Helicopter Field Testing of NASA's Autonomous Landing and Hazard Avoidance Technology (ALHAT) System fully integrated with the Morpheus Vertical Test Bed Avionics

Dr. Chirold D. Epp[1] and Edward A. Robertson[2]
NASA, Johnson Space Center, Houston,Texas,77058

Dr. David K Ruthishauser[3]
NASA, Johnson Space Center, Houston,Texas,77058

ABSTRACT

The Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project was chartered to develop and mature to a Technology Readiness Level (TRL) of six an autonomous system combining guidance, navigation and control with real-time terrain sensing and recognition functions for crewed, cargo, and robotic planetary landing vehicles. The ALHAT System must be capable of identifying and avoiding surface hazards to enable a safe and accurate landing to within tens of meters of designated and certified landing sites anywhere on a planetary surface under any lighting conditions. This is accomplished with the core sensing functions of the ALHAT system: Terrain Relative Navigation (TRN), Hazard Detection and Avoidance (HDA), and Hazard Relative Navigation (HRN). The NASA plan for the ALHAT technology is to perform the TRL6 closed loop demonstration on the Morpheus Vertical Test Bed (VTB). The first Morpheus vehicle was lost in August of 2012 during free-flight testing at Kennedy Space Center (KSC), so the decision was made to perform a helicopter test of the integrated ALHAT System with the Morpheus avionics over the ALHAT planetary hazard field at KSC. The KSC helicopter tests included flight profiles approximating planetary approaches, with the entire ALHAT system interfaced with all appropriate Morpheus subsystems and operated in real-time. During these helicopter flights, the ALHAT system imaged the simulated lunar terrain constructed in FY2012 to support ALHAT/Morpheus testing at KSC. To the best of our knowledge, this represents the highest fidelity testing of a system of this kind to date. During this helicopter testing, two new Morpheus landers were under construction at the Johnson Space Center to support the objective of an integrated ALHAT/Morpheus free-flight demonstration. This paper provides an overview of this helicopter flight test activity, including results and lessons learned, and also provides an overview of recent integrated testing of ALHAT on the second Morpheus vehicle.

Nomenclature

AES	=	Advanced Exploration Systems
AFM	=	Autonomous Flight Manager
ALHAT	=	Autonomous Landing and Hazard Avoidance Technology
APU	=	Avionics Power Unit (Morpheus flight computer and power distribution)
ARC	=	Ames Research Center
DEM	=	Digitial Elevation Map
FOV	=	Field Of View
GNC	=	Guidance, Navigation, and Control
GPS	=	Golobal Positioning System
HDA	=	Hazard Detection and Avoidance
HDS	=	Hazard Detection System
HRN	=	Hazard Relative Navigation
HDP	=	Hazard Detection Phase

[1] ALHAT Project Manager, Aerospace and Flight Mechanics Division, 2101 NASA Parkway, Houston, TX 77058/EG1, and AIAA Member Grade for first author.
[2] Deputy ALHAT Project Manager, Aerospace and Flight Mechanics Division, 2101 NASA Parkway, Houston, TX 77058/EG5, and AIAA Member Grade for second author.
[3] Insert Job Title, Department Name, Address/EA461, and AIAA Member Grade for third author.

IMU	=	Inertial Measurement Unit
JSC	=	Johnson Space Center
JPL	=	Jet Propulsion Laboratory
KSC	=	Kennedy Space Center
LaRC	=	Langley Research Center
LA	=	Laser Altimeter
LOX	=	Liquid Oxygen
MMCC	=	Mobile Mission Control Center
NDL	=	Navigation Doppler Lidar
SLF	=	Shuttle Landing Facility
TRL	=	Technology Readiness Level
TRN	=	time step
TRR	=	Test Readiness Review
VTOL	=	Vertical TakeOff and Landing
WFF	=	Wallops Flight Facility
σ	=	Standard Deviation

I. Introduction

Autonomous planetary landing with real-time hazard detection and avoidance has emerged as a technology of considerable interest to the U.S. and international aerospace communities. Much of this interest is due to the work of the Autonomous Landing and Hazard Avoidance Technology Project (commonly known as ALHAT[1,2]) funded by NASA starting in 2006. The ALHAT Project was chartered to develop and mature to a Technology Readiness Level (TRL) of six an autonomous system combining guidance, navigation, and control with terrain sensing and recognition functions for crewed, cargo, and robotic planetary landing vehicles. The ALHAT system combines three functions to achieve this goal: Terrain Relative Navigation (TRN), Hazard Detection and Avoidance (HDA), and Hazard Relative Navigation (HRN).

The TRN function compares terrain data collected by onboard sensors with stored reconnaissance maps to support precision global navigation. One of the basic development requirements for the ALHAT System is that it must be capable of navigating a vehicle within 90 meters (3σ) of a landing target selected by mission planners. TRN has long been employed in terrestrial military applications and, in 2009, the ALHAT Project successfully demonstrated several TRN techniques utilizing active and passive sensing systems on a winged aircraft over the Nevada Test Site and Death Valley.

The HDA function is the most challenging part of an autonomous safe landing system. Prior to FY2012, the ALHAT Project tested active terrain mapping techniques using helicopters and ground-based test configurations. The HDA implementation selected by ALHAT uses an onboard linear mode flash lidar sensor to scan the intended landing area during the approach phase. The Digital Elevation Map (DEM) resulting from the mosaic of 3-D frames is then parsed to identify and rank the available safe landing locations based on the design characteristics and operational constraints of the lander. The hazard detection requirements levied on the ALHAT System include the ability to reliably discern slopes of five degrees and variations in surface roughness of 30cm or greater under any lighting conditions. These challenging performance requirements were selected to drive the development of a safe landing system that would be applicable to a wide range of human and robotic exploration missions.

Identifying safe landing sites is only the first part of the HDA challenge. In order to avoid hazards and accurately land at the selected safe site, it is critical to maintain an onboard surface relative position and velocity navigation state. ALHAT utilizes HRN to supplement the ground-relative navigation data provided by highly accurate, lidar-based altimeter and velocimeter sensors. The HRN function correlates flash lidar frames acquired during the latter stages of the approach phase with the original DEM used for hazard detection, to provide position updates accurate to a few DEM pixels. With this surface relative navigation state knowledge the vehicle can descend precisely to the surface with minimal error for the last 80 m without external sensor inputs and avoid dust problems.

The goal given to the ALHAT Project starting in FY2012 was to demonstrate real-time HDA on a terrestrial Vertical Take-Off and Landing (VTOL) vehicle. This was accomplished by integrating the ALHAT sensors with the Morpheus vehicle navigation and avionics system. The original objective was to fly a planetary landing trajectory starting from a slant range of 1000 meters to the initial landing target and using closed loop, real-time hazard detection and onboard navigation to autonomously guide the vehicle to a safe and precise landing within hazardous terrain. To this end, the ALHAT and Morpheus projects were consolidated at JSC with the goal of demonstrating closed loop, safe landing capability on the Morpheus LOX-Methane VTOL. These closed loop flights were originally scheduled to be performed in FY2012 at KSC, but the Morpheus 1.5A vehicle was lost during free flight testing in August 2012, resulting in a one year delay. Morpheus 1.5B, the most recent iteration of the Morpheus VTB, is expected to provide a flight trajectory with a maximum slant range on the order of 500 to 600 meters. This is less than the original ALHAT objective of 1000 meters, but is sufficient to demonstrate the effectiveness of the ALHAT HDA and HRN techniques in a relevant flight environment.

The Morpheus-ALHAT free flight HDA testing is scheduled to be performed at KSC in the first quarter of FY2014. The Morpheus VTB will launch from a pad located just off of the west side of the Shuttle Landing Facility (SLF) landing strip and fly towards the ALHAT hazard field constructed by KSC near the north end of the air strip (Figure 1). To make these terrestrial tests representative of a lunar landing, the ALHAT team designed the hazard field using rock and crater frequency distribution models based upon the latest lunar reconnaissance data. The hazard field is intended to simulate lunar South Pole terrain with craters, rocks, and slopes in a realistic layout. All of the Morpheus-ALHAT flights performing real-time HDA will fly towards and, if successful, land at one of the two safest sites within this hazard field. In Figure 1, these safe sites are visible as 10-meter diameter concrete pads towards the left edge of the hazard field. For the flight tests, these pads will be covered with the same crawler fines used to construct the rest of the hazard field. The hazard field also incorporates several other potential landing sites that the ALHAT System should rank lower than the areas in proximity to these two pads.

Figure 1. ALHAT lunar-like hazard field constructed at the KSC SLF

Shortly after the Morpheus accident on August 9, 2012, the ALHAT team began to discuss the possibility of a helicopter test over the ALHAT hazard field at at KSC, and the search ensued for a helicopter that could be employed for an integrated test of the entire ALHAT System utilizing the Morpheus Avionics Power Unit (APU). Towards the end of September, sufficient information was gathered to support the feasibility of such a test campaign utilizing a LaRC Huey UH-1H helicopter (N535NA). This helicopter included extended struts that provided enough ground clearance to house the ALHAT sensors. Plans were put together that gained support of Advanced Exploration System (AES) program management, and a very intense effort followed to complete the flight tests at KSC before the end of December in order to avoid interfering with the planned ALHAT integration with Morpheus 1.5B in the summer of FY2013. Obtaining access to the helicopter, integrating the systems on the helicopter, and executing the tests in three months proved to be very difficult. But all of these activities were completed by December 14, 2012. A number of problems had to be managed in order to complete these test flights, but the end result was very successful. The helicopter flight test trajectories attempted to closely duplicate the planned Morpheus approach trajectories. However, for safety reasons, the helicopter had to break off its approach approximately 100 meters from the landing area in the hazard field.

II. SYSTEM OVERVIEW

The Hazard Detection System (HDS) consists of a linear mode flash lidar sensor with a 1° FOV lens and a 128x128 pixel detector array mounted on a gimbal with fast slewing capability. The flash lidar operates at 20 Hz, enabling the HDS to collect 100 frames within the five second period allocated by ALHAT requirements for terrain data acquisition and DEM generation. During the helicopter flights, the default frame overlap in the mosaic pattern was 50% between successive frames along a row and 20% between rows. The mosaic overlap percentages can be adjusted, as desired, although that affects the time required to map a given area of terrain. The overlapping frames are correlated to compensate for motion and sensor errors to generate the DEM. The ALHAT HDA algorithms require another five to ten seconds to parse the DEM and provide a ranked set of safe sites to the Autonomous Flight Manager (AFM). The AFM then re-designates the vehicle to target a safe landing site within the scanned area.

The current ALHAT HDS has some limitations that keep it from meeting the ALHAT level zero requirements. The current flash lidar (procured in 2007) utilizing detailed calibration can consistently measure the surface elevation changes accurate to approximately 40 centimeters, as opposed to the required 30 centimeters. This flash lidar also has significant limits on its dynamic range and must utilize automatic gain control (AGC) software to adapt to variations in the intensity of the reflected near-infrared (NIR) radiation, however, the AGC cannot compensate for large variations in reflectivity within a given frame. Modern manufacturing capabilities can produce larger flash lidar arrays with higher sensitivity, significantly larger dynamic range, and improved range precision. A hazard detection system incorporating a state-of-the-art flash lidar sensor will be able to meet or exceed the ALHAT level zero performance requirements. Although funding limitations have prevented the ALHAT project from obtaining an improved flash lidar sensor, the team has pressed ahead with the older flash lidar sensor to mature and demonstrate the ALHAT safe, precision landing approach and gain an improved understanding of the factors driving overall system performance.

At the time of the helicopter testing, the HDS processing had some limits on the speed at which the high volume of flash lidar data collected during an HDS mosaic scan could be processed. The ALHAT requirement is that this data must be collected, processed, and safe sites determined within ten seconds. The HDS uses a Tilera TILE64 multicore processor and parallelized software to maximize data throughput. The maximum size of the HDS scan area was limited to 60x60 meters during the helicopter test due to hard-coded buffer size limitations. In the months since the helicopter test, the HDS software has been refined to address these buffer limitations and increase processing efficiency.

Maintaining an accurate attitude state of the vehicle is critical to this landing process. The usefulness of the sensor measurements are dependent on knowing where the sensors are pointing relative to the vehicle. During actual space flight, this attitude knowledge is expected to be provided by star tracker sensors. For these terrestrial demonstrations the attitude is fine-tuned prior to liftoff and expected to be good enough to maintain pointing accuracy to better than 0.1° throughout the flight.

The initial attitude of the vehicle is obtained by gyro compassing with an IMU for several minutes. This very sensitive measurement uses the rotation rate of the Earth and provides good attitude in the vehicle pitch and yaw axes. To precisely determine the roll axis orientation, an optical camera system developed by Draper Laboratories was used. This camera is pointed at a specially designed target at a precisely surveyed location. The GIDE software determines the center of this target and returns a precision attitude measurement to the Morpheus navigation system.

Two other ALHAT sensors are essential to maintaining the accurate vehicle navigation state required to complete the safe landing. A laser altimeter measures the vehicle altitude above the surface accurate to ten centimeters and will function until the dust becomes an issue. At this point the navigation filter will cease to accept this data. Likewise the ALHAT Doppler lidar sensor provides surface relative velocity measurements accurate to approximately 1 cm/sec. This sensor is very important in maintaining an accurate navigation state as the vehicle flies the approach phase. At some point prior to dust becoming a problem, this sensor data is no longer incorporated into the navigation solution.

III. HELICOPTER INTEGRTION AND TESTING

The helicopter used for these tests at KSC was a LaRC Huey UH-1H providing approximately three feet of ground clearance under the belly. This was sufficient room to mount the ALHAT sensors underneath and point the flash lidar system forward in the direction of flight (Figure 2). Within six weeks, the test plan was developed and the helicopter configuration designed, approved, fabricated, and tested at LaRC before moving to KSC. All safety and air worthiness certifications were completed before flights began at KSC.

Figure 2. Flash lidar viewed from front of helicopter

Figure 3. Sensors under belly of helicopter

Integrating all the systems on the helicopter was a very challenging task, particularly given the short amount of time available to complete the testing. The gimbaled flash lidar, Doppler lidar, laser altimeter, Morpheus IMU, and several antennas were mounted under the belly of the helicopter, as shown in Figure 4. The Morpheus avionics, all of the ALHAT electronics, and all of the support computers were mounted in flight approved racks in the back of the helicopter as shown in Fig. 5. Two ALHAT operators were also located in the back of the helicopter.

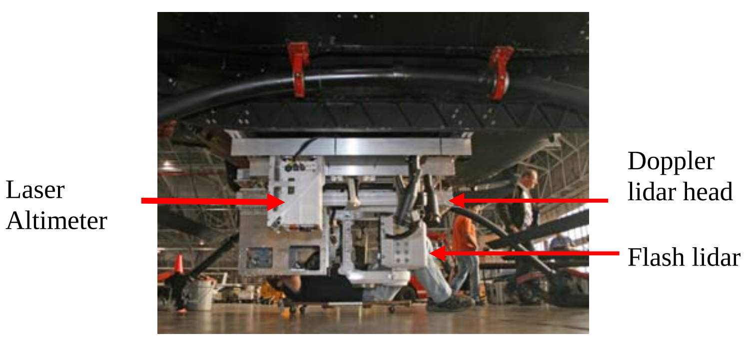

Figure 4. View from rear of helicopter

Figure 5. Avionics electronics inside helicopter

As shown in Figure 2, the flash lidar points in the direction of the forward motion of the helicopter. When the pilots attempted to fly the ALHAT planetary trajectories down to about 50 meters altitude, they determined that the trajectories had to be flown into the wind to maintain safety. Thus, the approach direction to the hazard field was always determined by the winds at the time of flight.

Because of the need to move ahead with Morpheus activities in early 2013 and the non-availability of engineers the last two weeks of December, it became clear that the JSC test window was limited to December 3 through December 14. Completing planning and design, obtaining preliminary approval from the Aviation Safety Review Board to perform some compatibility flights at LaRC before going to KSC, and working around the short week of Thanksgiving proved to be major challenges. But everyone stepped up and did what was necessary to make it happen. The helicopter arrived at KSC on Sunday, December 2, with only a few minor actions to be completed before getting final approval to move ahead with tbe KSC flight testing.

The ALHAT equipment arrived at the SLF Monday morning. KSC TRR, KSC safety briefing, ALHAT plans for the next two weeks, helicopter familiarization flights, surveying and placing the attitude camera targets in place off the runway, and other logistics took most of Monday. Integration of the ALHAT equipment on the helicopter, correcting some cable problems, completing a drip pan to keep helicopter hydraulic fluid from leaking on the sensors, etc took up most of Tuesday and Wednesday. Power up of the system with ground power and helicopter research power was successfully tested as well as switching over to helicopter power from ground power without any impacts was demonstrated. This was a necessary procedure because the alignment with gyro compassing had to be done with the system completely quite, thus using ground power and the system could not be shut down once the alignment was done. Switching from helicopter power to ground power was a problem and gave dangerous power drops and surges which caused the team to rule out the switch over in that direction without turning off all of the ALHAT equipment.

The LaRC review board certification to fly the ALHAT equipment for flight research was obtained on Wednesday. The first flight day on Thursday proved to be a challenge as the pilots, ALHAT system operators in the helicopter, and ground operators worked through procedures for the first time in real time in a real environment. The learning process took a good part of the day as techniques and procedure sequences became better understood. Some problems with the helicopter power occurred on the first flight day and continued to cause occasional problems throughout the flight tests. A voltage spike from the helicopter research power on Saturday actually blew the attitude camera computer. The team was able to work around this problem by gaining camera control on a laptop and manually inputting correct measurements. The final cause of the helicopter research power problems was determined to be a voltage regulator after the end of our test flights.

Despite these many difficulties the test team managed to fly 26 hazard field approaches of various kinds and collected data from every flight and all three sensors. This provided a very large amount of data for analysis. From the start, the plan was to fly varying approaches and not close the navigation loop since the helicopter never came any closer than 50 m to the hazard field and we had no way to autonomously navigate the helicopter. Weather was also a problem causing the loss of one full day of flight testing due to rain and part of two others. Cloud ceilings were present on several days limiting the approaches that could be flown.

The daily plans and desired approach paths of the helicopter towards the hazard field were determined at the end of each day and finalized the morning of the tests. Cue cards with waypoints (Fig. 6) were constructed for the pilots and onboard operators along with procedures and plans for each approach. Various parameters were varied such as flight path angle (30° or 45°), approach speed, and in some case the pilots were requested to hover at the HDP start point to allow more time to collect flash lidar data. Some fixed point tracking flights were also flown to measure the performance of the HDS motion compensation and the ability of the vehicle navigation system to maintain its attitude

A ground command and control center, KSC Mobile Mission Control Center (MMCC), was set at the midpoint of the SLF with command and telemetry links to the onboard systems. The system sequencing and associated commands were generally performed by operators in the MMCC, however, in some cases the onboard operators were given the ability to command via direct connected laptop computers.

Campaign 1 – HDP at varying look angles and ranges
Test 1: 30 degree look angle, 50/20 mosaic

LVLH Coords wrt Hazard Field	Range(m)	Alt(m)	Hdot(m/s)	Slant (m)
WP5	-1072	702	0	1281
WP4	-650	375	0	750
WP3	-562	326	0	650
WP2	-477	274	0	550
WP1	-389	226	0	450
WP0	0	50	0	50

LVLH Coords wrt Hazard Field	Range(ft)	Alt(ft)	Hdot(ft/s)	Slant (ft)
WP5	-3517	2303	0	4204
WP4	-2131	1230	0	2461
WP3	-1845	1070	0	2133
WP2	-1564	900	0	1804
WP1	-1278	740	0	1476
WP0	0	164	0	164

Notes:
- Hover until ALHAT operator advises (~90-180 seconds) at WP's to allow ALHAT to complete processing
- Target descent rate – 0 fpm @ WP
- Target airspeed (no wind) – 0 kts @ WP
- Sensor look angle to center of hazard field is 30 degrees at each waypoint
- Sensor slant range to center of hazard field at:
- WP1 450m
- WP2 550m
- WP3 650m
- WP4 750m

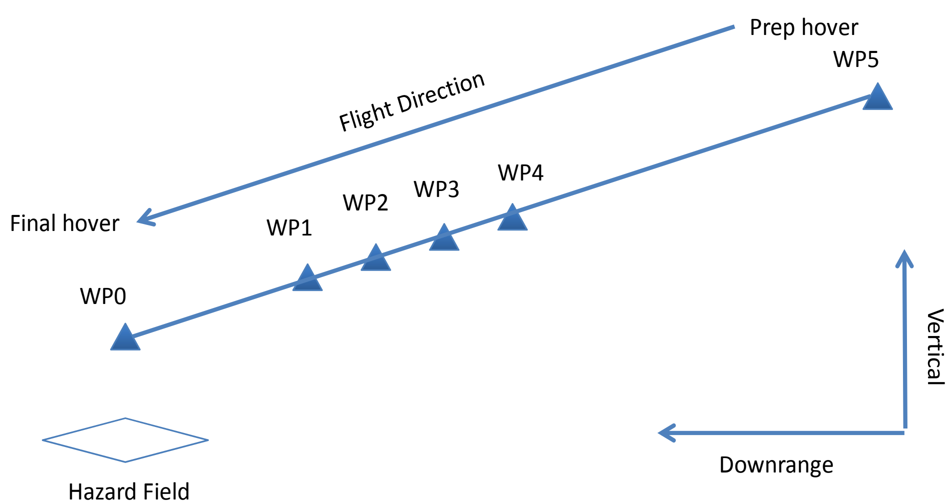

Figure 6. Helicopter Pilot cue card

IV. TEST RESULTS

The helicopter test was very successful accomplishing most of our objectives for all of our systems. The Navigation Doppler Lidar (NDL) successfully met its test objectives, with the exception of the final objective, which was to assess the performance of the sensor data by the ALHAT/Morpheus Navigation filter. Unfortunately, we were not able to activate the ALHAT/Morpheus Navigation filter during these flights. Analysis of the altitude data produced by the NDL demonstrates the robustness of the simultaneous altitude solution technique, which is insensitive to IMU, GPS, navigation filter, or pointing knowledge errors. Reliable and independent altitude measurements provided by the NDL and Laser Altimeter (LA) identified and quantified navigation filter state estimate errors attributed to data from an erroneous calibration factor associated with an Acuity altimeter sensor used by Morpheus nav. All data collected during this field test and associated analysis demonstrated that this sensor has reached a mature state of development and is now a prototype sensor ready for final development and certification as a descent and landing sensor for planetary landing spacecraft.

Likewise the ALHAT developed Laser Altimeter (LA) worked very well even though it had limited range due to a known misaligned laser during these tests. Because of the limited altitude of the helicopter from the ground, this misalignment was not a factor and the data obtained was very good and consistent with what was measured by the NDL. So again this LA is now a prototype sensor ready for final development and certification as a descent and landing sensor for planetary landing spacecraft. Some data from the NDL and the LA are shown in Fig 7.

The HDS system with the gimbaled flash lidar also performed very well. The HDS system clearly identified all of the hazards that it imaged and was consistently in precise agreement with existing truth data. In some cases the HDS images were clearly able to identify navigation attitude errors by comparing the location of its images with the ALHAT navigation system identified location of the image. An example of a flash lidar images is shown in Fig. 8.

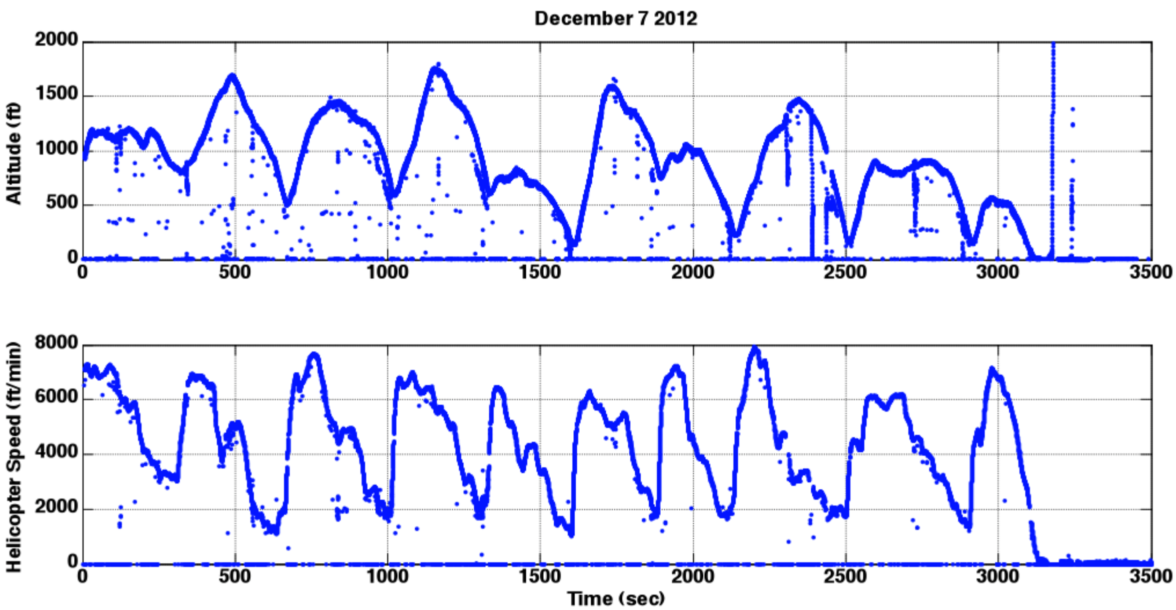

Figure 7. Laser altimeter and Doppler lidar data from sequential helicopter approaches

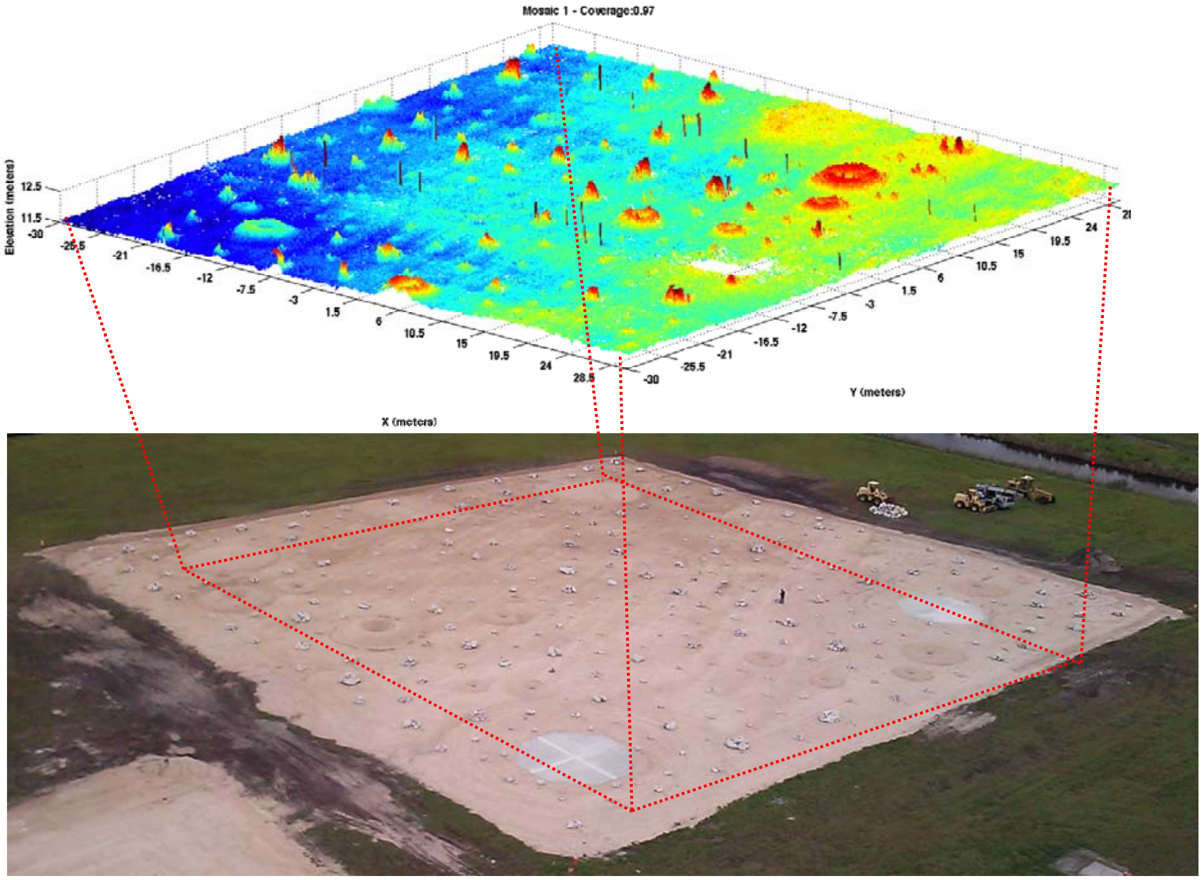

Figure 8. Flash lidar image correlated with picture of hazard field

The ALHAT navigation system performed well except for two problems that plagued the team during the days of this testing. One was our difficulty in getting the inertial attitude of the navigation state initialized correctly before takeoff of the helicopter. This was caused by several factors but the major one was learning a manual technique to align the roll attitude of the vehicle using manual techniques without the damaged attitude camera computer. The second problem with the navigation state was caused by issues with our GPS system which caused the navigation state to lose good state knowledge while on the ground and during flight. Most of the time these errors were not large enough to keep the HDS flash lidar from pointing at some portion of the hazard field so we were able to get good flash lidar images on most of the approaches.

Some long days of dedicated support from the ALHAT Team and the helicopter support team at KSC paid off and the overall test campaign was very successful. Good data was obtained from all of the sensors. A number of software and hardware problems and limitations with the ALHAT and Morpheus avionics systems were found but the team was able to work around many of them to obtain good data. All of these problems have been identified and fixed to support future testing on Morpheus.

V. FUTURE ACTIVITIES

Test campaigns of the new Morpheus 1.5B vehicle are planned to begin at KSC in September 2013 and continue through FY2014. After the Morpheus vehicle demonstrates the ability to successfully fly free flights of HDP trajectories, ALHAT sensors and associated computer elements with software will be integrated with the vehicle. Initial flights will be open-loop HDP trajectory flights with the ALHAT system supplying measurement data to the ALHAT navigation filter without the information used to navigate the vehicle. After analysis shows that this data will navigate the vehicle safely to the real-time determined safe site, this navigation filter will be utilized to navigate the vehicle closed loop safely to the ground. This is the ultimate desired result of these tests and will be the first demonstration on a VTOL vehicle of closed loop real-time hazard detection and avoidance system followed by a safe landing at the real-time determined safe site. Several closed loop flights are planned for FY2014 including higher altitude flights with a higher performance Morpheus engine. Also, some HDA flights utilizing modified ALHAT systems designed for a robotic mission may be demonstrated.

Acknowledgments

Elcellent support for these tests was provided by three nasa helicopter pilots; Alan L. Barringer, WFF, Munro G. Dearing, ARC, Thomas R. Friers, KSC. The Research Services Directorate at LaRC is greatfully acknowledged for their rapid prototype and development of the helicopter hardware required for airworthiness of the ALHAT systems on the helicopter. Safety and quality personnel from LaRC along with the LaRC Airworthiness Safety Review Board worked exceptionally well with the ALHAT Team to ensure the necessary flight safety approvals were reviewed and granted. The KSC quality and safety personnel along with the Ground flight support team provided excellent facilities and personnel support as required to make the two weeks of testing at KSC a success. Finally the entire ALHAT team from JSC, JPL, and LaRC went well beyond normal workloads to make this a successful venture.

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ALHAT/MORPHEUS HELICOPTER FLIGHT TEST

Presenter: Chirold Epp, ALHAT Project Manager
Edward Robertson, ALHAT Deputy PM
David Rutishauser, SE&I Support
NASA, JSC

ALHAT TECHNOLOGY

ALHAT

AUTONOMOUS LANDING AND HAZARD AVOIDANCE TECHNOLOGY

OBJECTIVE

DEVELOP TECHNIQUES AND A PROTOTYPE PLANETARY PRECISION LANDING SYSTEM INCLUDING REAL-TIME HAZARD DETECTION AND AVOIDANCE

CONSOLIDATED WITH MORPHUES IN FY13

HELICOPTER TEST

- Failure of the Morpheus Vehicle on August 9, 2012 provided an opportunity for additional testing of the ALHAT System
- The decision was made to perform a Hazard Detection and Avoidance (HDA) helicopter test of the ALHAT System integrated with Morpheus avionics over the ALHAT hazard field at the SLF at KSC
- Starting from time we received HQ approval to proceed, we had 10 weeks to perform the test so it could be completed by December 14, 2012

HELICOPTER TEST

- This test was successfully completed on the scheduled date
- All objectives were completed with real-time flight data
- This flight test campaign was the first time that the entire ALHAT system along with ALHAT/Morpheus avionics was tested for the Hazard Detection Phase of a planetary landing under real flight conditions flying towards a planetary landing site

TEST ARRANGEMENTS

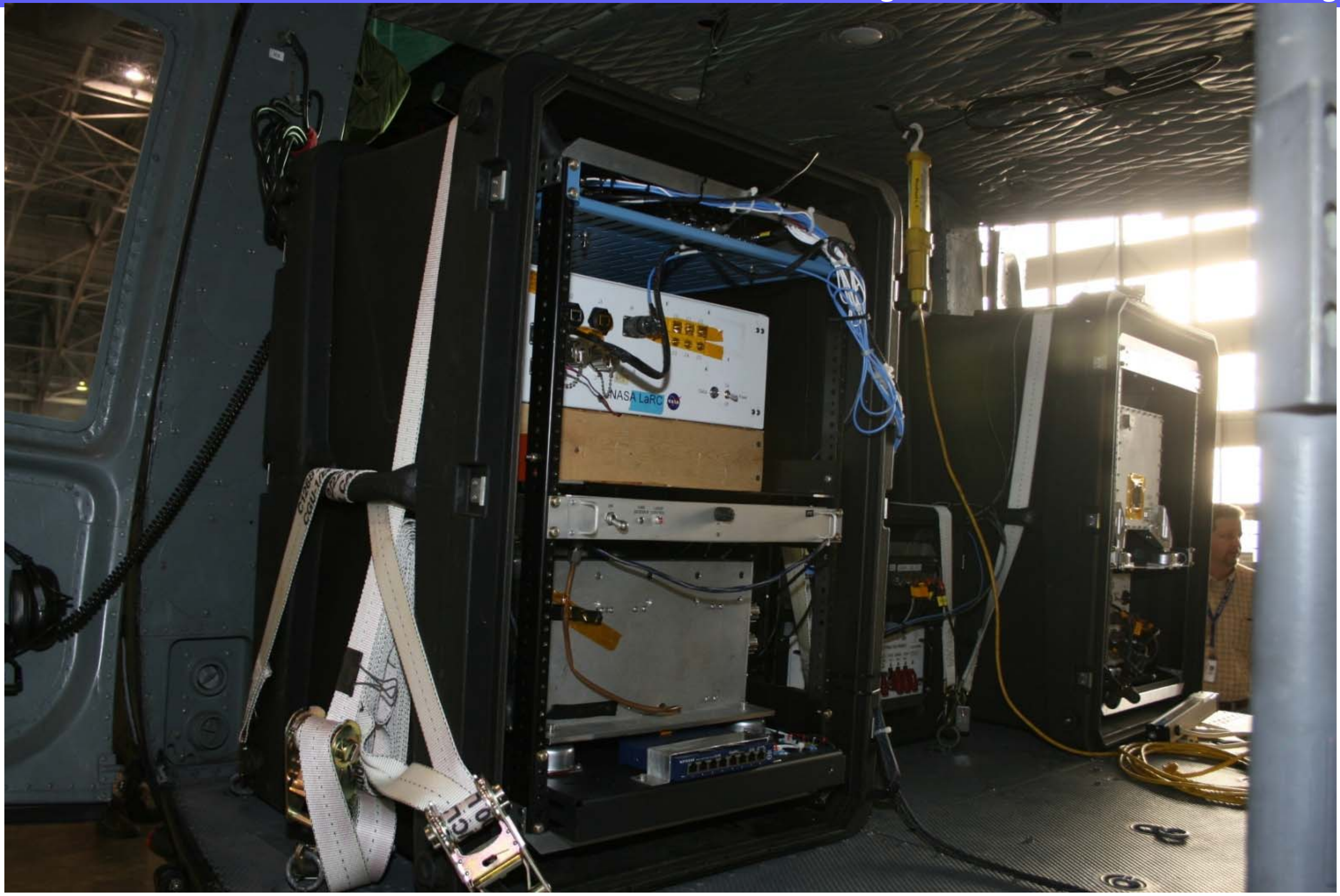
- A LaRC Huey helicopter was used which had about 3 ft of ground clearance under the belly giving enough room to mount the ALHAT sensors underneath and thus point the flash lidar system forward in the direction of flight
- The test plan was developed and the helicopter configuration was designed, approved, fabricated, and tested at LaRC before moving to KSC all within a six weeks time period
- The tests were conducted during a 2 week time slot at KSC, December 2 though the 14.
- All safety and air worthiness certifications were completed before flights began at KSC

FLIGHTS

- Approach flights began on Thursday, 12/6, with a steep learning curve for everyone involved including pilots, onboard operators, and ground support personnel
- Helicopter power glitches caused several problems including damaging the GIDE computer (GIDE is our fine alignment attitude camera system)
- Flight and ground operations procedures were reworked daily and the team converged quickly on most items
- Weather and communications between the ground and helicopter caused additional problems
- 29 approaches to the hazard field were flown with some data collected on every flight. Winds of the day dictated the direction of approach to the hazard field

HELICOPTER LAYOUT

Autonomous Landing Hazard Avoidance Technology (ALHAT)



Avionics components inside helicopter

HELICOPTER LAYOUT

Autonomous Landing Hazard Avoidance Technology (ALHAT)

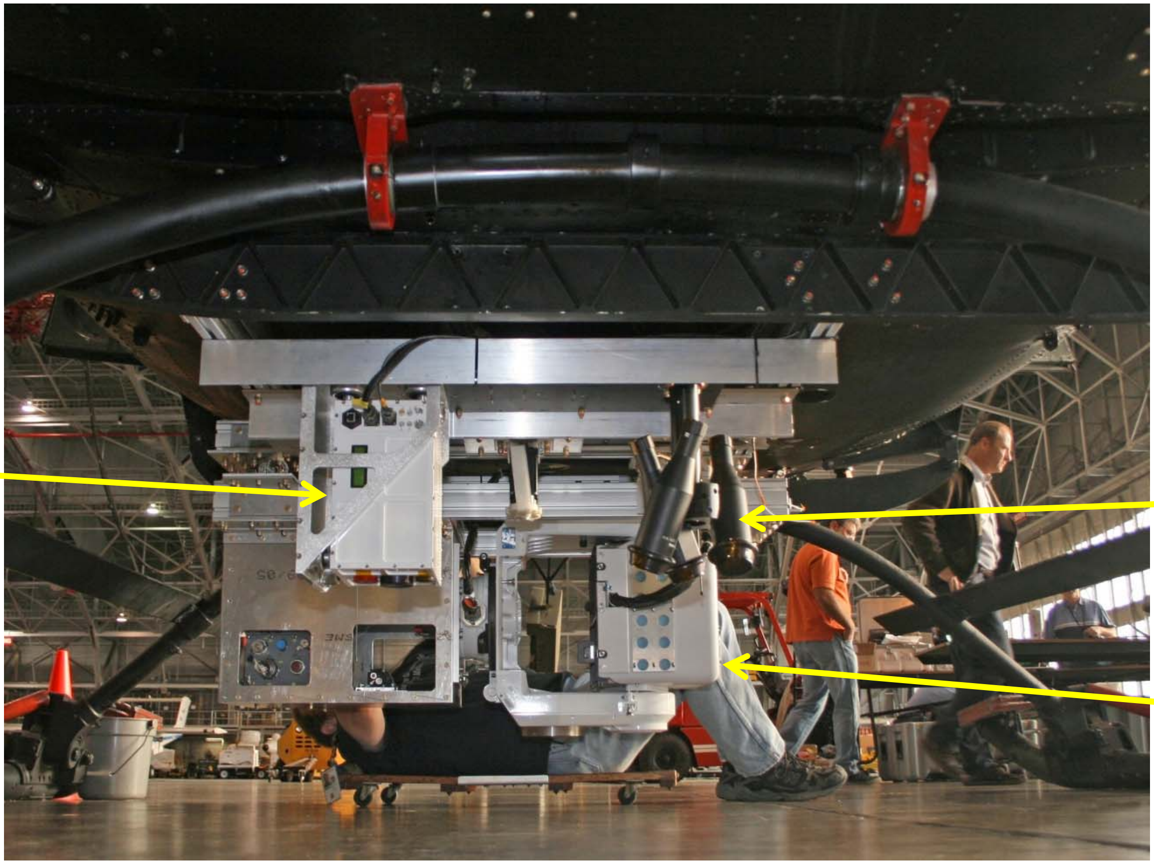
Flash lidar

View from front of helicopter

HELICOPTER LAYOUT

Autonomous Landing Hazard Avoidance Technology (ALHAT)

Laser altimeter



Doppler lidar sensor head

Flash lidar

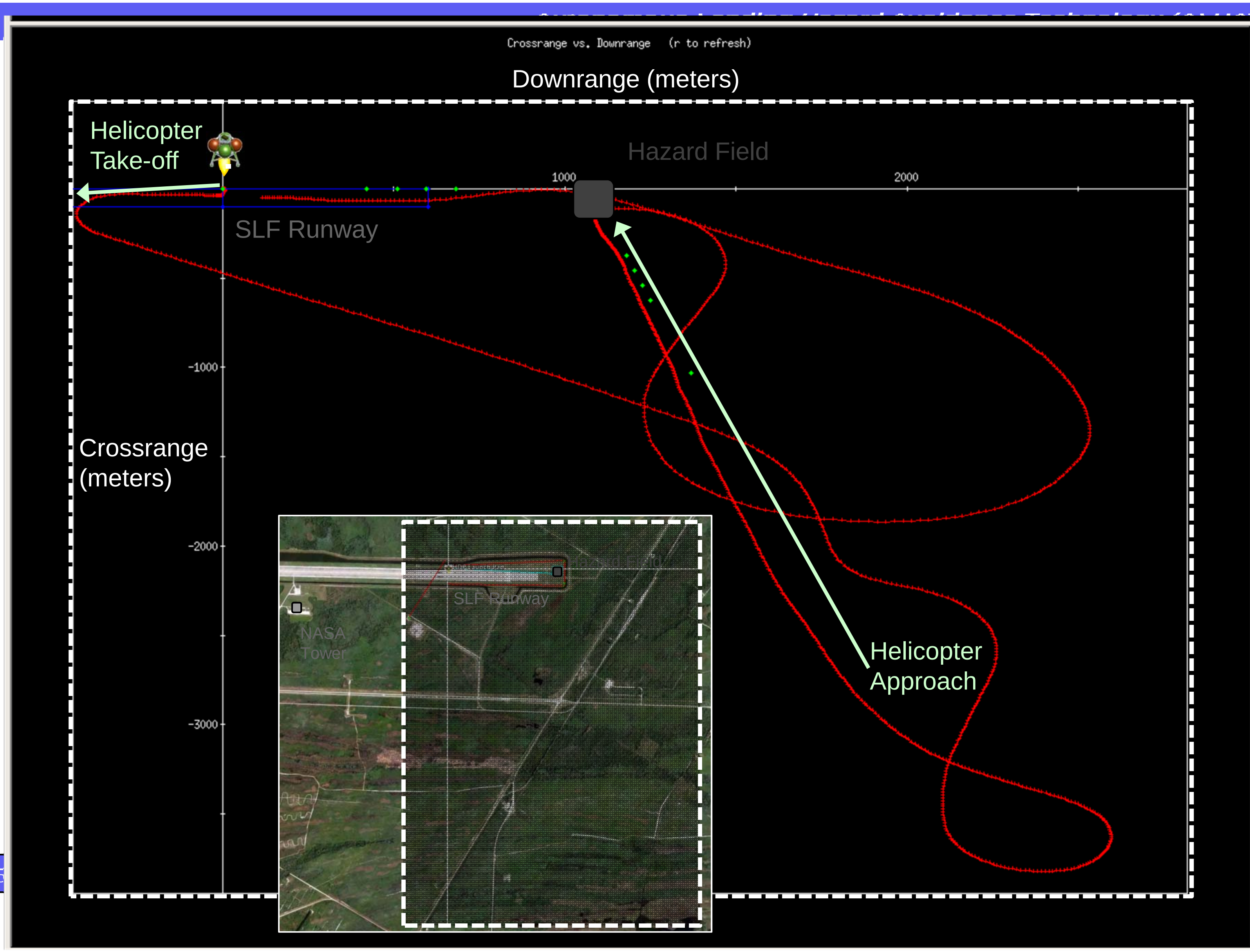
View from back of helicopter

HELICOPTER LAYOUT

Autonomous Landing Hazard Avoidance Technology (ALHAT)

KSC HAZARD FIELD

FLIGHT GROUNDTRACK, 12/11

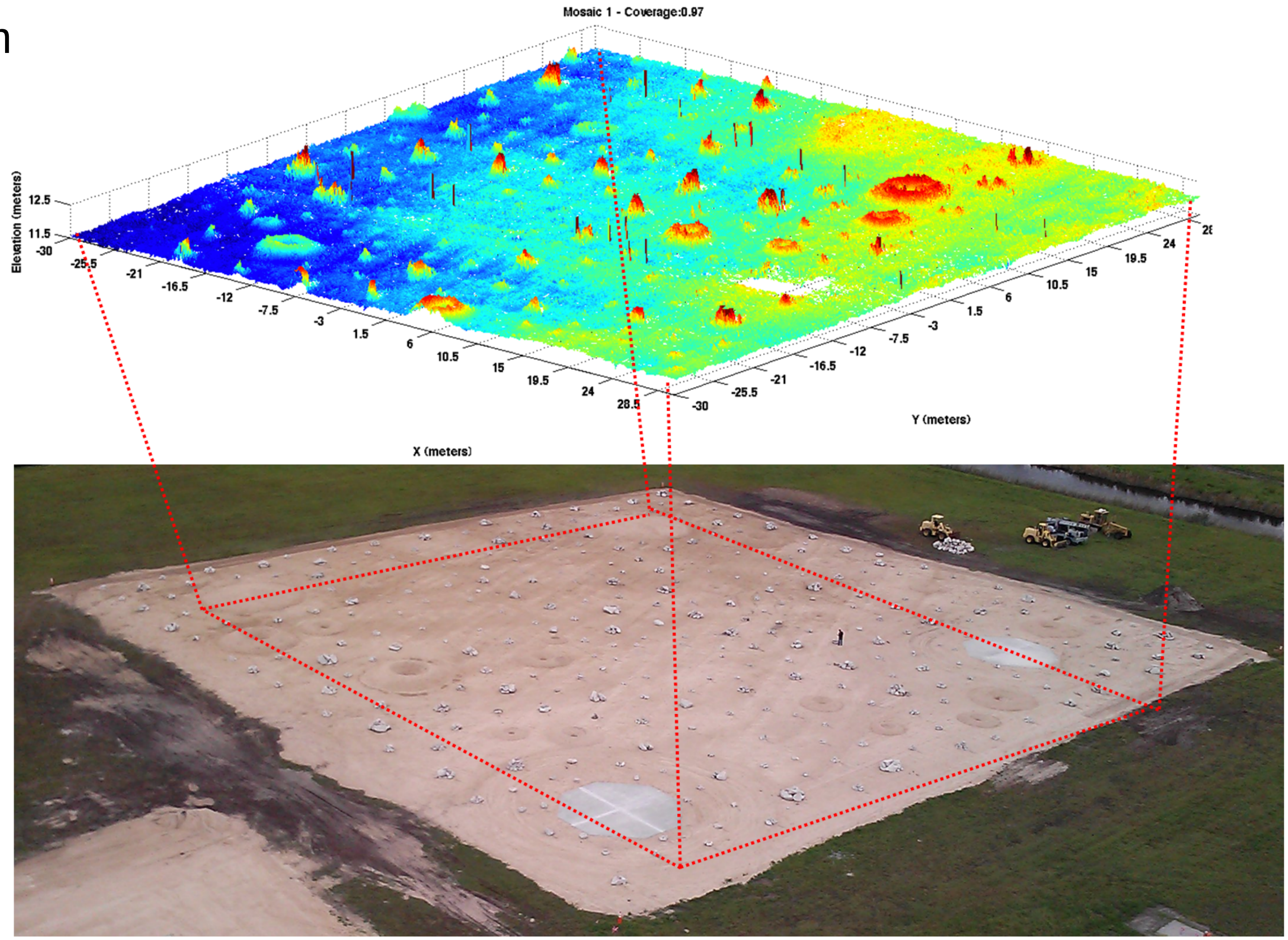


Mosaic/DEM Generation

Autonomous Landing Hazard Avoidance Technology (ALHAT)

Range: 742m
Angle: 20º

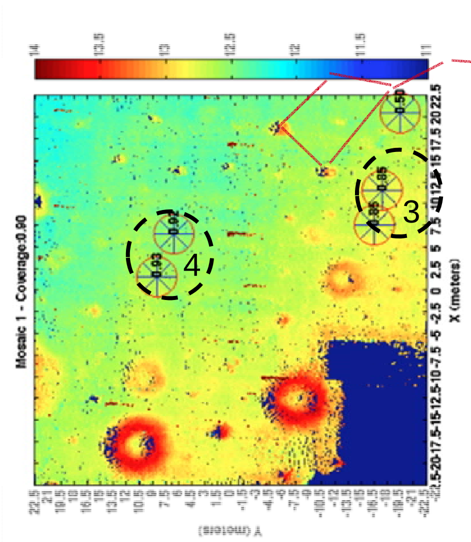
Largest mosaic produced, 60m x 60m

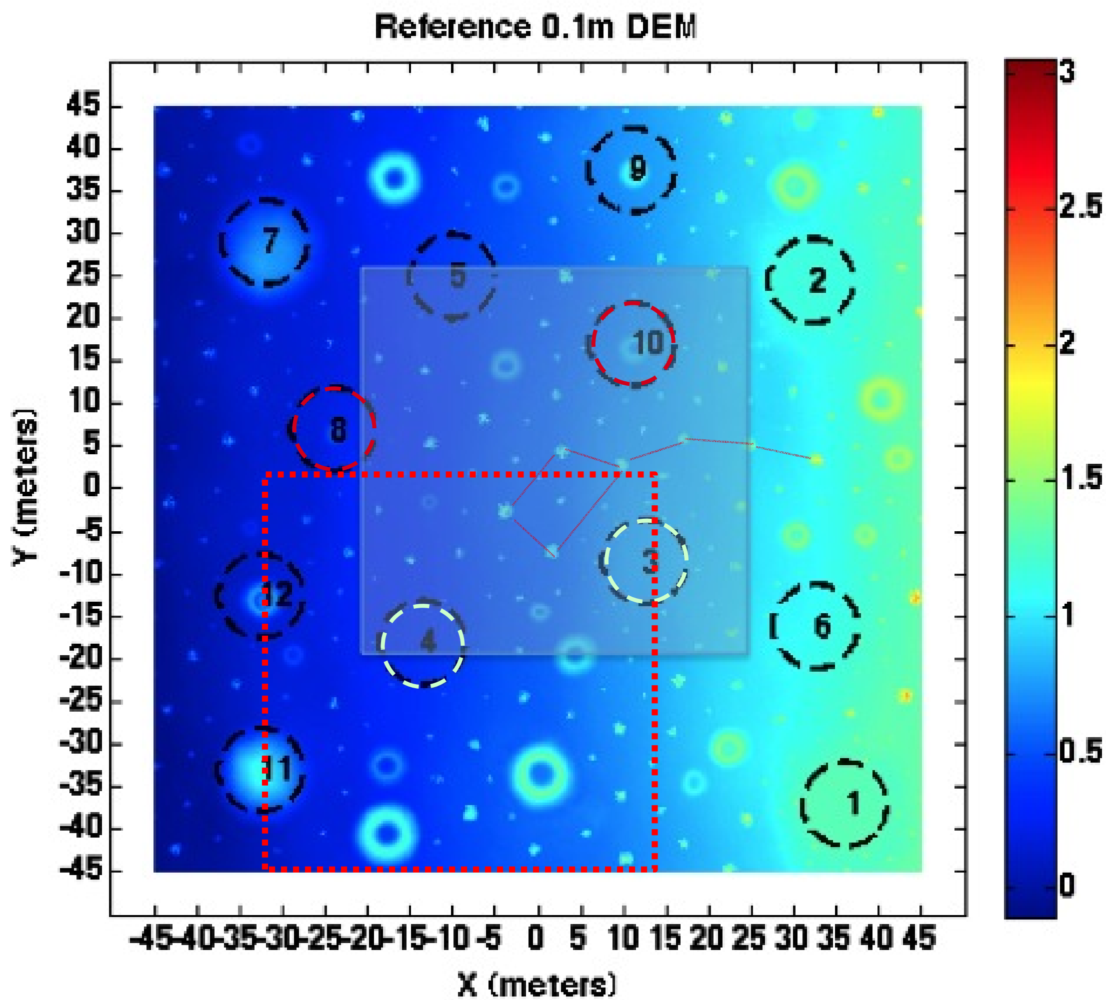


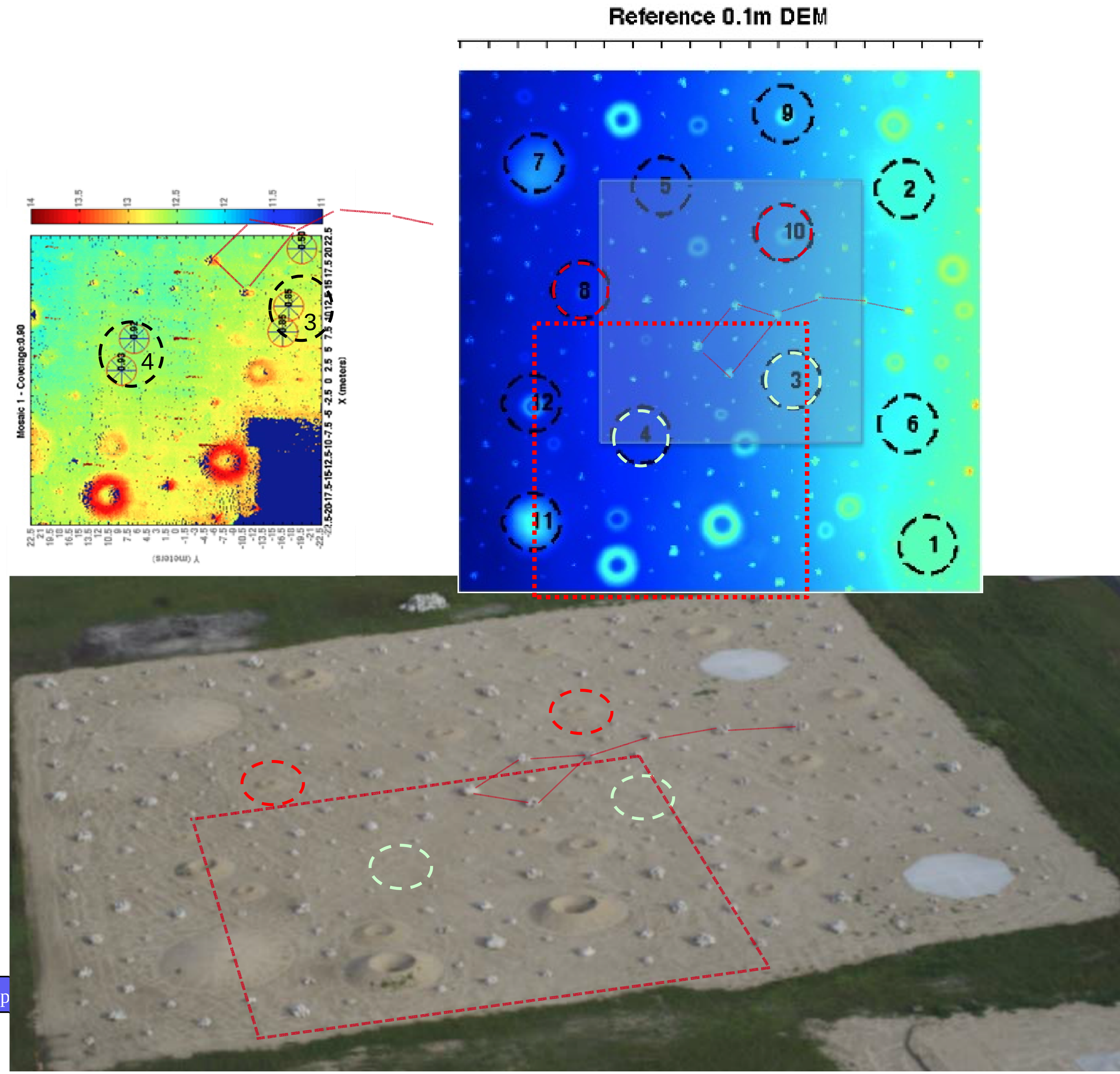
HAZARD DETECTION AND SAFE SITE SELECTION

Autonomous Landing Hazard Avoidance Technology (ALHAT)

*****All reported safe sites were actually safe*****



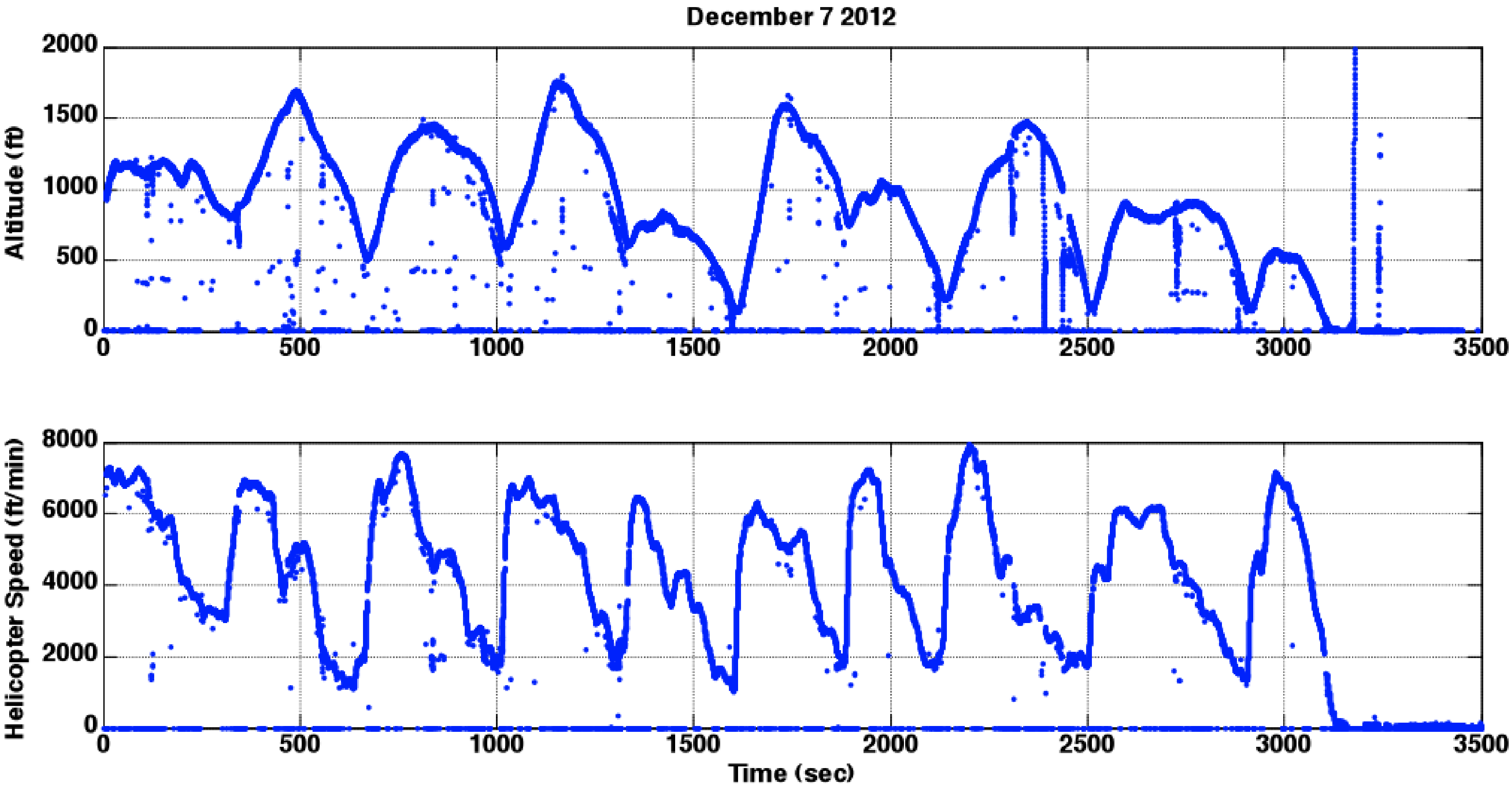




Reference 0.1m DEM
7
9
5
2
10
8
3
12
4
6
11
1
Mosaic 1 - Coverage:0.90
X (meters)
Y (meters)

DOPPLER LIDAR / LASER ALTIMETER DATA

Autonomous Landing Hazard Avoidance Technology (ALHAT)



Helicopter velocity and altitude during a series of flights towards the hazard field on 12/7/2012

OBSERVATIONS

- The test campaign was a test of opportunity and successfully fit into an extremely aggressive schedule
- Many unexpected issues were solved in real-time
- The campaign was very successful in providing critical performance data and identifying issues not possible with the fidelity of previous field testing
- All system modes were exercised with good results, providing confidence that the advertised capability can be demonstrated on Morpheus
- Needed updates and fixes are in work and on schedule to support Morpheus integration and flight testing