 to a close for the Morpheus team.

Future test campaigns (1-3) will continue to expand the flight envelope, demonstrate the full HDP trajectory profile, and closed-loop demonstration of the Morpheus/ALHAT system selecting and navigating to a safe site within the hazard field.

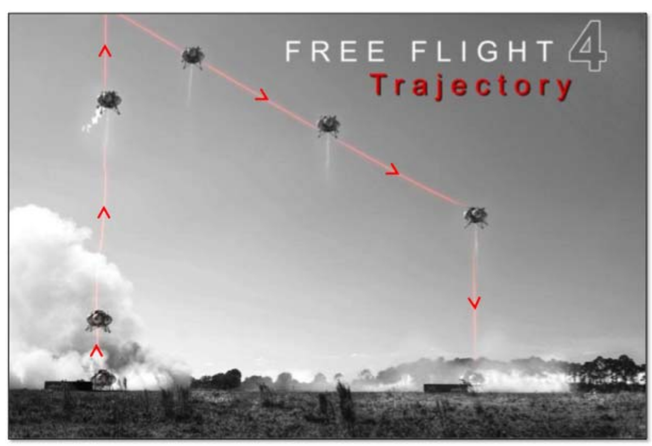


Figure 14 – Free-Flight 4 Trajectory

6. CONCLUSIONS

In early Fiscal Year 13, Morpheus built the 1.5B 'Bravo' vehicle after loss of the 1.5A 'Alpha' vehicle, and made a number of upgrades and improvements to the vehicle and ground subsystems, including integration of the ALHAT hardware and software components. These upgrades provided improved performance, expanded capabilities, and better robustness during the extended test campaign that will culminate in high energy trajectories that simulate a landing approach on a lunar, asteroid or planetary surface.

After the loss of the 1.5A vehicle, the 1.5B vehicle was built with many improvements and an emphasis on better resistance to single point failures. The 1.5B vehicle was built within nine months of the 1.5A vehicle loss, and has since performed five static hot fire tests, fourteen tether tests, one ground take-off and landing test, and two free flights. Several of these tests were included to test specific design improvements incorporated into the 1.5B vehicle. Each flight test opportunity provided valuable insights, even when the primary test objectives were not met, and provided the team with valuable data on how the integrated system performs. These lessons were then folded into the following tests resulting in numerous initially unanticipated design improvements.

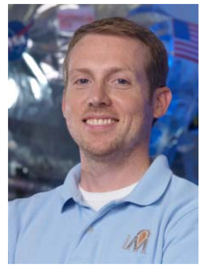
The early flight tests included many discrepancies and part failures. The project team often referred to the "bathtub curve," which describes a complex system that has higher failure rates in the early stages, but eventually reaches a low failure rate until component life once again increases the failure rate. Early failures included both parts failures (solenoid valves, seals, propulsion feed system contamination, issues due to electromagnetic interference) and software design issues (GN&C tuning). By Tether Test 28, nearly all major vehicle issues were resolved, until main engine instability became a concern during GTAL testing. This issue was resolved through modifying the main engine start conditions for a higher power start. Free flights 3 and 4 at KSC were highly successful, and the vehicle flight performance was nearly perfect with respect to the planned trajectories.

After the 1.5A vehicle crash, the project adopted a risk posture that was only slightly more risk averse for the 1.5B vehicle; more time was spent on analysis and testing following a major flight test issue than for the 1.5A vehicle. But the overall risk tolerance of the project continues to be moderately high compared to higher dollar projects and programs. The project has continued to find that the best way to learn how the system will perform is to perform testing rather than complex analysis. The testing completed to-date has demonstrated the capabilities of the Morpheus 1.5B vehicle as a viable planetary lander prototype for technology development.

REFERENCES

[1] Hart, Jeremy J. and Mitchell, Jennifer D., "Morpheus Lander Testing Campaign," presented at the IEEE Aerospace Conference, Big Sky, MT, 2012.

BIOGRAPHY



Jeremy J. Hart *– Mr. Hart is an aerospace engineer for NASA at the Johnson Space Center (JSC) and currently serves as the Guidance Navigation & Control (GN&C) Lead for the Morpheus Project. He has also served as the Flight Test Lead and Vehicle Manager for the Morpheus Project during the build-up and testing of the 1.0, 1.5A, and 1.5B Morpheus vehicle configurations. In those roles he has been responsible for managing the Morpheus flight test objectives, vehicle test configurations, and test schedules. Earlier in his career he served as the NASA lead for Orion GN&C automation and autonomy and as a result he has been very involved with the development of the Orion GN&C flight software architecture. He previously served as the NASA glided flight lead for the Shuttle Abort Flight Manager (SAFM) application and as a flight control analyst on the X-38 flight test program. Mr. Hart received a Bachelor of Science degree in Engineering Mechanics from the University of Wisconsin and a Masters of Science in Aerospace Engineering from Texas A&M University.*

Jennifer L. Devolites *- Ms. Devolites graduated from Texas A&M University with a Bachelor of Science Degree in Aerospace Engineering. She has worked at NASA JSC for 21 years in a number of technical and management roles on projects including Simplified Aid for Extravehicular Activity Rescue (SAFER), Autonomous Miniature Robotic Camera (AERCam), International Space Station Guidance, Navigation and Control (ISS GN&C), X-38, Exploration Technology Development Program Automated Rendezvous and Docking Sensor Technology Project (ETDP AR&DSTP), and Orion GN&C. She has served as the systems engineering and integration lead for Project Morpheus since 2009, and has been Test Conductor for 23 Morpheus flight tests.*

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APPENDIX A: TEST SUMMARY

Test Name	Date	Hardware/GSE/FSW changes since last test	Description / Objectives	Pass/ Fail	Burn Time	Test Results and Notes
HF7	4/23/13	Initial Morpheus 1.5B vehicle test firings	Main Engine Ignition Tests Methane RCS Testing	Pass	1.4 s	- 3 main engine ignitions (200 ms, 600 ms, 600 ms) Methane RCS testing
HF8	5/1/13		Ignition Test, Main Stage, Engine Gimbaling, ME+RCS, and RCS-only testing	Pass	58 sec	- Three 1-sec firings, one 5-sec firing, one 42-sec with RCS firings (actual firing was 50 seconds due to commanding conflict with RCS) - RCS Test following 40 sec burn
HF9	5/16/13		Ground Hot Fire	Fail	0.4 s	Engine instability terminated during startup
			Ground Hot Fire	Pass	5 s	Successful startup, throttle up, and shutdown (2.6 sec mainstage)
			Hot Fire (1 m above ground)	Pass	5 s	Successful startup, throttle up, and shutdown (2.6 sec mainstage)
TT21	5/24/13	Initial 1.5B vehicle closed-loop GNC test	Nominal Tether Test (60 sec duration)	Fail	11 s	Soft abort, Lateral violation
TT22	6/6/13		Nominal Tether test (60 s duration)	Pass	60 s	
TT23	6/11/13	Backup Inertial Measurement Unit (BIMU) set to prime	Backup IMU (SDI-500) tether test Nominal Tether test (60 s duration)	Pass	25 s	- Soft abort commanded during loss of telemetry - Test objectives still accomplished (sufficient time on BIMU)
TT24	6/14/13		- Switch to Backup IMU during flight - Switch to Backup (GHe) RCS during flight - Nominal Tether test (60 s duration)	Fail	12 s	Soft abort, Lateral violation
				Pass	30 s	- Nominal engine shutdown after 30 second tether test - BIMU switch completed during hover, stable vehicle before/after switch - Insufficient time to switch to Backup RCS during flight

Test Name	Date	Hardware/GSE/FSW changes since last test	Description / Objectives	Pass/ Fail	Burn Time	Test Results and Notes
TT25	7/11/13	- Initial 1.5B Vehicle Test with ALHAT - Added adjustable rigging for leveling	- Two-stage ascent profile tether flight - ALHAT Hazard Detection System (HDS) track target point - ALHAT HDS mozaic scan - Switch to Backup RCS during flight	Fail	11 s	Soft abort, Lateral violation
TT26	7/23/13	- Modified Guidance & Control gains - Increased limit on allowable vehicle tilt - Updated Main Engine model (v1.4)	Repeat of TT25	Pass	55 s	- Nominal engine shutdown after 55 second tether test - Completed both ALHAT HDS modes - Backup RCS switch during hover 2, stable vehicle before/after switch
TT27	7/26/13	Two-stage ascent profile changed to include 1 m lateral motion (using variable gain "Qudratic Descent" guidance)	- Two-stage ascent with lateral motion (1 m) - ALHAT Hazard Detection System (HDS) track target point - ALHAT HDS mozaic scan - Long duration tether flight (~80 sec), high thrust due to high propellant load	Fail	81 s	- Nominal engine shutdown after 81 second tether test - Largest commanded lateral motion to date (1 m) - Oscillatory motion during the end of both "Quad" segments - Motion was damped when vehicle switched back to hover segments - Sufficient ALAHT data was collected - including some data on higher dynamics due to oscillatory motion

Test Name	Date	Hardware/GSE/FSW changes since last test	Description / Objectives	Pass/ Fail	Burn Time	Test Results and Notes
TT28	8/7/13	Two-stage ascent profile changed to include 3 m lateral motion (GTAL analog) Note: ALHAT de-integrated from vehicle - Limited guidance gains during "Quad" segments by increasing Tgo Min - Attitude bias filter from ENU to Body - Moved to VFC2 test area	- Two-stage ascent with lateral motion (3 m) - Long duration tether flight (~80 sec), high thrust due to high propellant load - Mars soil simulant test	Pass	77 s	- Nominal engine shutdown after 77 second tether test - Largest commanded lateral motion to date (3 m) -Data collection of plume interaction with Mars soil simulant
TT29	8/23/13	- Modified Guidance & Control gains for improved stabilty margin - Improved attitude rate filtering - Added delta-V trigger to landing logic	- Two-stage ascent with lateral motion (3 m) - Repeat of TT28 with shorter duration to simulate GTAL flight loading and test duration	Pass	50 s	- Nominal engine shutdown after 50 second tether test
TT30	8/29/13	Two-stage ascent profile changed to include 5 m ascent and 3 m lateral motion (GTAL analog) - Modified rigging for higher ascent and appproximation of GTAL rigging - Minor landing logic modifications	GTAL-like flight profile with higher ascent and rate	Pass	64 s	- Nominal engine shutdown after 64 second tether test - Highest commanded ascent (5 m) and ascent rate (1.2 m/s) to date
GTAL attempt 1	9/5/13		Ground Take-off and Landing	Fail	n/a	- Test aborted due to BIMU data drops (later attributed to vehicle grounding issues)
TT31	9/18/13	- Electrical system modifications - Tuning of Accel bias filter - Terminal descent Kr = 0 for lateral - Added GPS fail detection	Repeat of TT30	Pass	63 s	- Nominal engine shutdown after 63 second tether test

Test Name	Date	Hardware/GSE/FSW changes since last test	Description / Objectives	Pass/ Fail	Burn Time	Test Results and Notes
GTAL attempt 2	9/24/13		Ground Take-off and Landing	Pass	0.2 s	- Flight terminate during engine startup due to false burn-through signal - Engine instability also observed during startup
Hot-Fire 10	9/26/13		Main Engine Ground Ignition Stability	Pass	--	- Numerous test firings at various start conditions - Injector face cracks
Hot-Fire 11	10/29/13	- Engine repairs - Increased start-up throttle setting	Main Engine Ground Ignition Stability	Pass	--	- 11 test firings including 1 second at mainstage - Increased initial throttle setting resolved instabilities
TT32	11/1/13	- Gains for improved stability margin	Confirm engine recalibration Repeat of TT30, TT31	Pass	62 s	- Nominal engine shutdown after 63 second tether test
GTAL	11/7/13		Ground Take-off and Landing 7 m Altitude 3 m Downrange	Pass	42 s	- Successful test flight - Minor rigging interaction - Altimeter optics chipped during landing
TT33 (KSC)	12/6/13	- Gains for improved stability margin	Post-shipping and KSC operations checkout TT28, TT29 profile	Pass	54 s	- Successful 1.5B KSC checkout flight
FF3	12/10/13		First 1.5B Free-flight 15 m Altitude 7 m Downrange	Pass	54 s	- Landed within 0.15 m (6 inches) from target - GPS data lost due to C&T radio interference
FF4	12/17/13	- Replaced C&T radio	First landing in Hazard field 50 m Alt 47 m Downrange	Pass	82 s	- Landed within 0.1 m (3.5 inches) from target