AUTONOMOUS PRECISION LANDING AND HAZARD AVOIDANCE TECHNOLOGY (ALHAT) PROJECT STATUS

AS OF MAY 2010

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IPPW-7 International Planetary Probe Workshop 2010
Barcelona, Spain

ALHAT CHARTER

Autonomous Landing Hazard Avoidance Technology (ALHAT)

Develop and mature to TRL6 an autonomous lunar landing GN&C 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.

- Project includes development of precision landing and hazard avoidance landing system technologies for lunar missions including crewed, cargo, and robotic systems to support precision navigation relative to hazards
  - Detection of hazardous landing conditions (surface topography, slopes, etc.) & display landing site recommendations (during piloted lunar landings)
  - Automated, accurate & safe lunar landings of un-crewed cargo & robotic vehicles
- Capability Development Primary Tasks – Develop to TRL6
  - Hazard Detection Sensor Development – Demonstrate required system performance over relevant ranges, power requirements & accuracy.
  - Terrain Mapping and Site Selection – Demonstrate computations and display of terrain information along with logic for selection of safe landing zones. Demonstrate relevant computational speeds
  - Autonomous Hazard Avoidance – Demonstrate closed-loop vehicle control characteristics by coupling site selection functions with vehicle targeting & GNC

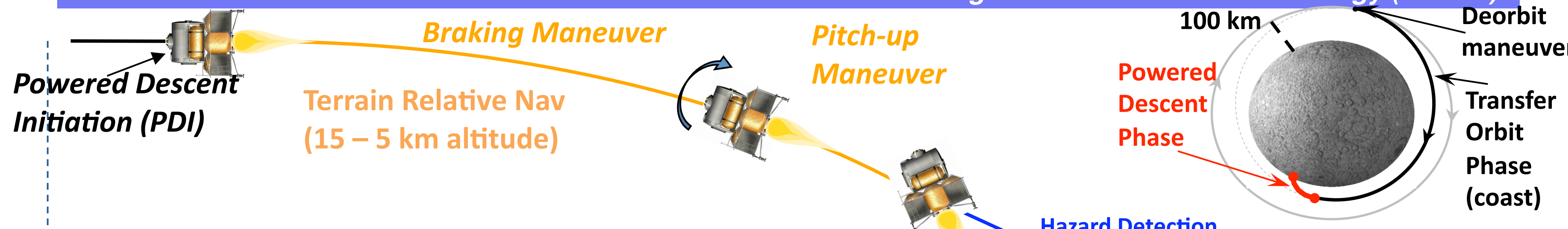
ALHAT TEAM

Autonomous Landing Hazard Avoidance Technology (ALHAT)

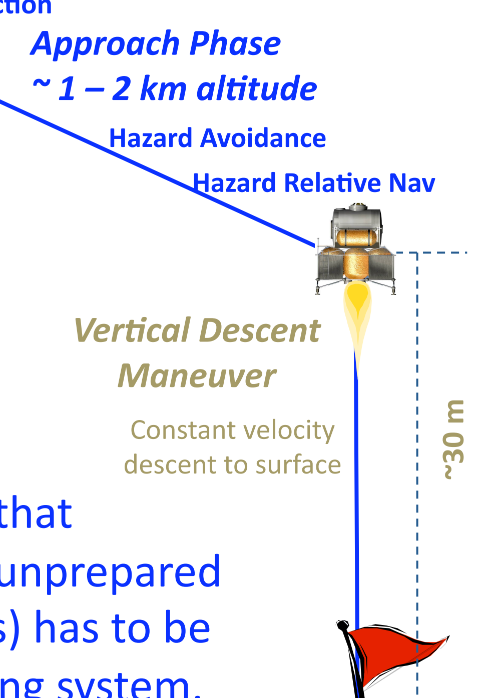
- Exploration Systems Mission Directorate (ESMD)
  - Exploration Technology Development Program (ETDP)
    - ALHAT (JSC)
      Project Manager: Chirold Epp
      - JSC
        - •Systems Engineering
        - •G&N Algorithms
        - •HWIL Testbed
        - •System Avionics
        - FastMetrix
          Jacobs Engineering
          University of Texas
          Utah State
      - LaRC
        - •Sensor Development & Selection
        - •Sensor Testing
        - •6 DOF POST2 Simulation
        - SSAI/CAI
      - JPL
        - •TRN & HDA Algorithms
        - •Terrain Recognition Ana.
        - •Sensor Field Testing
      - Draper (CSDL)
        - •Systems (co-lead)
        - •Autonomy
        - •GN&C Integration
        - •G&C Algorithms
      - APL (JHU/APL)
        - •Optical TRN
        - •Lunar environment
        - •Free flyer test modeling

ALHAT System & Landing Sequence

Autonomous Landing Hazard Avoidance Technology (ALHAT)



- The ALHAT System is an integrated system which includes:
  - Autonomous Flight Manager (AFM) for onboard autonomy (robotic capability), sensor/algorithm executive, and pilot situational awareness
  - Guidance and Navigation (G&N) algorithms are part of integrated ALHAT System of algorithms and sensors for precision landing with hazard avoidance.
  - Sensors and Algorithms for Terrain Relative Navigation (TRN), Hazard Detection and Avoidance (HDA), Hazard Relative Navigation (HRN) and velocimetry
  - COTS sensors such as IMUs & star trackers representing the actual lander sensors that will provide vehicle state and attitude knowledge



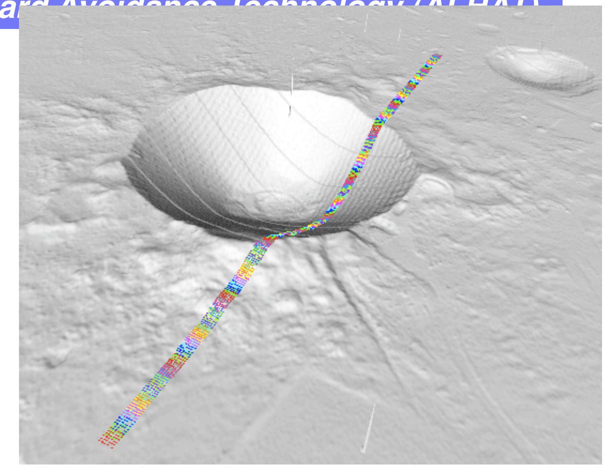
ALHAT development is focused in the areas of additional capability that standard GN&C design would need for precise & safe landing at an unprepared site…but the whole system (algorithms, sensors, vehicle subsystems) has to be modeled in order to verify that it works as an integrated lunar landing system.

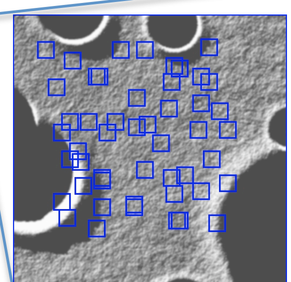
ALHAT System Level 0 Requirements

- **1. Landing Location**
  - The ALHAT System shall enable landing of the vehicle at any surface location certified as feasible for landing.
- **2. Lighting Condition**
  - The ALHAT System shall enable landing of the vehicle in any lighting condition.
- **3a. Landing Precision - Global**
  - 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.
- **3b. Landing Precision - Local**
  - The ALHAT System shall enable landing of the vehicle at an intended landing point with a 3-sigma error of less than 3 meters
- **4. Hazard Detection**
  - The ALHAT System shall detect hazards with an elevation change of 30 cm or larger objects and detect slopes of 5 degrees and steeper, and provide landing point designation based on detected hazards.
- **5. Vehicle Commonality**
  - ALHAT System shall enable landing of crewed (humans on board), cargo (human scale w/out humans onboard) & robotic (smaller exploration vehicles w/out humans onboard) vehicles.
- **6. Operate Autonomously**
  - The ALHAT System shall have the capability to operate autonomously (without command and control intervention from sources external to the vehicle).
- **7. Crew Supervisory Control**
  - The ALHAT System shall accept supervisory control from the onboard crew.

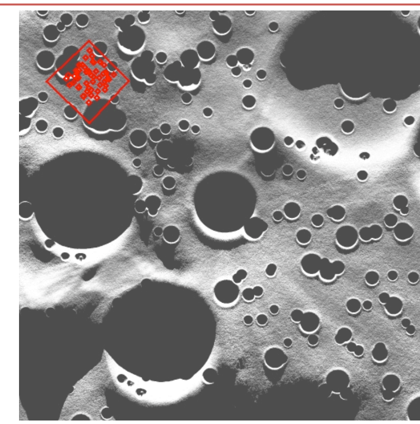
Precision Landing Navigation

- Terrain Relative Navigation (TRN) is ALHAT chosen method to enable precision landing (w/ standard GNC sensors)
- Basic idea: match a priori DEM using passive optical or active sensing to provide state update
  - LIDAR TRN algorithm constructs an elevation contour from multiple LIDAR images, correlate contour with reference DEM and then solves for a position fix
  - Another matches features in a descent image to reference map image to generate bearing angles to known landmarks.
  - These measurements are used by the navigation filter to update inertial position.
- 3 sensor sets:
  Flash LIDAR, Laser Altimeter,
  Passive Optical Sensors
- 6 TRN algorithms:
  LIDAR & Altimeter Tercom,
  LIDAR Area Correlation,
  Passive Optical Crater Matching,
  Passive Optical MAIA,
  Passive Optical, Passive Optical

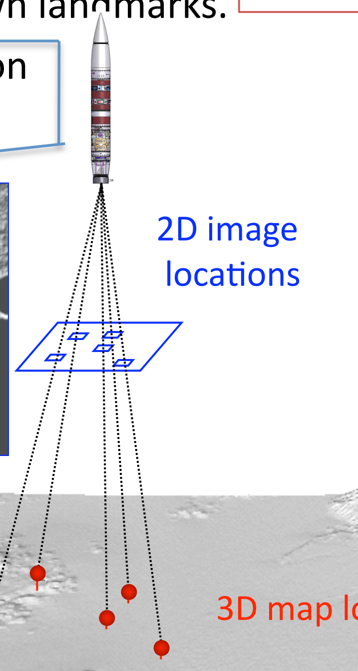




Descent Image



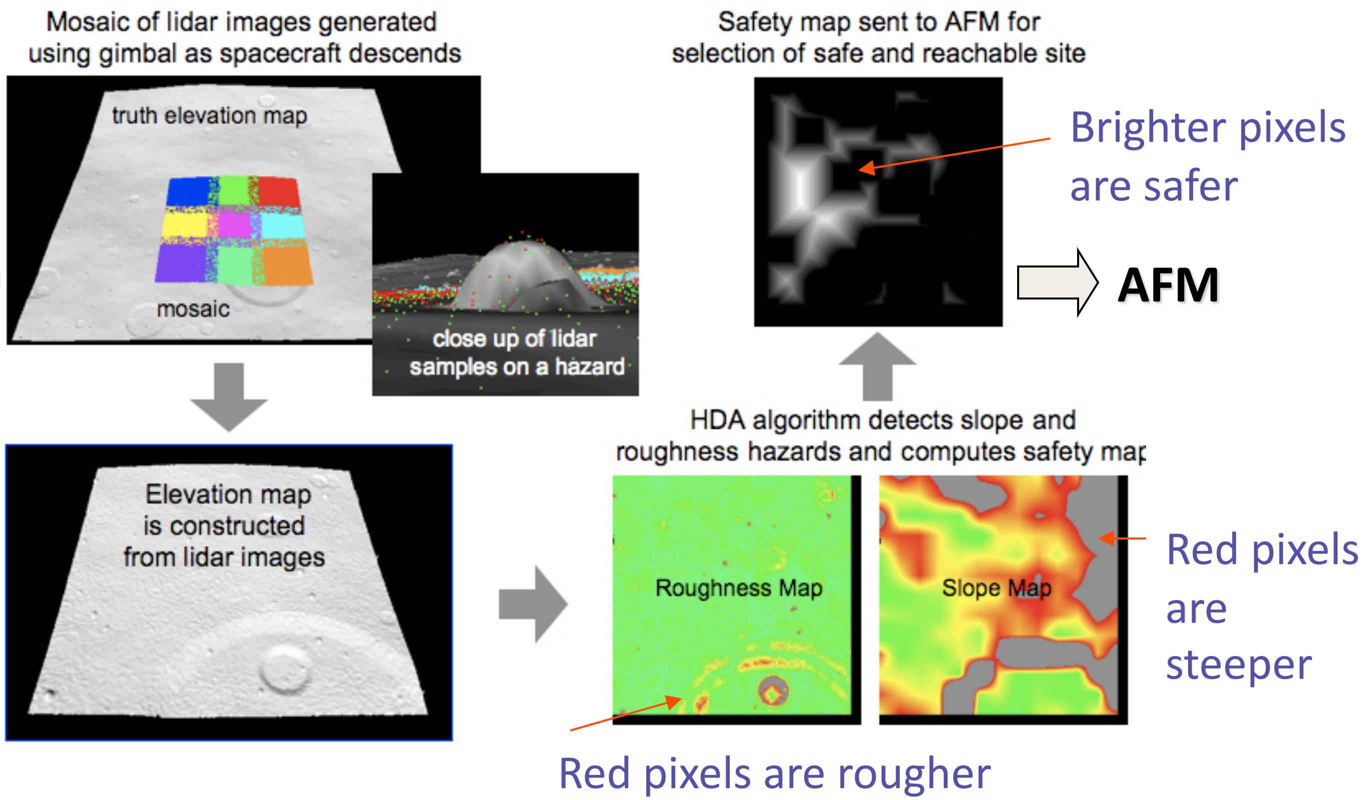
Orbital reference map



Hazard Detection/Avoidance Process

Autonomous Landing Hazard Avoidance Technology (ALHAT)

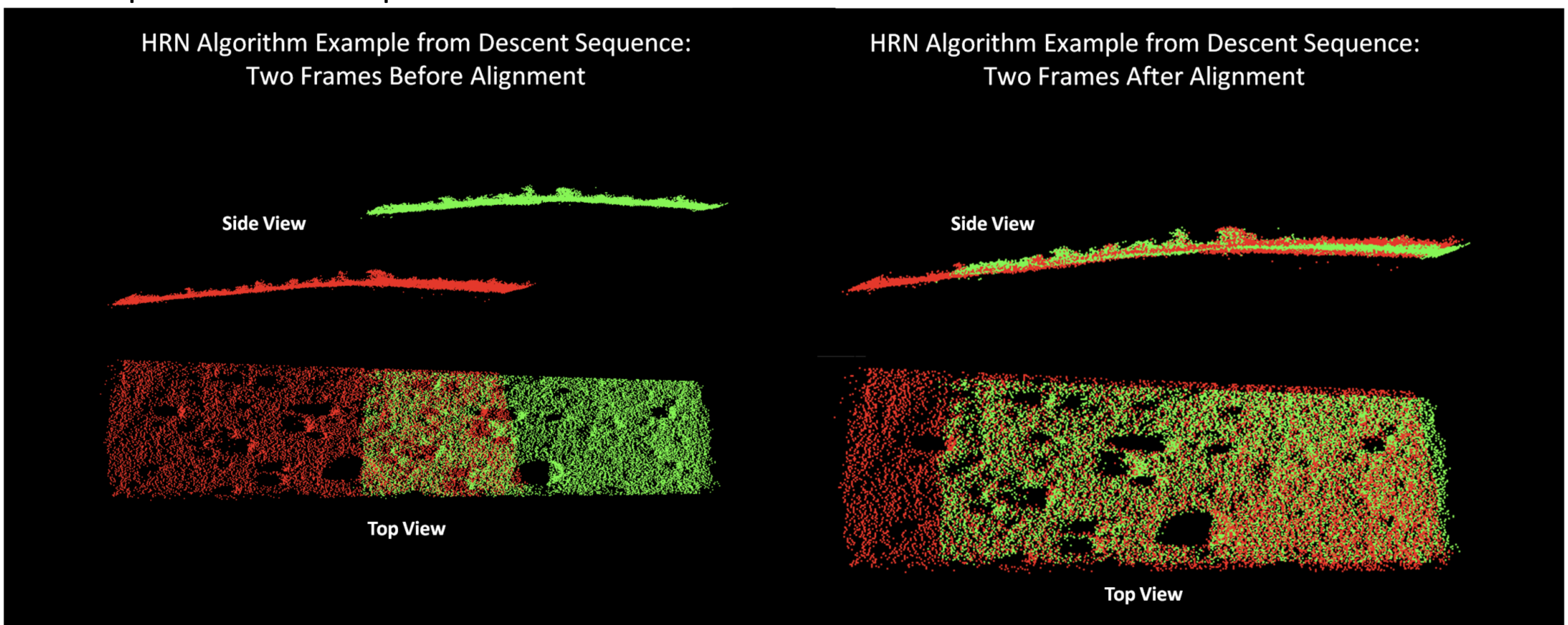
Trajectory determines when LIDAR measurements are taken along descent path



- **LIDAR images collected during descent used to construct mosaic representing elevation map**
- **Surface roughness and slope maps generated from elevation map to detect hazards.**
- **Hazard free areas are represented in a safety map identifying safe locations for landing.**

Hazard Relative Navigation

- Concept is to continue using the Flash LIDAR following the HDA scan and compare back to the original map in order to provide measurement updates
  - "Hazard" identified and tracked on subsequent images to determine state adjustment/ measurement
- Current work in ALHAT is investigating this technique in detail and understanding performance improvements and limitations



ALHAT Development - SENSORS

Autonomous Landing Hazard Avoidance Technology (ALHAT)

<u>Under development by ALHAT</u>

- *3-D Flash Lidar:*
  - HDA/HRN (1000 m to 100 m)
  - TRN (15 km to 2 km)
  - Altimetry (20 km to 100 m)

Flash lidar

- *Doppler Lidar:* Velocity and Altitude (2500 m to 10 m)
- *Laser Altimeter:* Altitude Measurements (20 km to 2 km)

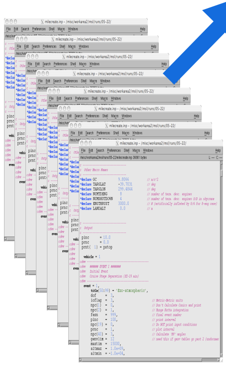
<u>COTS with some modifications</u>

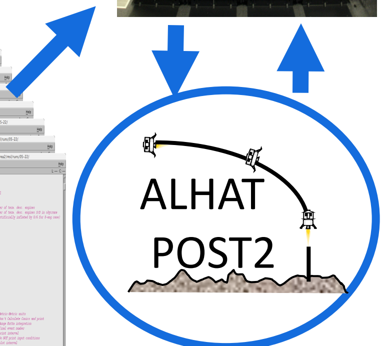
- *Optical Camera:* TRN

ALHAT Testing/Analysis Approach

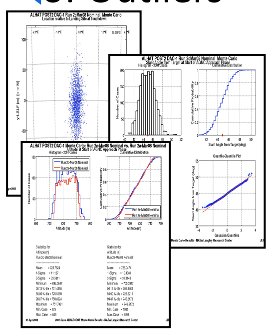
Autonomous

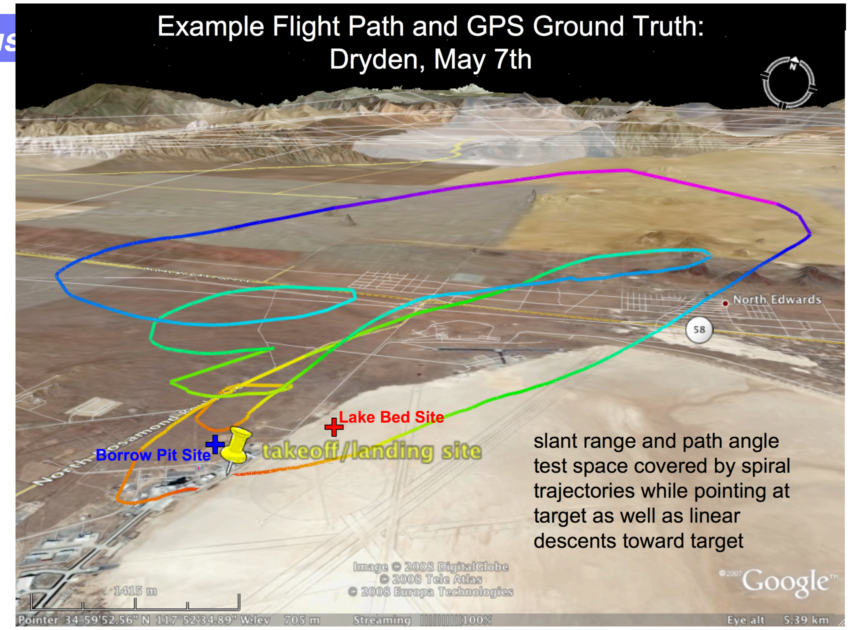
2000 or more Monte Carlo Dispersed Cases

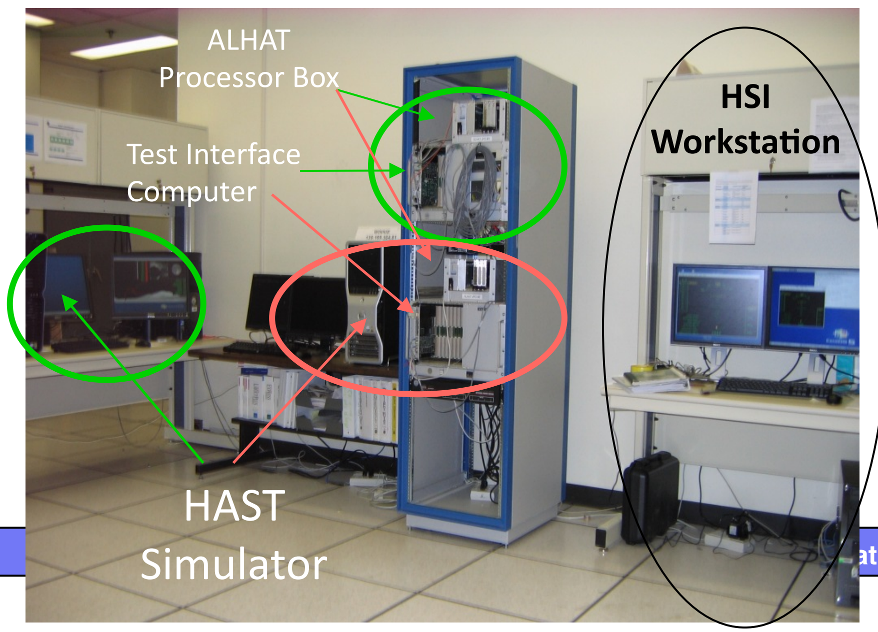




- Key Outputs Statistics
- Landing Footprint/ Touchdown conditions
- Detailed examination of Outliers

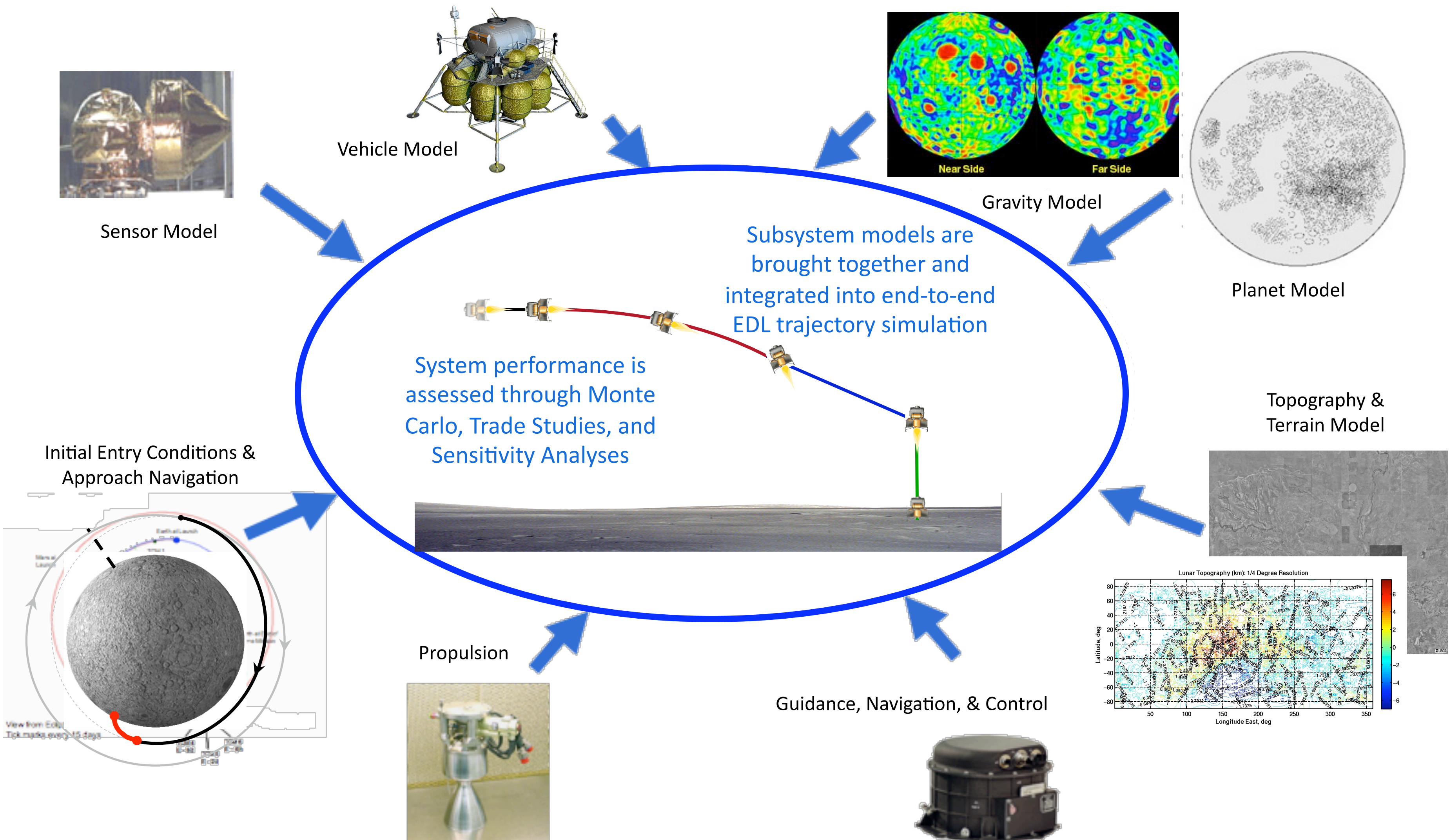






- Testing includes:
- ALHAT POST2 Simulation Monte Carlos
- Field Tests
- Real-Time H/W in the loop ALHAT Simulation Testbed (HAST)

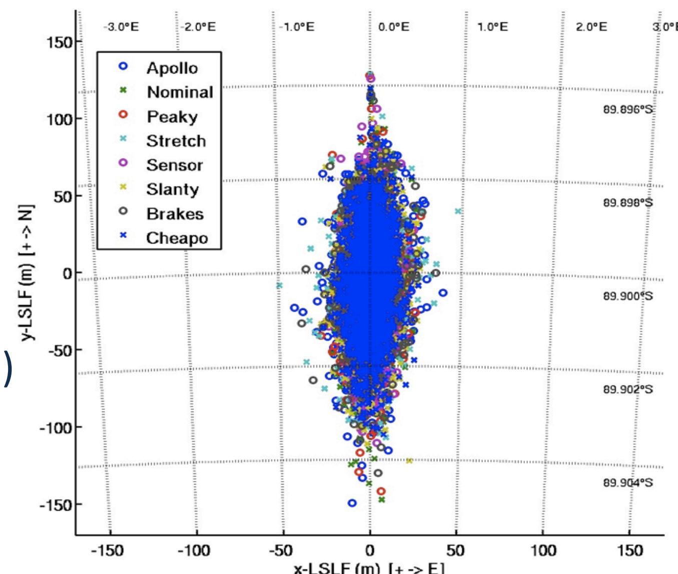
ALHAT POST2 Trajectory Simulation



ALHAT Design Analysis Cycle 1

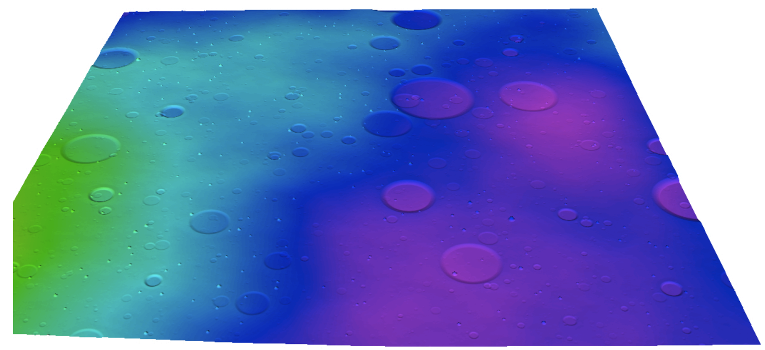
Autonomous Landing Hazard Avoidance Technology (ALHAT)

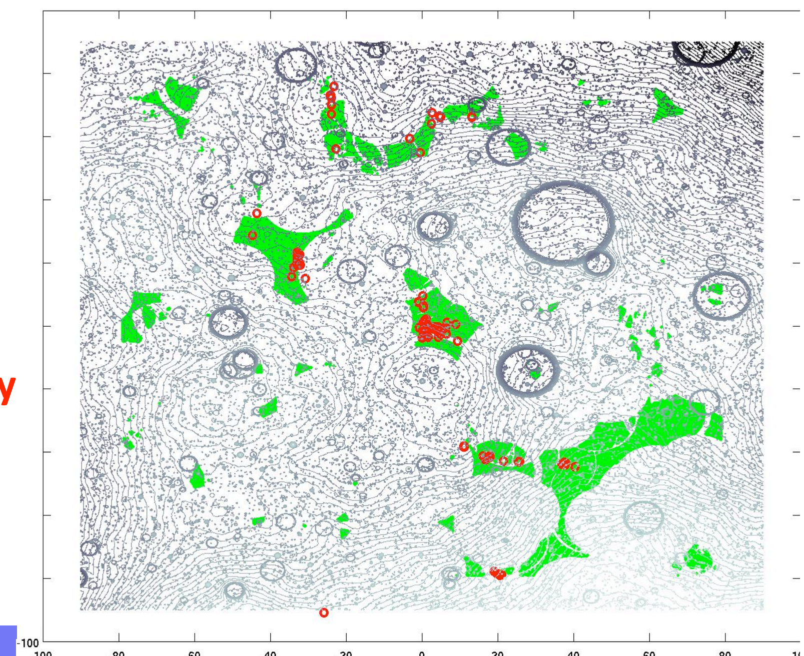
- Objectives:
  - Characterize the overall integrated ALHAT system performance as well as focusing on the Hazard Detection and Avoidance aspects.
  - Validation of HDA algorithm and identification of refinements
  - Evaluate effects of GNC errors on landing location/ Fuel sensitivity
- Utilize independent, focused "sand-box" simulations as well as the integrated end-to-end ALHAT POST2 environment.
- Results from multiple Monte Carlo sets of analyses confirmed:
  - System met touchdown conditions for most cases (within few % in others)
    - Downrange/crossrange variation < 30m (1-sigma)
    - Vertical velocity < 2 m/s (99-percentile)
    - Horizontal velocity < 1 m/s (99-percentile)
    - Attitude rate < 2 deg/s (99-percentile)
    - Lander central axis < 6 deg of vertical (99-percentile)
  - Slant range/angle quantities at HDA start confirm closed-loop G&C system is working in presence of system uncertainties and navigation error



ALDAC-1 Conclusions

- **Slant range and deceleration** rates do not influence **DEM fidelity** or **hazard detection** metrics.
  - Sensor is optimized for **slant range** and flash LIDAR data collection is so fast that velocity does not appear to have a significant effect.
- As **path angle** increases **Detection Rate (DR)** and **False Alarm Rate (FAR)** increase.
  - Reduced elevation noise at low path angles because LIDAR noise is converted from vertical to horizontal orientation.
  - At low **path angles** then it is possible to miss top of small hazards, and it is possible to miss hazards due to stretching of samples.
- As **slant range** increases, **safe landing probability (SLP)** decreases; as **path angle** decreases, **SLP** decreases.
- HDA trends with respect to **vehicle tolerance** and **rock abundance** are as expected.
  - **DR** does not depend on **rock abundance**. **DR** increases as **hazard tolerance** is increased while elevation map GSD and lidar noise are held constant.
  - As **rock abundance** increases **safe landing probability** decreases (fewer places to land). Increased **rock abundance** can be mitigated with a corresponding increase in vehicle tolerance.
- HDA performs very well in terms of final **goal**: **the probability** of selecting a safe site if one exists is above 97% for cases analyzed.
  - To guarantee a higher **probability** of safe site selection and detection, **FAR** need to be addressed by algorithm refinements.
- **Not always landing in safe area due to changing Nav error**



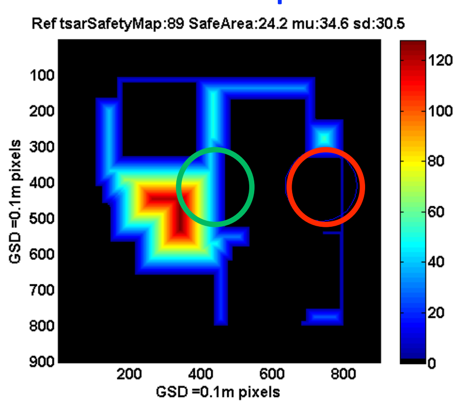


ALDAC-2: HRN Focus & HDA Update

- ALDAC-2 Objective:
  - To prove HRN is working in the integrated system.
    - How much does adding HRN improve the integrated system performance?
    - What are impacts of sensor parameters on HRN performance over a variety of terrain?
    - Does HRN improve the functionality or performance of the integrated system?
    - Does HRN reduce Nav error growth between HRN start & touchdown?
  - Continue evaluation & improvement of HDA (especially with HRN active)

original

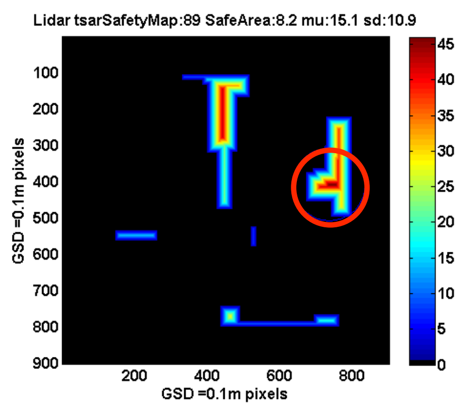
Truth Map



Reference Safety Map

Smooth Mare, 3% Rocks

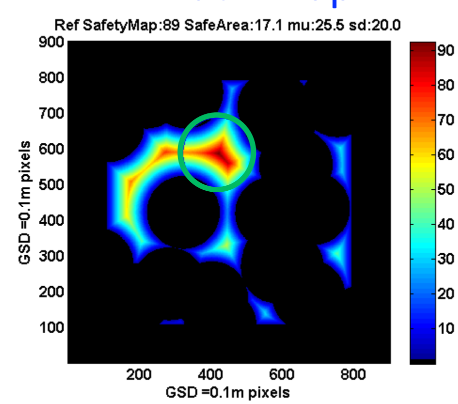
Lidar Map



TSAR selects unsafe site with thr=0.25m (red).

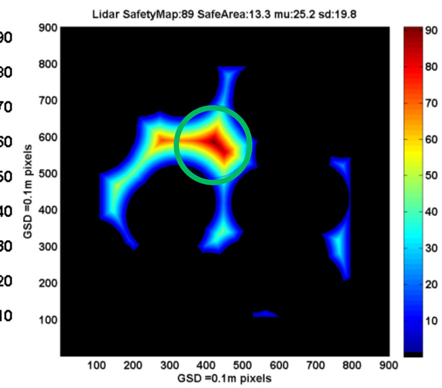
updated

Truth Map



Reference Safety Map

Lidar Map



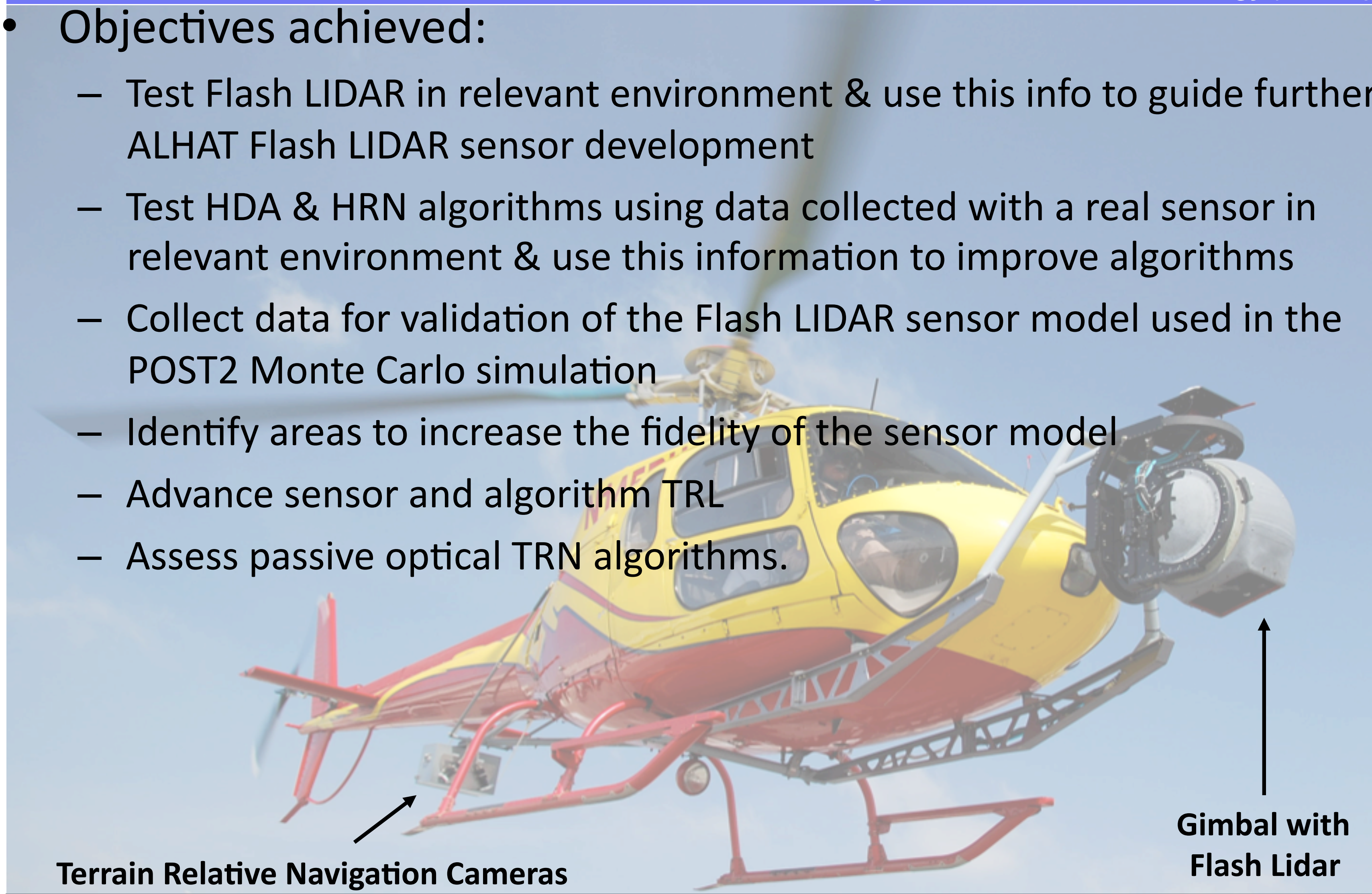
TSAR selects safe site with thr=0.25m (green). Secondary peaks safe.

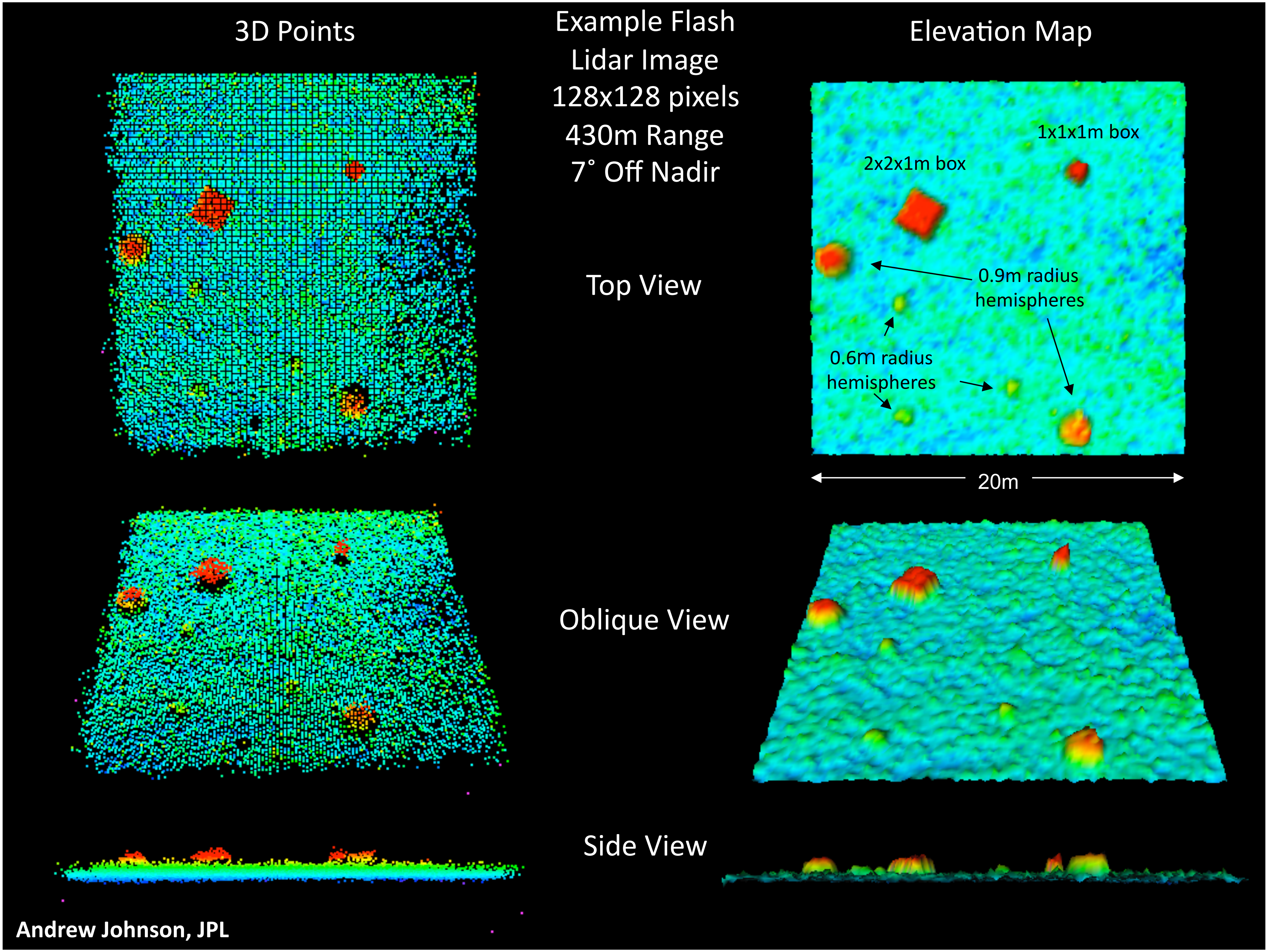
ALDAC-2 Conclusions

- When HRN provides valid measurements (successful correlation), they meet ALHAT relative navigation accuracy requirement. That is, all points lie within 0.5 m radius, indicating that 3 m radius (3σ) estimation error requirement is easily met
- Trajectory path angle should be greater than 15°
  - 15˚ path angle and 1500 m slant range trajectories have poor HDA performance. Flash LIDAR designed for 1000m operational range & low path angles result in significant terrain shadowing & pixel stretching in downrange direction
  - Poor HRN performance associated with 15˚ path angle. Performance improves for 45˚ angle
- Excellent performance with 4 cm LIDAR range precision; performance is unacceptable with 12 cm range precision
  - Connected to Project Level 0 requirement for detecting hazards of elevation change > 30 cm
- HDA and HRN performance appears to be insensitive to array size and sample rate
- The ALHAT System meets the system-level and AGNC subsystem requirements, except the local safe site precision (final range to ILP > 3m 3-sigma)
  - Caused by Nav error change after HRN completes, and residual Nav Velocity error.
- Based on Monte Carlo results, if the vehicle arrives at the start of HRN with a low navigation knowledge error, the position error will naturally tend to stay low
- Thus, HRN approach was re-evaluated & modified to address these issues (in ALDAC-3)

Field Test 1 – April 2008

- Objectives achieved:
  - Test Flash LIDAR in relevant environment & use this info to guide further ALHAT Flash LIDAR sensor development
  - Test HDA & HRN algorithms using data collected with a real sensor in relevant environment & use this information to improve algorithms
  - Collect data for validation of the Flash LIDAR sensor model used in the POST2 Monte Carlo simulation
  - Identify areas to increase the fidelity of the sensor model
  - Advance sensor and algorithm TRL
  - Assess passive optical TRN algorithms.



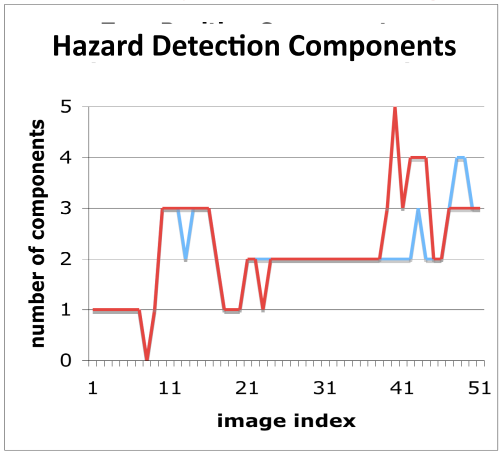

3D Points
Example Flash
Lidar Image
128x128 pixels
430m Range
7˚ Off Nadir
Elevation Map
1x1x1m box
2x2x1m box
0.9m radius
hemispheres
0.6m radius
hemispheres
20m
Top View
Oblique View
Side View
Andrew Johnson, JPL

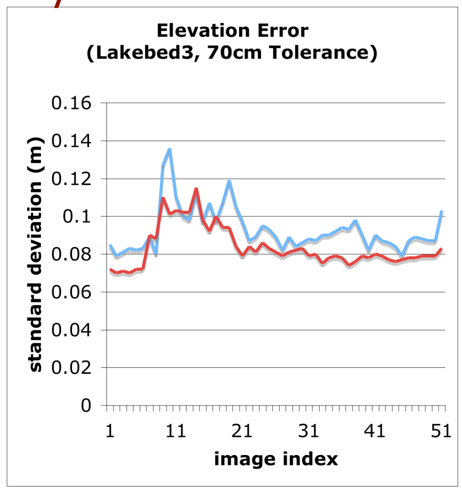
Example FT1 Analysis Results

Autonomous Landing Hazard Avoidance Technology (ALHAT)

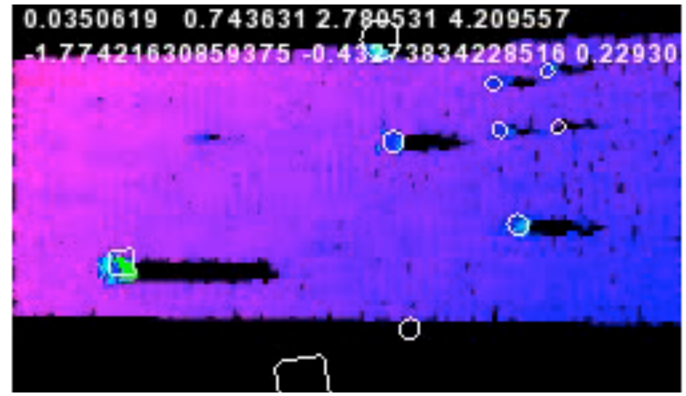
field test results

comparison to high fidelity simulation

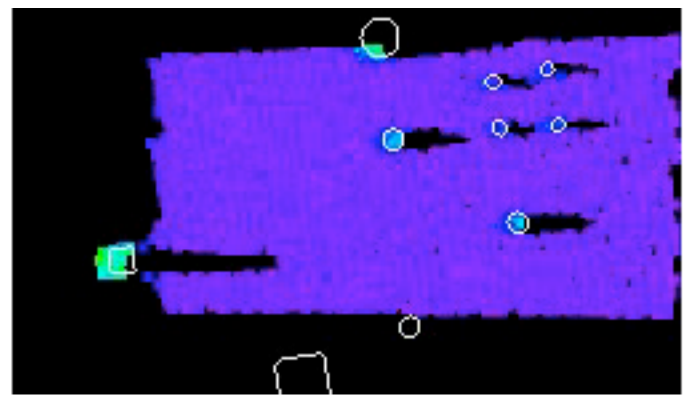




Real LIDAR Data



Simulated LIDAR Data



- **Simulation sensor model can replicate sensor performance when in nominal operational regime (high trigger fraction)**
- **Able to discriminate 0.6-0.9m high hazards while limiting false positives to 1 out of 5 VFDE**
- **HDA & HRN algorithms and sensor models were adjusted based on FT1 results.**

ALDAC1 sensor model validated; HDA algorithm raised to TRL5 & HRN to TRL4

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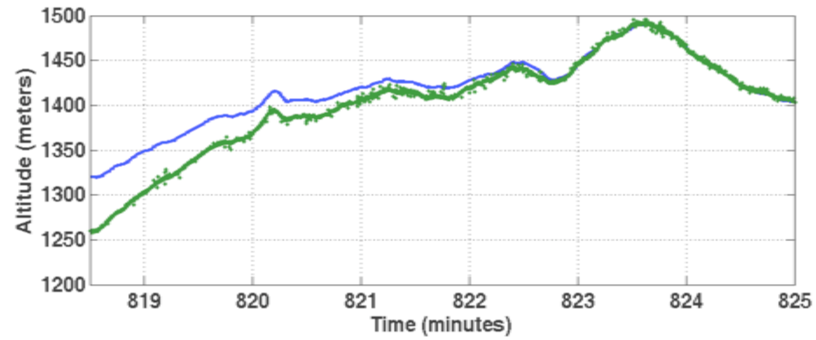
Field Test 2 – August 2008

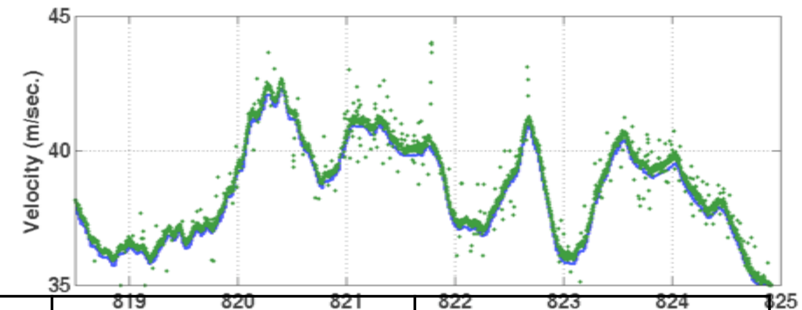
- Objectives:
  - Demonstrate the Doppler LIDAR (DL) capabilities to provide vehicle velocity vectors, altitude above ground level, and surface-relative attitude.
  - Characterize its performance (operational range and accuracy)
  - Evaluate its capabilities in meeting the ALHAT needs and demonstrate its viability for future landing missions
  - Analyze the test data in support of the prototype system design
- Helicopter figure-8 flight paths over surveyed area at NASA Dryden
- Sensor specifications:
  - All fiber optic design Doppler LIDAR
  - Three Transmit/Receive Apertures
  - 2” aperture diameter
  - 1 Watt/channel transmit power.

Field Test 2 Results

Autonomous Landing Hazard Avoidance Technology (ALHAT)

- **Neither terrain type nor vehicle attitude affects velocity measurements.**
- Ground elevation profile is difference between DL altitude and GPS altitude.
- GPS does not account for terrain elevation.
- Velocity measurements to within 98% correlation to numerically derived GPS data - Precision <5 cm/sec



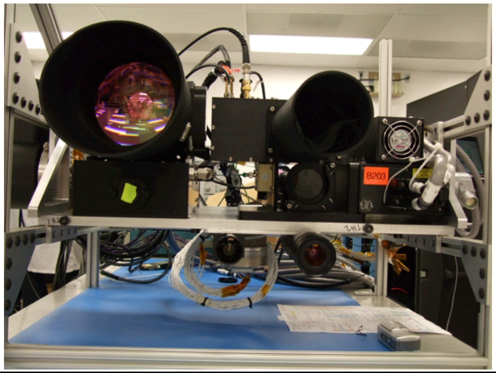


Advanced the Doppler LIDAR TRL to 4

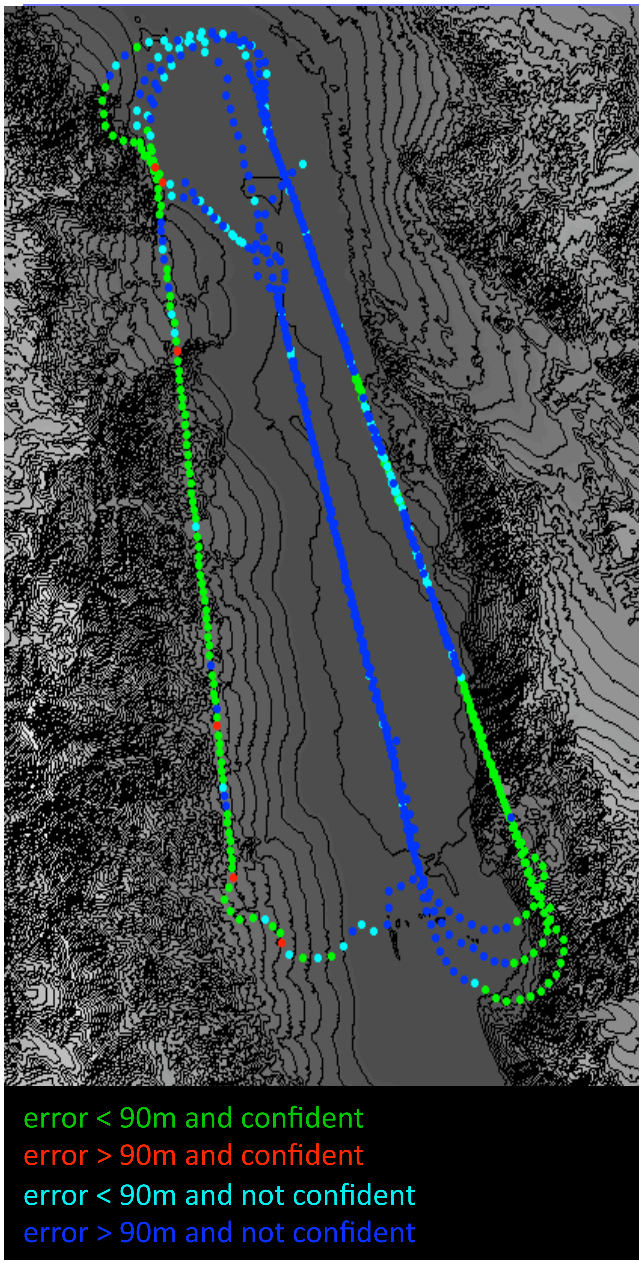
Parameter	Brassboard (Helicopter Test)	Demonstrated in FT2
Maximum Operational Altitude	> 1000 m	5000 m
Instantaneous LOS Velocity Noise	0.05 m/sec	< 0.05 m/sec
Range Accuracy	4cm + 0.03%	< 4cm + 0.03%
Surface Relative Attitude Precision	TBD	< 0.1 deg
Data Update Rate	10 Hz [1]	10 Hz

Field Test 3 - June/July 2009

- Objectives: FT3 performed TRN testing of LaRC flash LIDAR, laser altimeter, passive optical sensors, and their associated TRN algorithms in a dynamic Moon-like terrain environment
- Inform the design and development of the ALHAT system for the TRN sensor phase
  - Characterize the Behavior of 3 sensor sets and 6 TRN algorithms
- 7 days testing @ various alts & light conditions
  - 3 shakeout flights over NTS Yucca Lake, Yucca Flats, &DV
  - 3 flights over NTS Yucca Lake and Yucca Flats
  - 4 flights over Death Valley National Park

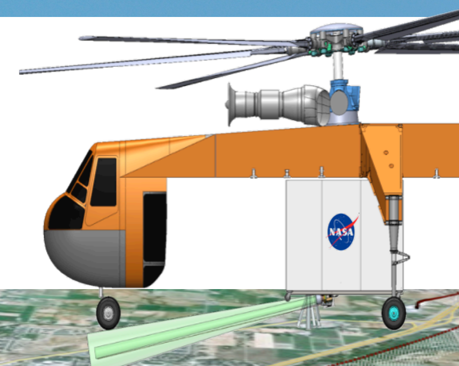


Field Test 3 Camera TRN

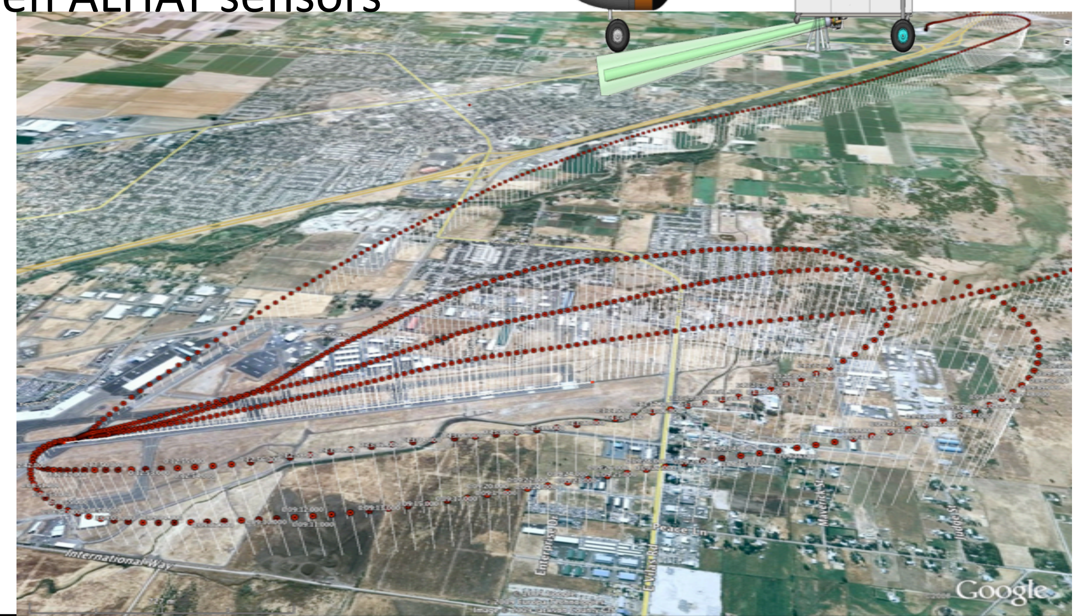


- LIDAR data from all flights was processed.
  - 4 out of 8 flights produced acceptable TRN results
  - problem with other flights were most likely due to errors in trajectory
- Position estimates well below 90m required.
  - mean errors = 10 & 20 m; standard dev. = 7 & 15 m
- Algorithm was capable of eliminating contours that could result in incorrect matches
  - If terrain relief > 25m then there is 95% chance that the position estimate will be within 90m of correct value.
- These results with prior analyses advances LIDAR TRN algorithm to TRL 4
- APLNAV TRN
  - Accuracy results were excellent, Flights with a stable time-base: 50% & 90% spherical errors were < ~3 m & < ~8 m
  - APLNav robust against experienced operational issues (time stamp synch), Flights with a stable time-base: > 97% good fixes

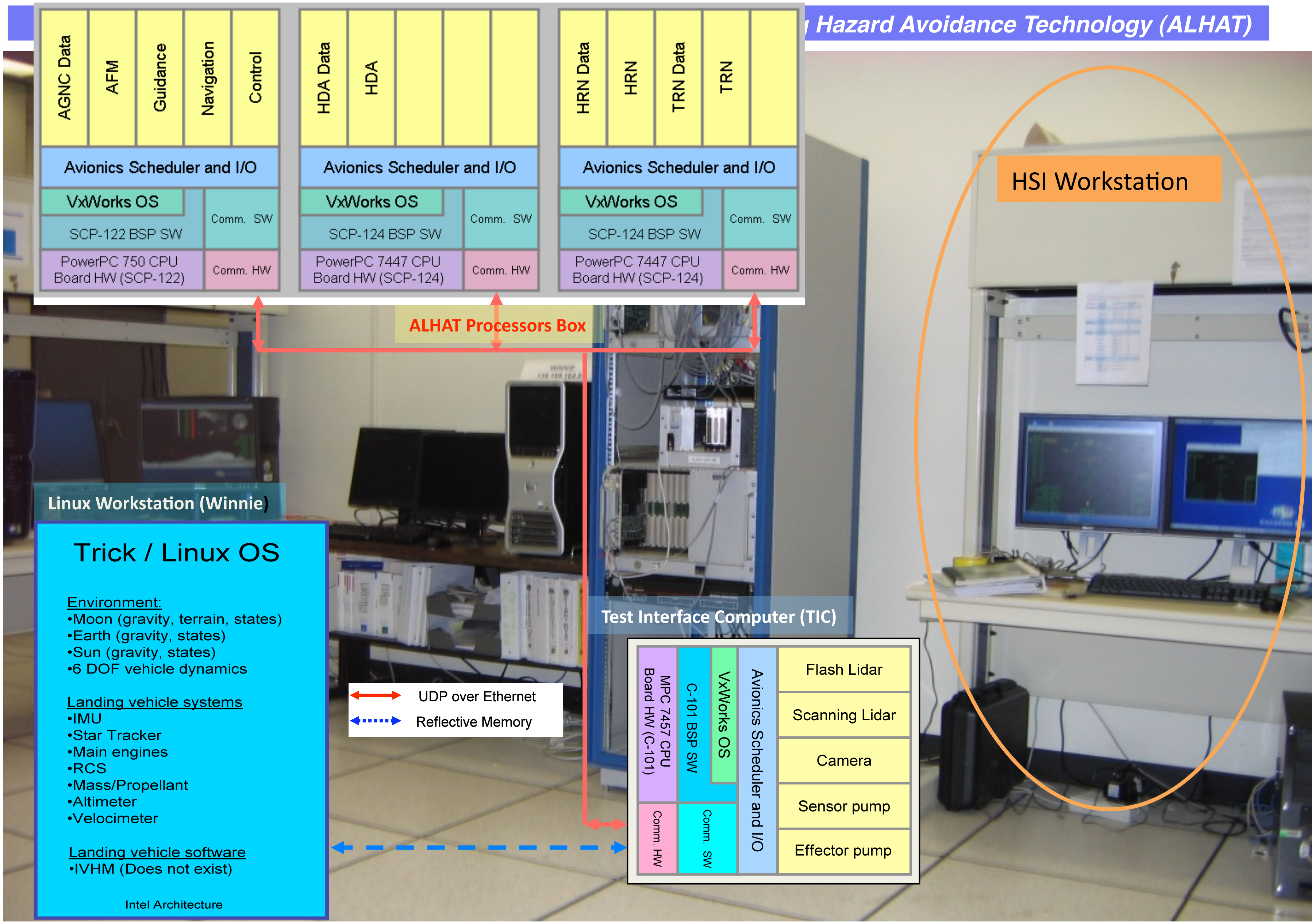
Field Test 4 Objectives – July 2010



- Demonstrate application of integrated real-time GN&C system over range of approach conditions (element of ALHAT system)
- Demonstrate precision pointing of gimbaled Flash LIDAR using real-time GNC data with gimbal manager and TSAR mapper in a dynamic environment
  – CDSU-3, APB, ADNF, TSAR Gimbal Manager, TSAR Exec S/W
- Characterize performance of 2nd gen ALHAT sensors
  – Fixed Optics Flash LIDAR
  – Variable Optics Flash LIDAR
  – Doppler LIDAR
  – Laser Altimeter
- Sensor data collection for algorithm advancement
  – Terrain DEM generation using Mosaic & Super Resolution Methods
  – Hazard Relative Nav Algorithm



HAST Architecture



Future Field Tests – Subject to Change

ALHAT Project has been given increased funding & scope over next three years with mandate to perform closed loop, terrestrial ALHAT field test on Vertical Testbed (VTB) with real-time hazard detection, safe landing aim point selection, & precision landing performed autonomously by onboard system.

- ALHAT anticipates at least four VTB field test campaigns in the time period of FY 2011 through FY 2013.
- Flight demonstrations will reflect a "snapshot" of ALHAT technologies at a given time with an additional layer of maturation for flight packaging and environments
- FT5 (mid FY 2011) - focus on the verification of VTB operational reliability, closed loop GN&C functionality, control authority and stability, and performance
- FT6 (early FY 2012) - integration of the ALHAT Hazard Detection System (HDS) on the VTB along with a Doppler LIDAR sensor and laser altimeter
  - Will perform real-time, onboard HDA and HRN processing
- FT7 (mid/late FY 2012) - closure of the ALHAT loop with the VTB (including AGNC, TSAR, & Sensors) to achieve a fully autonomous lander that demonstrates the following:
  - 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,
  - Performing a precise and controlled touchdown at the selected location
- FT8 (in FY 2013) - stress the capabilities of the ALHAT System demonstrated during FT7 to establish its robustness in a dynamic landing environment

Future ALDACs – Also Preliminary

- ALDAC-3 Phase 1 - integrate and verify the revised ALHAT navigation filter with the ALDAC-2 software
  - Did HRN approach/implementation changes rectify ALDAC-2 issues?
- ALDAC-3 Phase2 – TRN focus, continue updates to models based on FT results, as well as HRN & HDA algorithms/models
  - Evaluate various TRN algorithms/methods in integrated simulation
  - Increase responsibility of AFM and evaluate performance
  - Consider other methodologies such as super resolution
- ALDAC-4 – Further increased AFM functional control & evaluation, HAST utilized for more real-time operation & tests
  - ALHAT POST2 will continue MC assessments using physics-based sensor models, but same algorithms as HAST
- ALDAC-5 & beyond – continued testing of updated, integrated ALHAT systems in HAST & POST2, potentially including Human interaction (HAST only) & Field Test simulation

Beyond Lunar Landings

- Although ALHAT used Lunar Landings for its technology assessments, there is nothing inherent in the ALHAT system that requires a Lunar mission.
- Same algorithm methodology and same (or slightly modified) sensors should work well at other extraterrestrial locations (Mars, asteroid, other planetary moon).
  - Several other technology programs (eg, EDLSA) and proposed non-lunar missions have approached ALHAT Project about using ALHAT system
- Some terrestrial applications may also exist (eg, helicopter pilots landing in brownout conditions)

Summary

- ALHAT project focusing on elements of HDA, HRN, & TRN individually and as integrated system for safe, precision landing
- ALHAT completed 3 field tests and 2 analysis cycles
  - TRL levels of several instruments and algorithms raised
- Future tests and analyses to continue technology development & system validation in these areas
  - VTB free-flying test & HAST real-time analyses planned
- ALHAT usable in landing on other planets, asteroids, or planetary moons – not limited to Lunar missions
- Strong team, good NASA support, in-line with planned technology development approach & focus