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, hazard relative navigation algorithms, and the guidance and navigation system employing 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 are also addressed. The current ALHAT plans as of May 2010 are discussed. Applications of the ALHAT system for landing on planetary bodies other than the Moon are also 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 can 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 as the new landing target.

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 a few meters or less of its divert target and within tens of meters of the original landing target.

This scenario outlines the landing system concept that 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 of 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 also demonstrating a system of sensors and algorithms/software providing 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]

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 (systems engineering, vehicle autonomy, guidance, and navigation); Johns Hopkins Applied Physiscs Laboratory (lunar terrain, lunar science, and systems engineering) and the University of Texas at Austin (navigation filter). Previous team members include the Utah State University. As of May 2010, ALHAT is funded through the NASA Exploration Technology Development Program Office located at the Langley Research Center.

The ALHAT system has three main elements: Sensors; Terrain Sensing and Recognition (TSAR); and Autonomy, Guidance, and Navigation (AGN). 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 alternatives, and then accurately guiding the lander to the selected location.

The current ALHAT sensor set includes a 3-D Flash Light Detection and Ranging (LIDAR) system 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 LIDAR 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, 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 system. 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 to 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 procurement is being used to evaluate current and advanced technologies 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 candidate advanced technologies. 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 executed, with additional test being 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 also involve 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. 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 intended to assess the hazard relative navigation functionality of the ALHAT system, while also refining and enhancing the HDA performance. 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 will be focused on all aspects of the ALHAT system performance in the HAST real-time simulation testbed. Certain aspects of previous ALDAC assessments will be included in these HAST-focused ALDACs. These analyses will be driving towards the ultimate verification and validation of the ALHAT system to a TRL of 6 using HAST in combination with Earth-based flight demonstrations.

Similarly, the field tests incrementally increase the ALHAT system functionality being tested. The primary objective of the early field tests were to characterize sensor performance and generate data to be used post-flight for algorithm assessment and development. The next 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 sensor measurements during the flight. Future field tests will bring in additional 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 will likely occur using a free-flying lander 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 other procurements. For example, Flash LIDAR technology advancement toward TRL 6 includes component technology development through NRA contracts, internal 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 evolved 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 have been completed and have resulted in technology advancements 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. The improvements that have been made over the past few years include 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 refinements. 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.

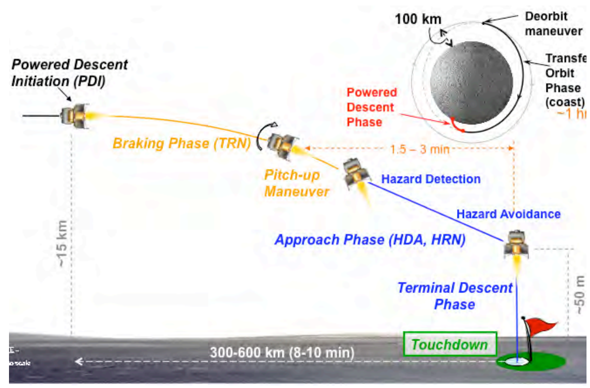

Fig. 1 ALHAT Lander Trajectory Illustration

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 ALDAC-1 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 99th-percentile vertical velocity less than 2 m/s, 99th-percentile horizontal velocity less than 1 m/s and 99th-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 Carlo runs addressed landings on smooth Mare terrains only (that decision dictated 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 and reducing feature shadowing and pixel stretching in the downrange direction. Area beam (flash) LIDAR technology images the landing site more quickly than other LIDAR 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. However, increased rock abundance can be mitigated with a corresponding increase in vehicle hazard tolerance. Slant range, path angle and deceleration rate all influence actual safe landing probability; the probability of safe landing decreases for longer ranges and shallower path angles. 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 three 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 near the top of each hazard. This pixel reduction makes it difficult to detect small hazards. Third, shallower path angles increase the amount of feature shadowing, resulting in "holes" in the digital elevation map (DEM).

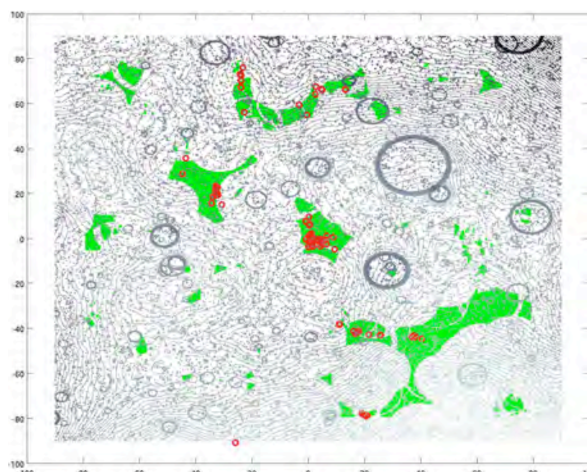

Fig. 2 Monte Carlo results: safe site comparison

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 exact same surface features (craters, rocks, slopes) and their same locations were on the map used by every trial of these Monte Carlo cases. This particular 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 and the onboard detection software) 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 as safe landing sites during the simulations were actually safe locations based upon the truth data. Also, each of these candidate landing aim points are within 90m of the original target (the center of the map in this figure) indicating that the GNC system was also functioning within desired parameters. Further information on ALDAC-1 is provided in [3], [5], and [6].

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 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 was designed to maintain a constant position knowledge error (truth minus estimated position) for the duration of HRN. ALDAC-2 was focused on determining the effectiveness of this implementation of HRN as well as tracking the progress of the ALHAT System technology development.

While ALDAC-2 had several similarities with the reference lunar landing mission used for ALDAC-1, there were some notable differences. A new approach trajectory subset of the original 252 trajectory space 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, 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 other 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 [2] (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 were included in Monte Carlo analyses to provide a measure of overall system performance and robustness. The ALHAT objectives for evaluating HRN during ALDAC-2 were: (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; (3) 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 (4) 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 resulting from the Flash LIDAR operational range limit. 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; note that this conclusion is directly related to the Level 0 requirement to detect hazards with an elevation of 30 cm. For the ALDAC-2 configuration, a rule of thumb for HDA is that a hazard height must be six 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) with 20 Hz and 5 Hz frame update rates were downselected for subsequent ALDAC-2 analyses. These integrated ALDAC-2 analyses indicated that the lower frame rate sensor is more sensitive to navigation errors during DEM generation. For HRN, the current ALDAC-2 configuration performance is: (1) generally insensitive to flash LIDAR array size (128x128 pixels versus 256x256 pixels) or frame rate (5 Hz, 10 Hz, 20 Hz); (2) strongly correlated with rock abundance (for all terrain types), degrading 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.

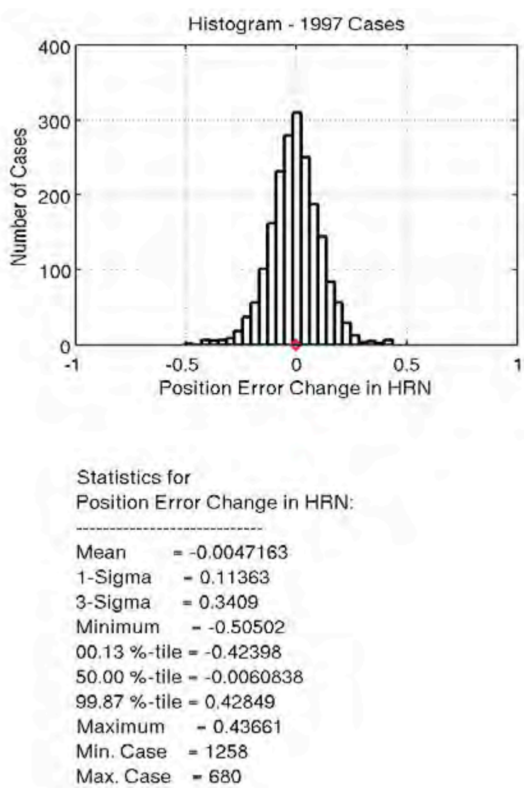

Fig. 3 Knowledge Error Change: HRN Start to Finish

Some additional observations from the ALDAC-2 analyses provide 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 in Fig. 4 showing the final touchdown performance 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 any other measurements (altimeter or velocimeter)

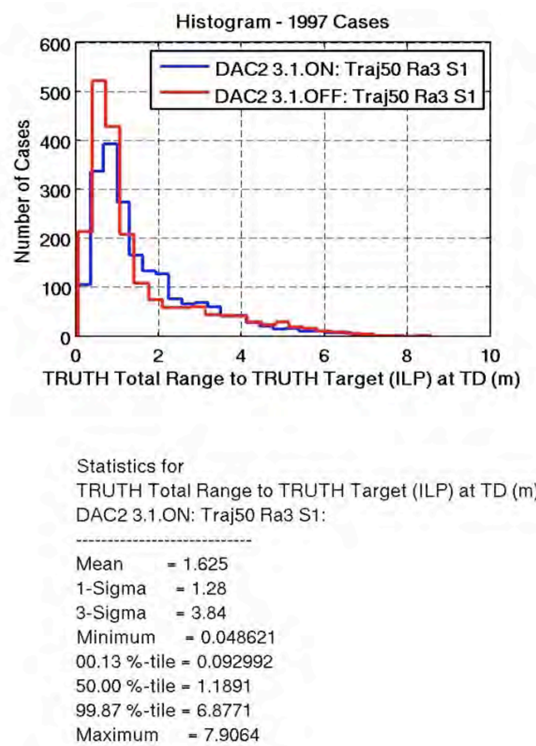

Fig. 4 Final Touchdown Range to ILP

during HRN. Any residual lateral velocity knowledge error would result in lander drift 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 position knowledge 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. That is, the ALHAT concept for HRN is switching from a position correction to a position measurement method during the Approach phase. 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 result, when coupled with the planned HRN adjustments for ALDAC-3, lead to the conclusion that no definitive statements can be made about the effectiveness of the current implementation of HRN. Further analyses are planned based on the revised HRN approach.

3.2 Field Tests

Field tests provide an evaluation of the ALHAT hardware in a dynamic and relevant test environment for application to landing systems. The ALHAT field test campaign started with manually operated sensors and is progressing to increasingly automated, real-time, closed-loop sensor and algorithm operation. Field testing has been performed using helicopters and fixed wing aircraft to date. However, the ALHAT Project has been directed to demonstrate the technological advancement of autonomous landing systems on terrestrial free flyer test platforms over the next several years in preparation for future planetary landing missions.

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 passive optical 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 TRN algorithms.

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 an example test flight path over Dryden. An inertially stabilized gimbal 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

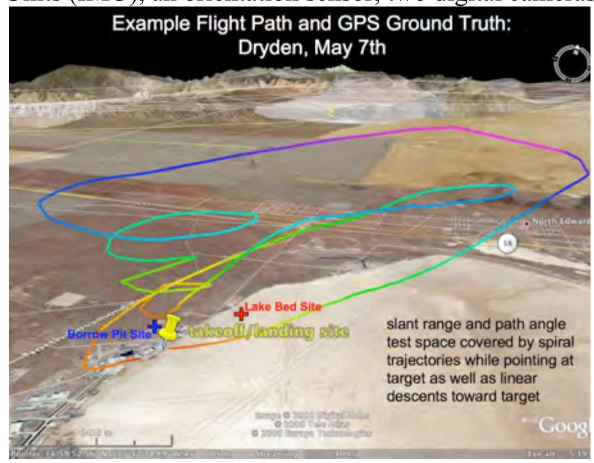

Fig. 5 Example FT1 Flight Profile

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 terrain images 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 eleven hazards grouped close to each other. There were hemispheres of various sizes and reflectivities as well as large and small boxes designed for LIDAR characterization. The Dryden site in the Borrow Pit had numerous hazards constructed 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 provides numerous rock fields of varying rock abundance as well as steep and shallow slopes. At Mars Hill the objectives were to obtain LIDAR data from natural terrain and assess 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 began development of a Flash LIDAR that will have significantly greater operational range (1000m) and significantly lower range measurement noise (0.05m, 1-sigma) targeted to meet the ALHAT Level 0 hazard detection requirement.

Hazard detection performance was evaluated 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 ALDAC-1. This field test analysis when combined with the validated comprehensive coverage of the HDA tests space in ALDAC-1 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 that could be used for TRN. FT1 brought out the importance of obtaining position and attitude information in conjunction with, and synchronized to, navigation sensor data. More information on FT 1 is provided in [8], [9] and [10].

3.2.2 Field Test 2

For ALHAT FT2, a breadboard Doppler LIDAR sensor was installed aboard a helicopter and tested over the California desert.[11] The Doppler LIDAR instrument developed at the NASA Langley Research Center is designed to provide high precision velocity and range measurements. FT2 had a total of six flights: four flights over a flat, dry lakebed; 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 included 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 highly 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 sensor 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.[12] 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 Test Site, in particular, was selected because it has a large crater field distributed over a barren and relatively flat terrain, analogous to the lunar mare. Each flight provided between one and two hours of useful data.

LIDAR data from all of the flights were 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 90m 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 50m. 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. As expected, TRN performance is strongly driven by the quality and resolution of the reference DEM.

Studies were also conducted to assess the sensitivity of the LIDAR TRN algorithm to various parameters. It was determined that 450m contours resulted in the greatest number of correct measurements while still keeping incorrect measurements at a minimum. It was found that about 25m 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 90m 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 25m 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 provided in [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 refinement of HDA and HRN. Long term ALHAT plans are to include more real-time, hardware-in-the-loop functionality into the ALDACs by including HAST analyses. In addition, HAST will be used to support and simulate ALHAT field test configurations. POST2 will continue to be used for Monte Carlo analyses as well as computationally intensive, high fidelity, physics-based environment and sensor models that aren't readily adaptable to real-time execution.

Detailed planning for ALDAC-3 is still in the early stages, but current plans are focused on performance updates to the HDA and HRN software and a thorough, end-to-end assessment of ALHAT system performance and sensitivities with respect to landing accuracy and landing safety. ALDAC-3 will also incorporate updates to the Autonomous Flight Manager software to provide an increased level of control over ALHAT system and sensor operation. Some of the ALHAT software modules will be migrated to a real-time implementation in FY11, and these new software releases will be integrated into the ALHAT simulation environments when available.

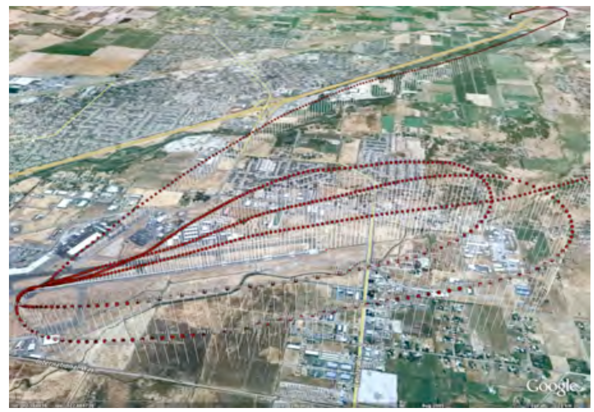

Fig. 6. Helicopter Verification Flights at ALHAT Approach Trajectory Path Angles

4.2 Field Tests

The next ALHAT field test, FT4, is scheduled for July 2010. FT4 has four primary objectives. The first objective 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 Air-Crane helicopter pilots to evaluate their ability to match the desired ALHAT trajectory characteristics. These approaches are 15, 30, and 45 deg path angle cases. The second objective is to demonstrate precision pointing of the gimbaled flash lidar using real-time GN&C data (position, velocity attitude, and attitude rates) in combination with the gimbal manager and mapper components of the TSAR software. The third 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 required for an autonomous safe precision landing.

The FT4 instrument suite includes four distinct sensor subsystems: two Flash LIDARs, a three-beam Doppler LIDAR velocimeter, and a laser altimeter. All of the sensors and support equipment are housed in an external pod attached to the bottom of the helicopter. The two Flash LIDARs are mounted on a shared gimbal mechanism. The Flash LIDAR sensors will be operated on separate test flights, but both will remain mounted on the gimbal throughout FT4 and will share a support electronics package by simply switching out cables. The Flash LIDARs are mounted to separate aluminum instrument plates, which are used in the laboratory and in flight. The design is such that the alignment of the optical components will not be disturbed while installing and removing the Flash LIDAR sensors from the gimbal. A rack mounted chiller is used to cool both plates simultaneously. The Doppler LIDAR and laser altimeter are mounted on a fixed plate next to the gimbal mechanism.

FT4 also takes advantage of previous field test equipment and experience. Examples of hardware that will be reused and revised for FT4 include instrumentation, truth data collection hardware, and ground support equipment and software to enable rapid analysis of data in the field. Lessons learned from FT1 through FT3 will also be applied.

The ALHAT system used on FT4 will be leveraged for subsequent field tests with the eventual goal being to raise the Technology Readiness Level of the entire ALHAT system to TRL 6. Additional flight tests are only in the planning stages at this point. However, 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 testing 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, or 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. 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 landing environment. The FT8 campaign in FY13 will incorporate more hazardous simulated lunar terrain and vary key operational parameters to establish the operational envelope 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 NASA Flagship Missions.

It should be noted that ALHAT's forward plans are tentative at this point, and are subject to change due to a wide range of cost, schedule, and technical factors. The major cost and schedule risk for the ALHAT Project in FY11 is the procurement, integration, and operation of a closed loop VTB platform. As a result, ALHAT field test plans will continue to include the potential for additional helicopter field tests to augment or replace VTB flights, as needed. The technical risks for the ALHAT Project are primarily associated with the maturation of the integrated Hazard Detection System, including the final stages of Flash LIDAR development and testing, and the implementation of real-time TSAR software on a high performance, multi-core processor.

5. POTENTIAL ALHAT USAGE

Although the ALHAT Project has focused predominantly on human and robotic lunar landing systems over the past few years, there is nothing inherent to the ALHAT system that would preclude its application to another planetary destination, such as Mars, an asteroid, or moon. In fact, the ALHAT Project has received inquiries regarding the suitability of ALHAT landing system technologies for several prospective missions.

There are also potential terrestrial applications for ALHAT sensors and algorithms in the areas of terrain mapping and precision navigation. For instance, the challenges faced by helicopter pilots landing under brownout conditions are analogous to the terrain visibility issues that will be encountered during future lunar landings. The ALHAT Doppler LIDAR sensor appears to have wide application to the navigation of terrestrial vehicles and the precision control of systems involving motion or moving parts.

6. CONCLUDING COMMENTS

The ALHAT team, which includes members from NASA, industry, and academia, has made significant advances to the state-of-the-art in autonomous landing system technologies in the areas of precision terrain relative navigation and velocimetry, as well as real-time terrain mapping and hazard detection. Major steps have been taken in the development and integration of a LIDAR-based landing system that is applicable to a range of planetary missions and is insensitive to ambient surface lighting conditions. The ALHAT Project has found that the development of a successful landing system is highly dependent on the effective integration of a number of coupled technical performance parameters involving both the landing system, itself, and the host vehicle. Through simulation and field tests, an ALHAT system is being evaluated and improved, with the ultimate goal of demonstrating an autonomous landing system on a terrestrial free flyer testbed with closed loop control to a maturity of TRL 6 no later than 2013.

7. ACKNOWLEDGEMENTS

The information contained in this paper is gathered from the efforts of the entire ALHAT team. The ALHAT Project, which is moving steadily along the path of landing system development, testing, and analysis, owes it success to a team of highly capable and dedicated people. Therefore, the authors wish to thank the entire ALHAT team, past and present, for their extraordinary efforts in support of this critical technology for planetary exploration.

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