AUTONOMOUS PRECISION LANDING AND HAZARD AVOIDANCE TECHNOLOGY (ALHAT) PROJECT STATUS AS OF MAY 2010

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ABSTRACT

This paper includes the current status of NASA's Autonomous precision Landing and Hazard Avoidance Technology (ALHAT) Project. The ALHAT team has completed several flight tests and two major design analysis cycles. These tests and analyses examine terrain relative navigation sensors, hazard detection and avoidance sensors and algorithms, and hazard relative navigation algorithms, and the guidance and navigation system using these ALHAT functions. The next flight test is scheduled for July 2010. The paper contains results from completed flight tests and analysis cycles. ALHAT system status, upcoming tests and analyses is also addressed. The current ALHAT plans as of May 2010 are discussed. Application of the ALHAT system to landing on bodies other than the Moon is included.

1. INTRODUCTION

A spacecraft hurtles forward towards an extraterrestrial landing at a location analyzed using the best pre-flight pictures available. The lighting is patchy at best with shadows increasing across the surface as the vehicle descends. All is proceeding nominally: guidance is leading the lander towards the desired target, the navigation filter is adjusting state estimates using all available measurements, and the engine is following the desired thrust profile. As the landing system approaches within kilometers of the surface, sensors reach out to query the approaching terrain. Even though the initial landing point is barely visible, algorithms specifically designed to search for unexpected obstacles begin their evaluation tasks. A scattering of rocks near a shallow crater located within meters of the landing site grabs the attention of the onboard systems. While the crater was shallow enough that the spacecraft could have safely landed, it was the rocks, which were registering between one-half to three-quarters of a meter above the local surface, which could have resulted in a bad day. Now additional systems kick in. Some assess the sensed area for a new, safer target within the shrinking area the lander could reach with its remaining propellant. Others begin the process of identifying a feature that would be unique enough to recognize in future scans. Alternate landing aim points are identified and the best candidate is selected.

Events begin happening in rapid succession onboard the spacecraft. Divert commands are sent to the guidance algorithm identifying the new landing site. Sensors continue to provide surface information that the algorithms can compare with previous scans. Engines gimbal, control thrusters fire, and the spacecraft rotates to adjust the flight path to the new target. Some sensors are gimbaled to compensate for the changing spacecraft attitude as they continue to return data about the surface below. Data is passed to the navigation system so that state estimates can account for the spacecraft's motion relative to the surface. This flurry of activity continues until the spacecraft is only tens of meters above the surface. The vehicle must now make final preparations for landing. After deftly closing to just above the new, safe landing site, the spacecraft levels itself for the slow, vertical terminal approach. The lander touches down softly, and safely, within mere meters of its divert target and within tens of meters of the original landing target.

This scenario is precisely what the Autonomous precision Landing and Hazard Avoidance Technology (ALHAT) Project intends to make a reality. The ALHAT team of engineers from government, industry, and academia are striving to define a system capable of achieving the above scenario with today's systems, and to advance the technology necessary to improve the system for the next-generation robotic and human landers. That is, the team is working to make ALHAT functional today while driving the technology necessary to improve its capability in the near future.

2.0 BACKGROUND

The Autonomous precision Landing and Hazard Avoidance Technology (ALHAT) project was started in 2006 to address the technologies necessary to ensure safe, precise landings on future planetary and lunar missions. The overarching goal is to advance technology while developing a system of sensors and algorithms/software that provides the capability to safely land a small robotic or large human/cargo vehicle near a desired target regardless of lighting conditions, and with limited *a priori* knowledge of the terrain and surface features at or near the landing site. The technologies advanced by the ALHAT Project include sensor hardware and software, detection and avoidance algorithms, as well as integration with a closed-loop guidance and navigation system that utilizes this data to achieve a safe and precise landing.[1]

When ALHAT started, another industry-led effort funded by NASA was incorporated into the project. This inclusion led to the current team configuration. The ALHAT team is led out of NASA's Johnson Space Center by Chirold Epp. The current ALHAT team is composed of members from government, industry and universities: NASA JSC (areas of involvement include systems engineering, vehicle guidance and navigation, real-time simulation); NASA JPL (hazard detection and avoidance algorithms, flight tests); NASA Langley (sensor hardware and software, flight dynamics and engineering simulation); Charles Stark Draper Labs (vehicle autonomy, guidance, and navigation); and the University of Texas at Austin (navigation filter). Previous team members have included the John's Hopkins Applied Physics Lab and Utah State University. As of May 2010, ALHAT is funded through the Exploration Technology Development Program Office (NASA HQ entity at NASA Langley).

The ALHAT system has three main elements: Sensors; Terrain Sensing and Recognition (TSAR); and Autonomy, Guidance, and Navigation. Each of these areas are involved in the integrated ALHAT system. Each also has an element of advancing technology including: improved sensors to provide larger, more detailed surface data from higher altitudes; more accurate and computationally faster algorithms to evaluate the surface data; and robust algorithms for state estimation, as well as quickly defining safe landing alternative and then accurately guiding the lander to that location.

The current ALHAT sensor set includes a 3-D Flash LIDAR used to image the surface for hazard detection and avoidance (HDA) as well as hazard relative navigation (HRN). Navigation specific sensors include an inertial measurement unit (IMU), star tracker (ST), altimeter (ALT), and doppler velocimeter (VEL). The ALHAT system also includes algorithms for feature recognition in the 3-D Flash LIDAR generated surface image and algorithms that assess the image for hazards and safe landing areas. Integral to the ALHAT system is the AGN system that provides state estimates based on sensor measurements including HRN (navigation), guidance to the landing target, and the Autonomous Flight Manager to evaluate the flight systems capability to reach alternate, safe landing sites as well as manage certain sensor and system functions. Terrain relative navigation (TRN) is also included in the navigation filter, but a particular sensor for that function will be defined after future analyses.

2.1 ALHAT Project Requirements

ALHAT established several Level 0 requirements to direct the project. These requirements are listed in Table 1. These requirements are maintained in the Project Technical Requirements Specification document [2] and can be adjusted. In fact, the third requirement was recently updated to more directly address global and local landing precision. This requirement was split into the two requirements (shown in Table 1 as R0.003a and R0.003b) to clarify that the global precision requirement excludes the effect of a hazard avoidance maneuver, while the local precision is required to place the lander within 3 m of the hazard avoidance driven target. This modification helps clarify the metric by which hazard (or feature) relative navigation will be measured.

Table 1. ALHAT System Level 0 Requirements

R0.001 Landing Location
The ALHAT System shall enable landing of the vehicle at any surface location certified as feasible for landing.
R0.002 Lighting Condition
The ALHAT System shall enable landing of the vehicle in any lighting condition.
R0.003a Global Landing Precision
The ALHAT System shall enable landing of the vehicle at a landing target with a 3-sigma error of less than 90 meters in the absence of a hazard avoidance maneuver.
R0.003b Local Landing Precision
The ALHAT System shall enable landing of the vehicle at an intended landing point with a 3-sigma error of less than 3 meters.
R0.004 Hazard Detection
The ALHAT System shall detect hazards with an elevation change of 30 cm or larger and detect slopes of 5 deg and steeper, and provide landing point designation based on detected hazards.
R0.005 Vehicle Commonality
The ALHAT System shall enable landing of crewed, cargo, and robotic vehicles.
R0.006 Operate Autonomously
The ALHAT System shall have the capability to operate autonomously.
R0.007 Crew Supervisory Control
The ALHAT System shall accept supervisory control from the onboard crew.

While there is no particular location specified in these requirements, the ALHAT project has been using lunar missions as a reference for comparison and evaluation of the ALHAT systems. The ALHAT vision statement also reflects these driving requirements and this reference mission selection: "Develop and mature, to Technology Readiness Level 6, an autonomous lunar landing guidance, navigation, and sensing system for crewed, cargo, and robotic lunar descent vehicles. The System will be capable of identifying and avoiding surface hazards to enable a safe precision landing tow within tens of meters of certified and designated landing sites anywhere on the Moon under any lighting conditions."

2.2 ALHAT Development and Testing

The ALHAT project approach to technology development and testing brings several elements of NASA's current approach into one project. A mix of research, development, testing, and off-the-shelf purchasing is being used to evaluate current and advanced systems for safe, precise landing where limited *a priori* knowledge of the site exists. End-to-end trajectory and system simulations applying models of the ALHAT system in a simulated flight environment are used to investigate current and proposed elements' performance relative to the aforementioned requirements. Tests using actual system hardware and real-time algorithm computations in Earth-based flights over known terrain with predetermined surface objects and characteristics are also used to evaluate the ability of current and proposed advanced systems. Real-time simulation testing is also used to bridge the end-to-end simulation and field tests in evaluating these ALHAT systems, or emulators where required, in a controlled, simulated flight environment.

2.2.1 ALHAT Test and Verification Approach

A series of tests to evaluate the ALHAT system being researched using detailed simulations and field tests have been planned. ALHAT Design Analysis Cycles (or ALDACs) are used to investigate current and proposed systems in computer simulation. The initial ALDACs use an end-to-end engineering simulation using the Program to Optimize Simulated Trajectories II (POST2) in conjunction with ALHAT specific modules developed by the Sensor, TSAR, and Autonomy, Guidance, Navigation and Control (AGNC) groups. [3,4] Future ALDACs will use the Hardware-in-the-loop ALHAT System Testbed (HAST) which evaluates real-time operation of algorithms and sensor emulators on potential flight computer hardware in a simulated flight environment. Field tests evaluate real-time operation of ALHAT system in Earth-based flights. The initial flights used helicopters to fly approach trajectories to evaluate sensor hardware over known terrain. Future flights will include closed-loop, real-time algorithm computations using the sensor hardware generated datasets during the flight.

The ALHAT Project is investigating the Guidance, Navigation, and Control algorithms, Terrain Sensing and Recognition algorithms, sensors, and Avionics to enhance safe and precise lunar landings in a series of ALHAT Design Analysis Cycles (ALDACs). The ALDAC plan calls for incrementally evaluating different aspects of the ALHAT system. ALDAC-1 focused on evaluating the hazard detection and avoidance aspect. This first ALDAC was also used to ensure that the ALHAT POST2 simulation properly included all of the ALHAT specific models and operated as anticipated for the de-orbit to touchdown lunar trajectory. ALDAC-2 and ALDAC-3 are for assessing the hazard relative navigation functionality of the system, while also ensuring that the HDA performance was not degraded. Currently ALDAC-4 will be used to analyze the terrain relative navigation of the ALHAT system, while keeping track of the impact (if any) on HDA or HRN performance. ALDAC-5 and beyond would be focused on all aspects of the ALHAT system performance in the HAST real-time simulation testbed. Certain aspects of previous ALDAC assessments would be included in these HAST-focused ALDACs. These analyses will be driving towards the ultimate validation of the ALHAT system to a TRL 6 level in HAST.

Similarly, the field tests incrementally increase the ALHAT system functionality being tested. The first field tests were mainly to characterize the sensor performance and generate data to be used post-flight for algorithm assessment and development. The current field test (FT4) will not only test new sensor systems developed as part of the research aspect of this project, but also begin to fold in real-time algorithm computations, specifically the navigation filter processing measurements during the flight. Future field tests will bring in more aspects of real-time algorithm computation using ALHAT sensor generated data, culminating in a closed-loop sensor, TSAR, and AGNC using ALHAT software and hardware. This closed-loop flight would potentially be on a free-flying testbed based on Lunar Lander X-prize Challenge flight systems. Additional details for the ALDACs and Field Tests are given in Sections 3 and 4.

2.2.2 ALHAT Technology Development

Advancing the state-of-the-art for ALHAT systems involves development from within the team as well as utilizing the best research being performed in industry and academia. Elements from outside the team are brought in through NASA Research Announcements (NRAs), direct contracts and purchases. For example, Flash Light Detection and Ranging (LIDAR) technology advancement toward TRL 6 includes component technology development through NRA contracts, within-NASA development of calibration and image processing software and hardware, as well as characterization of LIDAR components and software individually and in concert as an integrated system. The developed Flash LIDAR system is then field tested with other ALHAT systems.

A sensor-related NRA was released in 2007 to solicit technology applicable to 3-D imaging LIDAR focused on five specific areas: detector focal plane arrays, Read Out Integrated Circuits (ROIC), 3-D image pre-processing and enhancement, variable focal length optics, and improved laser performance for Flash LIDAR applications. After detailed peer-review by a multidisciplinary evaluation panel of technical experts from within the ALHAT team and NASA Langley Research Center, eight proposals were selected for award. Several of these tasks are complete and have resulted in advancing technology in areas of variable focal length optics, 3-D image pre-processing and enhancement, ROIC, and improved laser performance. These improvements are incorporated into the Flash LIDAR sensor to be tested in FT4 this summer.

Upgrades and improvements to various algorithms developed by the ALHAT team follow analyses of ALDAC and Field Test results. Reductions in the false positive hazard identification (where the algorithm indicates a hazard exists when one actually does not), incorporation of HRN measurements into an inertial navigation filter, improved feature recognition algorithms, and guidance algorithm adjustments are several of the improvements made. This advancement of the state-of-the-art for these algorithms is as important as the improved hardware noted above.

3. ALHAT COMPLETED STUDIES AND TESTS

As of May 2010, two design analysis cycles and three field tests have been completed. Each of these have resulted in reports that were completed by the ALHAT team. A summary of the objectives and results from each completed ALDAC and field test is given in sections 3.1 and 3.2.

3.1 ALHAT Design Analysis Cycles

Preliminary ALHAT studies concluded that hazard detection and avoidance, terrain relative navigation, hazard relative navigation, altimetry, and velocimetry functions are critical to meeting safety and precision goals for future lunar landings. As mentioned previously, the ALDACs completed to date examined certain aspects of the ALHAT system in the ALHAT POST2 integrated, end-to-end, engineering simulation. A mission to the south polar region of the Moon was used for these analyses. A representative Lunar landing vehicle based on Altair-type Landers was defined and used. Models were developed and validated for the sensors, AGNC, and TSAR by various elements of the ALHAT team, then passed to POST2 for integration with vehicle and environment models. An illustration of the lunar landing trajectory with a representative sensor operations concept is shown in Fig. 1.

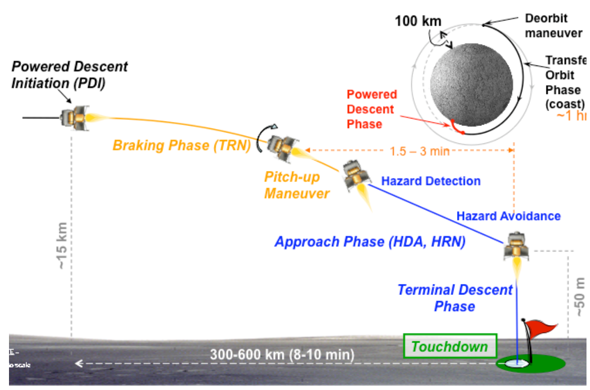


Fig. 1 ALHAT Lander Trajectory Illustration

3.1.1 ALDAC-1

ALHAT Design Analysis Cycle 1 (ALDAC-1) was focused on the HDA function of the ALHAT System.]5[This functionality occurs during the Approach phase of the trajectory once the vehicle has pitched up, the landing site comes into view, and prior to the initiation of Terminal Descent. All of the analyses in ALDAC1 are focused on the performance parameters relevant to the Approach phase GNC and HDA sensor trade space. The GNC goals of ALDAC-1 were to understand the controllability, precision, delta-V, vehicle dispersions, hazard avoidance, and timing of the system using a representative Altair-like Lunar lander vehicle, while varying the slant range, trajectory path angle, and acceleration profile of the Approach trajectory. The TSAR goals of ALDAC-1 were to understand the capabilities of LIDAR systems to perform hazard detection as a function of the sensor specifications and trajectory parameters. The end goal of ALDAC-1 was to understand the tradeoffs between vehicle, GNC, and sensor performance for HDA and narrow the trade space of options for trajectories and sensor technologies going into future ALDACs.

The 252 trajectory tradespace considered in initial analyses was a combination of 6 initial slant ranges (SR) at HDA start (500, 667, 800, 1000, 1500, and 2000 m), 6 initial trajectory path angles (PA) relative to the landing target at HDA start (15, 30, 45, 60, 75, and 90 deg), and 7 constant acceleration profiles (ACC) used for guidance design (1.05, 1.1, 1.2, 1.3, 1.4, 1.5, 2.0 lunar g's). This trajectory space was further narrowed based on early results for most of ALDAC-1 to focus on the following eight trajectories (given in sets of SR, PA, ACC): (500,45,1.05); (2000,15,1.1); (2000,45,1.2); (1000,45,1.2); (1000,60,1.2); (500,30,1.2); (1000,90,1.3) and (800,45,1.5). The nominal trajectory profile used was the 1000m SR, 45 deg PA, and 1.2 lunar g ACC.

ALDAC-1 includes Monte Carlo trajectory analyses that focus on the ALHAT GNC and TSAR systems. The set of Monte Carlos analyzed in ALDAC-1 were performed with navigation active, sending guidance and the controller the navigated (estimated) state, while perturbing not only vehicle properties such as engine thrust, specific impulse and mass properties, but sensor errors and the navigated initial state. For the GNC assessments, preliminary touchdown requirements were used to assess the integrated system performance consisting of a 99-percentile vertical velocity less than 2 m/s, 99-percentile horizontal velocity less than 1 m/s and 99-percentile attitude rate (RSS of pitch and yaw rate) less than 2 deg/s, and the vehicle must be close to vertical (99% within 6 deg). Additional Monte Carlo cases were run to assess the effect of a range of trajectories on HDA performance. These Monte Carlos considered landings on smooth Mare terrains only (that decision dictates the distribution of craters and surface slopes) while parametrically varying rock abundances and lander hazard tolerances.

The ALDAC-1 analysis showed that the ALHAT GNC algorithms provide the desired trajectory profiles and vehicle state control within the required landing precision. The general trend, all other things being equal, is that Approach phase deltaV requirements increase and the time available from the end of pitch-up to the beginning of the terminal descent phase increase as slant range increases, path angle increases, and/or the acceleration profile decreases. Hazard detection performance improves as the path angle increases, providing more of a "top-down" view of the landing site. Area beam (flash) LIDAR technology scans the landing site quicker than other technologies and is, therefore, less sensitive to navigation errors and timing constraints.

Based on ALDAC-1 results, the HDA performance trends relative to vehicle tolerance and rock abundance are as expected; hazard detection rates do not depend on rock abundance, and increase with increased lander mechanical tolerance. As rock abundance increases, safe landing probability decreases as there are fewer places to land. Increased rock abundance however can be mitigated with a corresponding increase in vehicle tolerance. Slant range, path angle and deceleration all influence actual safe landing probability; the probability of safe landing decreases for longer ranges and shallower path angles, while it increases with increased deceleration. There is clear indication that slant range and deceleration have no influence on DEM accuracy or hazard detection metrics. Path angle variation however does have an impact on hazard detection and false alarm rates. This result is due to two effects. First, a decrease in elevation precision as path angle decreases, caused by LIDAR induced noise shifting from vertical to horizontal, results in less detections and less false positives. Second, as path angle decreases, the LIDAR samples are stretched down track, which results in fewer pixels on the top of each hazard. This pixel reduction makes it difficult to detect small hazards.

Fig. 2 shows the safe site identifications for each case in a set of Monte Carlo runs that used the same truth surface map; that is, the same surface features (craters, rocks, slopes) were on the map used by every trial of these Monte Carlo cases. This particular digital elevation map (DEM) was challenging as less than 20% of the potential landing area was safe. This gray-scale contour map shows the areas deemed safe by a detailed, pixel-by-pixel assessment of the truth DEM (completed independently of the simulation runs) as patches of green (dark gray regions when shown as gray scale image). The small darker (red) circles mainly within the larger patches are the sites selected by the onboard algorithm based on the flash lidar data returned during each of the Monte Carlo trajectory runs. Nearly all of the cases identified safe landing sites in actual safe locations. Also, each of these redesignated targets are within 90 m of the original target (the origin in this figure) which indicates that the GNC system was also functioning within desired parameters. Further information on some of ALDAC-1 is in [3] and [6].

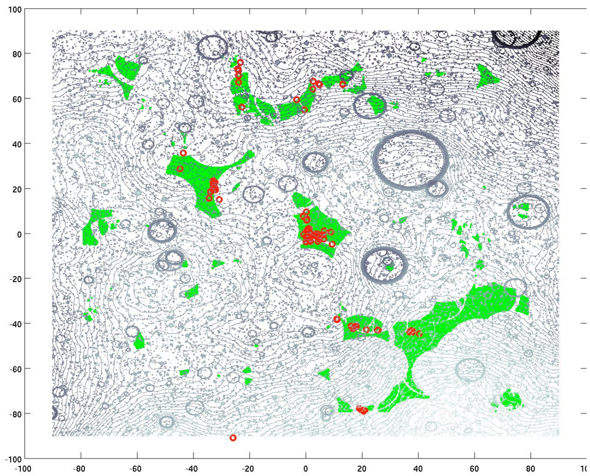


Fig. 2 Monte Carlo results: safe site comparison

In a general overall assessment of ALDAC-1 results, HDA performs very well in terms of the final goal. The probability of finding and selecting a safe site, if one exists, is above 97% for the cases analyzed in detail. At the time of ALDAC-1, a conclusion to guarantee a higher probability required that the false alarm rates be addressed by means of reasonably straightforward refinements in the HDA algorithm.

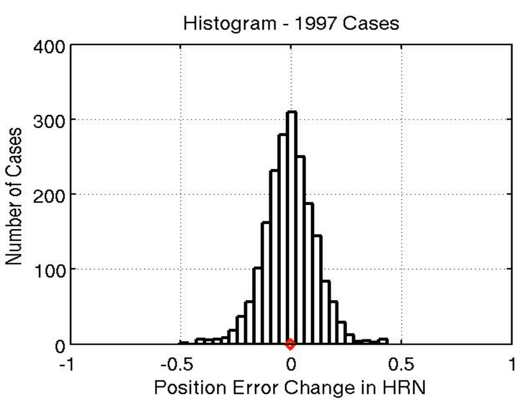
3.1.2 ALDAC-2

The recently completed ALHAT Design Analysis Cycle 2 (ALDAC-2) System improved upon the Hazard Detection and Avoidance (HDA) and Guidance, Navigation and Control technologies developed for ALDAC-1 and extended this core functionality to include Hazard Relative Navigation.[7] HRN is an ALHAT function that updates local, relative position estimates by tracking sensed terrain features (such as rocks and craters) on the lunar surface. HRN is intended to improve local precision relative to a target landing site that is chosen using a flash LIDAR sensor and onboard hazard detection algorithms to identify safe areas. The HRN function for ALDAC-2 is designed to maintain a constant position knowledge error (truth minus estimated position) for the duration of HRN. ALDAC-2 is focused on determining the effectiveness of HRN as well as tracking the progress of the ALHAT System technology development.

While ALDAC-2 had several similarities with reference Lunar landing mission used for ALDAC-1, there were some notable differences. A new approach trajectory subset was used for the ALDAC-2 analyses. Using the same notation as above (SR, PA, ACC) the "Magic 7" for ALDAC-2 analyses were: (1000,30,1.05); (1500,30,1.1); (1000,15,1.1); (1000,30,1.1); (1000,45,1.1); (500,30,1.1); and (1000,30,1.2). These trajectory choices reflected the propensity to test the newly developed systems for HDA starting at 1000m slant range and the expectation that near-term lunar landing missions would tend towards a 30 deg path angle approach. The nominal reference trajectory for this Magic 7 set was the 1000m slant range, 30 deg path angle, and 1.1 lunar-g constant acceleration profile for guidance design. Another difference from the previous design cycle was an updated version of the lander system to more closely reflect the Altair vehicle configuration current at the time of ALDAC-2. Other major elements of the reference mission (e.g., landing location, initial lunar orbit) stayed the same.

ALDAC-2 had elements of integration and testing of the sensor, AGNC, and TSAR models. Also part of this effort was a trade space reduction for subsequent analyses, that included down-selection, tuning and continued refinement of the parameters and algorithms for all three ALHAT elements. Several studies evaluated HRN and HDA performance with respect to terrain type, HRN and HDA performance with respect to sensor type, HRN performance with respect to different correlation patch sizes used in HRN, select sensor performance for all of the "Magic 7" trajectories, and comparative performance of a select set of sensors. Some of these analyses were performed by each ALHAT element independently in "sandbox" simulations while others investigations used the integrated ALHAT and lander system in the POST2 simulation. All of the assessments used the system performance objectives as defined in the ALHAT Project Technical Requirements Specification document (which contains the Level 0 requirements listed in Table 1 above). Furthermore, off-nominal conditions such as randomly varied sensor measurements, vehicle characteristics, and surface terrain are included in Monte Carlo analyses to provide a measure of overall system performance and robustness. The ALHAT objectives for evaluating HRN during ALDAC-2 are: (1) understand the degree to which the HRN functionality improves the integrated system performance; (2) understand the impact of sensor selection on the performance of HRN over a variety of terrains and understand the impact of the HRN functionality on the integrated system performance as a function of sensor selection, terrain, navigation errors, and trajectory variance; and (3) collect HRN performance statistics for a reduced set of trajectories as well as for two HRN sensors in order to measure the progress of the ALHAT System technology development.

Several major results and conclusions were determined in ALDAC-2. For a Flash LIDAR configured for 1000m, not only should the initial path angle be greater than 15 deg to ensure acceptable HRN performance, but also the 1500 m initial slant range (and higher) should not be used for further assessments due to poor HDA performance. From the sensor assessment, Flash LIDAR range precision of 4 cm provided excellent performance while 8 and 12 cm values performed poorly for both HDA and HRN. For the ALDAC-2 configuration, a rule of thumb for HDA is that a hazard height must be 6 times the range precision in order to be detectable and differentiable from false positives. Two Flash LIDAR sensor models (both with 256x256 pixel detector arrays and 4 cm range precisions) having 20 Hz and 5 Hz frame update rates were downselected for ALDAC-2 analyses remaining to be done at that time. Subsequent, integrated ALDAC-2 analyses indicated that the lower frame rate sensor is more sensitive to navigation errors during DEM generation leading to degraded HDA and HRN performance and led to the suggestion that only the higher frame rate sensor be used unless the algorithms can be improved to negate this effect. For HRN specifically, the current ALDAC-2 configuration performance is: (1) generally insensitive to flash LIDAR array size (128x128 pixels versus 256x256 pixels) and frame rate (5 Hz, 10 Hz, 20 Hz); (2) strongly correlated with rock abundance (for all terrain types) and degrades quickly for rock abundances below 2%; (3) weakly correlated with terrain type (i.e., smooth mare, rough mare, hummocky upland, rough uplands); and (4) improved as path angle increases and rock abundance increases.

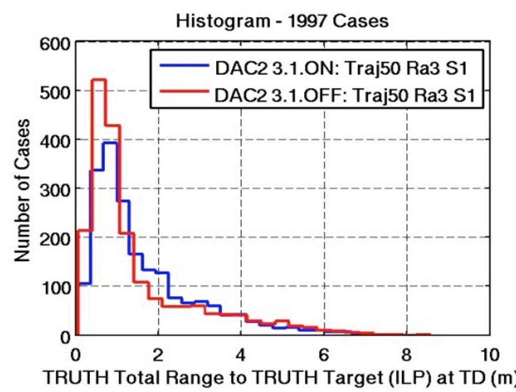


Statistics for
Position Error Change in HRN:

Mean = -0.0047163
1-Sigma = 0.11363
3-Sigma = 0.3409
Minimum = -0.50502
00.13 %-tile = -0.42398
50.00 %-tile = -0.0060838
99.87 %-tile = 0.42849
Maximum = 0.43661
Min. Case = 1258
Max. Case = 680

Fig. 3 Change in Knowledge Position Error between HRN Start & Finish

Some additional observations from the ALDAC-2 analyses provide some positive conclusions, while others leave questions remaining. When HRN provides valid measurements, these measurements meet the ALHAT relative navigation accuracy requirement. This result is shown in Fig. 3 for an integrated system Monte Carlo run using the nominal reference trajectory (1000m SR, 30 deg PA, 1.1 lunar-g ACC). In this figure, the change in position knowledge error (i.e., the change in the value of truth minus estimated position) is well below the required 1 m during HRN. Another observation is that the ALHAT System in ALDAC-2 meets the system-level and AGNC subsystem requirements specified in the PTRS, with the *exception of the local safe site precision*. The change in navigation error following the end of HRN appears to be the largest contributing factor to the local safe site precision. This point is illustrated by comparing Fig. 4 showing the final touchdown range is outside the required 3-sigma, 3 m value. Although the exceedance is small, it is unexpected based on the system performance during HRN (less than 0.5 m 3-sigma) shown in Fig. 3. For ALDAC-2, recall that the knowledge position error was desired to remain constant and this requirement was met by prohibiting



Statistics for
TRUTH Total Range to TRUTH Target (ILP) at TD (m)
DAC2 3.1.ON: Traj50 Ra3 S1:

Mean = 1.625
1-Sigma = 1.28
3-Sigma = 3.84
Minimum = 0.048621
00.13 %-tile = 0.092992
50.00 %-tile = 1.1891
99.87 %-tile = 6.8771
Maximum = 7.9064

Fig. 4 Final Touchdown Range to ILP

any other measurements (altimeter or velocimeter) during HRN. Any residual lateral velocity knowledge error would result in the lander drifting during the terminal, constant vertical velocity phase, thus adversely impacting the local landing precision. A modified approach to HRN has been proposed which allows for changing knowledge position error (and thus permitting other measurements during HRN) but using HRN to aid in estimating onboard the amount of that knowledge error so elements dependent on the estimated state (e.g., sensor pointing, landing targets) can be adjusted. Additionally for the ALDAC-2 configuration, integrated Monte Carlo analyses showed that if the vehicle arrives at the start of HRN with a low navigation knowledge error, the position error will naturally tend to stay low. This unexpected result coupled with the planned HRN adjustments lead to the conclusion that no definitive statements can be made about the effectiveness of the current implementation of HRN. Further analyses are planned after algorithms and software adjustments based on the revised HRN approach are completed.

3.2 Field Tests

The Field Tests provide an evaluation of the ALHAT hardware as it is operated in a relevant test environment for application to landing systems. Field tests begin with manually operated sensors and progress to more automated, real-time, closed-loop sensor and algorithm operation. Field testing has been done with flights on helicopters to date, however consideration is being given to flying test articles on free-flying robotic flight vehicles at Earth.

3.2.1 Field Test 1

The ALHAT Project Field Test 1 (FT1) was conducted in April 2008.[8] This test flew a Flash LIDAR on a helicopter over a variety of natural and man-made targets. The purpose of the test was to assess the performance of Flash LIDAR technology and algorithms for Hazard Detection and Avoidance (HDA) and Hazard Relative Navigation (HRN) in an environment that was relevant to lunar landing, with a secondary objective of verifying the concept of the APLNav TRN methodology. The primary environmental variables investigated were ranges and angles relative to the target and hazard feature size. From a development point of view the FT1 objectives were to: (1) Test a Flash LIDAR in a relevant environment and use this information to guide the development of the ALHAT Flash LIDAR sensor; (2) Test HDA and HRN algorithms using data collected with a real sensor in a relevant environment and use this information to improve algorithms; (3) Collect data for validation of the Flash LIDAR sensor model used in the POST2 Monte Carlo simulation; (4) Identify areas to increase the fidelity of the sensor model; (5) Advance sensor and algorithm TRL; and (6) Assess passive optical sensors TRN algorithm.

To obtain a variety of slant ranges and path angles as well as descents toward the target a helicopter was used as the test platform. Fig. 5 shows and example test flight path over Dryden. An inertially stabilized gimbal

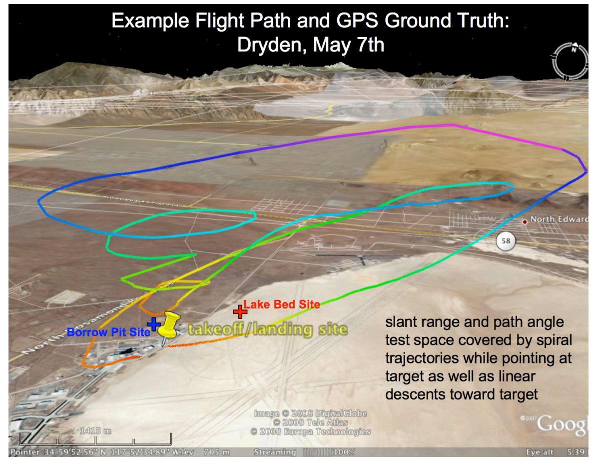


Fig. 5 Example FT1 Flight Profile

was mounted to the front of the helicopter. The gimbal contained the Flash LIDAR, two Inertial Measurement Units (IMU), an orientation sensor, two digital cameras and an analog camera. A Global Positioning System (GPS) antenna was attached on the fixed structure above the gimbal. To verify the concept of APLNav TRN, visible cameras were mounted to the helicopter to capture images of terrain as the helicopter flew to, from, and around the HDA target areas. The visible camera images, along with IMU and GPS data, were collated and used as input to the APLNav algorithm for post-processing.

The testing was conducted at two locations: Dryden and Death Valley. One site on a lakebed at Dryden was very flat and was composed of 11 hazards grouped close to each other. There were hemispheres of various sizes and reflectivity as well a large and small box. The lakebed site was designed for LIDAR characterization. The Dryden site in the Borrow Pit had numerous hazards made out of 1x1x1m boxes, fields of hemispheres following a 5% and 10% rock abundance and two 3m wide craters. The Borrow Pit site was designed for assessing hazard detection and safe landing probability. The final site was at Mars Hill in Death Valley National Park. Mars Hill has numerous rock fields of varying rock abundance as well as steep and shallow slopes. The purpose of the Mars Hill site was to obtain LIDAR data from natural as opposed to man-made hazards as well as slope hazard detection.

The analysis first assessed the Flash LIDAR in terms of its sensitivity (pixel trigger fraction) and range measurement precision as a function of path angle and slant range. The results showed that the LIDAR has a range precision (random noise) of 0.20m one sigma. The LIDAR has a maximum range between 400m for nadir viewing and 250m for oblique viewing (15˚ from horizontal). The tested sensor was a commercial unit that was not developed for the landing application. After FT1, ALHAT planned to build a Flash LIDAR that will have significantly more range (1000m) and significantly lower range measurement noise (0.05m, one sigma).

Hazard detection was then assessed by processing 450 images though the hazard detection algorithm. The results showed that the LIDAR and algorithm can detect 90cm high hazards while keeping the probability of a false hazard detection less than 20% per a 380 m^2 vehicle footprint dispersion ellipse (VFDE). The hazard detection results were also compared to results obtained from simulated Flash LIDAR imagery. The real and simulated results were well correlated when the Flash LIDAR is in its nominal operational regime. This correlation validated the implementation of the ALHAT Flash LIDAR simulator used in a high fidelity Monte Carlo simulation in POST2 for ALDAC1. This field test analysis when combined with the validated comprehensive coverage of the HDA tests space in ALDAC1 advanced the HDA algorithm from TRL4 to TRL5.

The critical algorithmic components of the HRN algorithm were also tested using consecutive Flash LIDAR images. After processing more than 2000 image pairs, the results showed that the HRN algorithm provided motion estimates with an accuracy of 0.38m (97% circular error probability) while being able to reject most incorrect estimates using internal algorithm checks. Processing of a significant set of real data when combined with a recent stand alone simulation of the HRN algorithm with lunar terrain have advance the TRL of the HRN algorithm from TRL3 to TRL4.

FT1 was successful in meeting the APLNav TRN objectives of the testing as well. In all cases the APLNav process was able to render imagery from the DEM and SRM that was realistic enough to generate useful correlations with captured imagery and to produce accurate position reference data which could be used for TRN. FT1 brought out the importance of obtaining position and attitude information in conjunction with, and synchronized to, the camera images so that all of the images have the potential to be used for APLNav TRN processing and eventually for navigation of a descent vehicle. More information on FT 1 is in [8[and [9].

3.2.2 Field Test 2

For ALHAT FT2, a breadboard navigation Doppler LIDAR was installed aboard a helicopter and tested over the California desert.[10] The LIDAR instrument is a fiber-based Doppler laser radar developed at NASA Langley Research Center capable of providing precision velocity and range measurements. FT2 had a total of six flights: four flights over a flat, dry lake bed; and two over rough, hilly terrain. The helicopter was flown over varying desert terrain at different altitudes. In these flight tests, the performance of the LIDAR instrument in measuring the helicopter ground velocity and altitude was demonstrated. Field-testing operations were based out of Dryden Flight Research Center. Instrumentation for the LIDAR sensor within the gimbal include an Inertial Measurement Unit (IMU), two visible cameras collecting image data, GPS position instrumentation, and one observation video camera. The data collected during FT2 proved to be valuable in demonstrating the capabilities of the Doppler LIDAR, and also served as a tool to test and develop signal processing and analysis algorithms. Analysis of the data showed velocity measurements in excellent agreement with the high accuracy GPS derived velocities. Ground relative altitude and attitude measurements were also demonstrated. The successful flight test of this Doppler LIDAR established it at a TRL of 4.

3.3.3 Field Test 3

The ALHAT Project Field Test 3 (FT3) was conducted in June and July 2009.[11] This test flew a flash LIDAR, a laser altimeter, and six cameras on a fixed wing airplane over a variety of natural lunar-like terrains. The purpose of the test was to assess the performance of sensors and algorithms for Terrain Relative Navigation in a Moon-like environment. The primary environmental variables investigated were terrain type, altitude, and illumination conditions. The test objectives were to perform TRN testing of Flash LIDAR, passive optical sensors, altimeter, and associated algorithms on a dynamic, Moon-like terrain environment to improve the design and development of the ALHAT system for the TRN sensor phase. Eight data collection flights were flown. For most flights, the plane flew horizontally at 60 m/s. The flights were conducted at 2, 4, and 8 km altitudes over two test sites: Death Valley and Nevada Test Site. A variety of terrain was imaged including mountains, hills, washes, dry lakebeds, and craters. The Nevada Site in particular was selected because it has a large crater field on a flat terrain, analogous to the lunar mare. Each flight had between one and two hours of valid data.

LIDAR data from all flights was processed, but only four out of the eight flights produced acceptable TRN results. The most likely reason for the poor TRN performance in the other flights was errors in the ground truth trajectory and not a deficiency in the LIDAR data, the LIDAR TRN algorithm, or the reference maps. Further analysis will look into cleaning up the trajectory data so that more flights can be used.

The TRN approach used in FT3, based on correlation of LIDAR data and elevation map, meets the objective of 90 m landing precision under any lighting conditions. TRN works well for both flash LIDAR and laser altimeter data. In both cases, TRN estimates have errors typically less than 50 m. Most incorrect estimates are eliminated using confidence metrics based on terrain relief. Instrument misalignments are the main causes of large global errors. Disregarding those, 99% of the TRN estimates passed on to the navigation filter are accurate. Nevertheless, TRN performance degrades with larger map resolutions.

Studies were also conducted to assess the sensitivity of the LIDAR TRN algorithm to various parameters. It was determined that 450 m contours resulted in the greatest number of correct measurements while still keeping incorrect measurements at a minimum. It was found that about 25 m peak-to-valley terrain relief over 100m of a contour is required to have confidence in the TRN measurement. The LIDAR TRN algorithm showed the expected sensitivity to map resolution where coarse maps lead to coarser position estimates. Finally, the algorithm was shown to be very insensitive to position uncertainty; a 1600 m position uncertainty had little effect on the confidence, accuracy, or number of matches.

The processing of FT3 data clearly shows that the LIDAR TRN algorithm will achieve the 90 m ALHAT landing accuracy requirement. The algorithm was tested over a wide range of altitudes and terrains and worked well as long as there was at least 25 m of terrain relief in the contour. These results, when combined with sandbox analysis of TRN performance, advance the TRL of the LIDAR TRN algorithm from TRL3 to TRL4. More information on FT3 is in [11] and [12].

4. PLANNED ALHAT TESTS AND STUDIES

4.1 ALDACs

Although not yet completely defined, future ALDACs are planned that will focus analyses on TRN, Autonomy, Real-time system execution, and address remaining questions about HRN. Long term ALHAT plans are to include more real-time, hardware-in-the-loop functionality in the ALDACs by including HAST analyses. Thus, as the field tests begin testing more of the integrated ALHAT functions, the HAST simulator will be including the same (or very nearly the same) components in the simulated analyses. POST2 will continue to be used as it can maintain the computationally intensive physics-based models for some of the ALHAT sensor systems that aren't readily adaptable to the real-time execution.

For ALDAC-3, current plans are to finish the assessment of HRN. Also, ALDAC-3 will include more autonomy. The Autonomous Flight Manager will begin to control more commanding of the ALHAT sensor and overall system executive control. Some of the ALHAT software will be migrating to real-time operation and these versions will also be included starting with ALDAC-3. Detailed planning for ALDAC-3 is just beginning, so exact details of the tests and analyses to be done are not yet established.

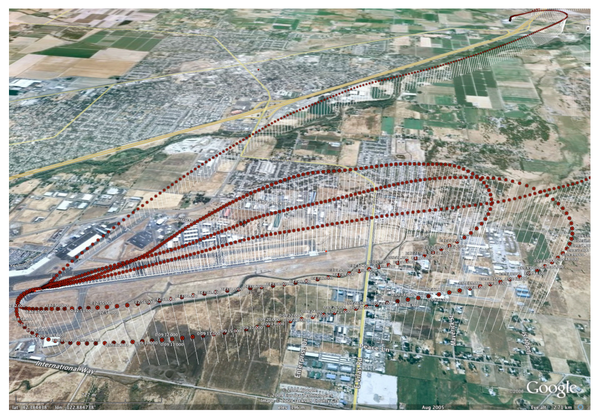


Fig. 6. Helicopter Verification Flights at ALHAT Approach Trajectory Path Angles

4.2 Field Tests

The next field test (FT4) is coming later this summer. FT4 has four primary objectives. First one is to demonstrate the application of an integrated, real-time GN&C system (derived from a lunar lander implementation) for Earth-based flight testing over a range of vehicle approach conditions consistent with the ALHAT simulation studies to date. Fig. 6 shows three approach runs used by the pilots to evaluate their ability to match the desired ALHAT trajectory characteristics. These approaches are 15, 30, and 45 deg path angle cases. Next objective is to demonstrate precision pointing of the gimbaled flash lidar using real-time GN&C data (position, attitude, etc.) in combination with the gimbal manager and mapper components of the Terrain Sensing and Recognition (TSAR) software. Next objective is to characterize the performance of second generation ALHAT sensors –

Flash LIDAR, Doppler LIDAR, and laser altimeter – along with accessories such as Flash LIDAR zoom optics. The last objective is to demonstrate the ability to utilize the recorded ALHAT sensor data to generate a 3-D terrain map and perform the hazard detection, landing aim point selection, and local relative navigation functions to support an autonomous safe precision landing.

The FT4 instrument suite will include four distinct subsystems: two Flash LIDARs, a 3-emitter Doppler velocimeter, and a laser altimeter. The instrumentation will be housed in an external pod attached to the bottom of the helicopter. Unlike past field tests, the only necessary operator will be in the helicopter cabin and will be shielded from the lasers. The Flash LIDARs are two distinct, independent subsystems that will mount on either side of the system gimbal. They will be operated on separate test flights but remain on the gimbal at all times. The two subsystems will use the same support electronics package by simply switching out cables. The LIDARs will be mounted to separate aluminum instrument plates, which will be used in the laboratory and in flight. The design is such that alignment of the optical components will not be disturbed while installing and removing from the gimbal. A different, rack mount chiller will be used to cool both plates simultaneously by a series tubing system running within the two plates beneath the lasers.

The demonstrated system is to be re-used and enhanced for subsequent field tests, FT5 and FT6, with the eventual goal being to raise the Technology Readiness Level of the entire ALHAT system to TRL 6. Post-test, data from the Flash LIDAR sensors will be evaluated using the HDA and HRN algorithms. In addition to the above objectives, the scope of FT4 also includes application of as much prior field test technology and experience as possible. Examples of hardware include instrumentation, data collection hardware, and ground support equipment to enable rapid analysis of data in the field. Expertise and lessons learned from FT1 through FT3 are also to be applied.

Additional flight tests are only in the planning stages at this point. The ALHAT Project has been given increased funding and scope over the next three years with the mandate to perform a closed loop, terrestrial ALHAT field test on a Vertical Testbed (VTB) with real-time hazard detection, safe landing aim point selection, and precision landing performed autonomously by the onboard system. This will solidly demonstrate the ALHAT System to a TRL of 6. ALHAT anticipates at least four VTB field test campaigns in the time period of FY11 through FY13. Each field test campaign will involve multiple VTB flights over several days. Current ALHAT thinking with regards to flight tests and VTBs is as follows.

The first VTB field test campaign, designated FT5, is targeted for mid-FY11 assuming the availability of a suitable VTB platform. The VTB will carry a reduced set of sensors and the flights will be focused on the verification of VTB operational reliability, closed loop GN&C functionality, control authority and stability, and performance (payload, altitude, vertical and lateral velocity limits, and flight time). The VTB must demonstrate the capability to adequately simulate the last one or two kilometers of a lunar approach and landing trajectory.

The second VTB field test campaign, designated FT6, is targeted for late FY11 to early FY12, depending on the successful completion of FT5. The major step from FT5 to FT6 is the integration of the ALHAT Hazard Detection System (HDS) on the VTB along with a Doppler LIDAR sensor and laser altimeter. The HDS will drive the Flash LIDAR gimbal using navigation data supplied by the VTB GN&C system, and will perform real-time, onboard HDA and HRN processing. The data from the HDS, laser altimeter, and Doppler LIDAR will be recorded for post-processing. But the ALHAT System will operate open loop during FT6 rather than updating the VTB landing target or navigation state.

The third VTB field test campaign, designated FT7, Is targeted for mid- to late 2012. The major step from FT6 to FT7 is the closure of the GN&C loop with the VTB to achieve a fully autonomous lander capable of accurately navigating towards a pre-defined surface target, rapidly mapping the simulated lunar terrain at high resolution, identifying landing hazards, selecting and diverting to a safe landing aim point, and performing a precise and controlled touchdown at the selected location. The FT7 campaign is intended to demonstrate the ALHAT objectives for hazard detection, safe landing site identification, and precision landing to a maturity of TRL 6.

The fourth VTB field test campaign, FT8, will stress the capabilities of the ALHAT System demonstrated during FT7 to establish its robustness in a dynamic environment. The FT8 campaign in FY13 will incorporate more hazardous simulated lunar terrain and vary key operational parameters to establish the operational limitations of the ALHAT System. FT8 will also provide opportunities to evaluate alternative approaches for key ALHAT functions as well as options for tailoring the ALHAT System for near-term Flagship Missions.

Obviously these plans are subject to change due to any number of factors. Without adequate out-year funding levels, this plan is unattainable. Likewise if any technology show stoppers occur in either the ALHAT technology or the ALHAT integration with a VTB, then these plans will change. Field test plans will continue to include the potential for additional helicopter tests to augment or replace VTB tests.

5. POTENTIAL ALHAT USAGE

Although the lunar mission has been used to date by the ALHAT Project to evaluate its systems, there is nothing inherent to the ALHAT system that would forego application to another destination, such as Mars, an asteroid, or another moon. In fact, ALHAT has received several inquiries about applying the technology and system being developed on various proposed missions. While technology development remains a key aspect of the ALHAT Project, providing a system to ensure safe landing for a near-term mission whether at the Moon or another extraterrestrial location is definitely within the capability of the ALHAT team.

6. CONCLUDING COMMENTS

The ALHAT project has shown that the integrated system of sensors, algorithms for detection and avoidance must be designed together to ensure precision landing and hazard avoidance are achieved. Through ALHAT team development efforts coupled with other industry and academia, the state-of-the-art in 3-D surface sensors as well as hazard identification, avoidance, relative navigation and guidance algorithms are being advanced. Through simulation and field tests, an ALHAT system is being evaluated and improved, with the ultimate goal of defining a system that can be shown to be at TRL 6.

7. ACKNOWLEDGEMENTS

The tremendous work contained in this paper is gathered from the efforts of the ALHAT team and in no way is done solely by the authors. The entire ALHAT team is continuing its tradition of excellence and is moving steadily along the path of development, testing, and analysis. ALHAT is an important project with dedicated people producing outstanding results. Therefore, the authors wish to thank the entire ALHAT team for their extraordinary efforts supporting this very important technology development program.

8. REFERENCES

1. Epp, C., and Smith, T., "The Autonomous Precision Landing and Hazard Detection and Avoidance Technology (ALHAT)," *Proc. of the Aerospace Conference*, Big Sky, MT, March 2008, pp. 1-7.

2. Cohanim, B., "Project Technical Requirements Specification For the Autonomous Landing and Hazard Avoidance Technology (ALHAT) System," ALHAT-2.0-001, 5 August 2009.

3. Davis, J., Striepe, S., et. al., "Advances in POST2 End-to-End Descent and Landing Simulation for the ALHAT Project," AIAA-2008-6938, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Honolulu, Hawaii, August 2008.

4. Davis, J., Striepe, S., et. al., "POST2 End-to-End Descent and Landing Simulation for ALHAT Design Analysis Cycle 2," International Planetary Probe Workshop 2010, Paper 434, Barcelona, Spain, 14-18 June 2010.

5. Cohanim, B., and Manuse, J., "Trade Report ALDAC1- HDA Methodology For the Autonomous Landing and Hazard Avoidance Technology (ALHAT) System," ALHAT-2.0-010, 2 August 2009.

6. Johnson, A., Huertas, A., Werner, R. and Montgomery, J., "Analysis of On-Board Hazard Detection and Avoidance for Safe Lunar Landing," IEEE Aerospace Conference, 1095-323X, Big Sky, MO, March 2008, pp. 1-9.

7. Manuse, J., "Summary Report ALDAC-2: HRN Methodology For the Autonomous Landing and Hazard Avoidance Technology (ALHAT) System," ALHAT-2.0-011, 29 March 2010.

8. Keim, J., "Field Test 1 Final Report For the Autonomous Landing and Hazard Avoidance Technology," ALHAT-9.0-005 Vol. 3, JPL D-49550, 24 February 2009.

9. Johnson, A., "Analysis of Flash Lidar Field Test Data for Safe Lunar Landing," IEEE/AC-1659, October 2009

10. Pierrottet, D., "Field Test 2 Doppler LIDAR Analysis Report For the Autonomous Landing and Hazard Avoidance Technology," ALHAT-9.0-006 Vol. 4, 9 March 2009.

11. Johnson, A., "ALHAT Field Test 3 Report, Volume 3: LIDAR Terrain Relative Navigation Algorithm Performance For the Autonomous Landing and Hazard Avoidance Technology (ALHAT)," ALHAT-9.0-007 Vol. 3, 13 May 2010.

12. Keim, J., "Field Test Implementation to Evaluate a Flash Lidar as a Primary Sensor for Safe Lunar Landing," *Proc. of the Aerospace Conference*, Big Sky, MT, March 2010, paper 2.0304.