Autonomous precision **L**anding and **H**azard **A**voidance **T**echnology

ALHAT GN&C Technologies for Safe and Precise Landing

An Overview of NDL, TRN and HD

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Briefing Outline

- Overview of the NASA ALHAT domain
- Highlights of three ALHAT technologies
  - NDL: Navigation Doppler Lidar
  - TRN: Terrain Relative Navigation
  - HD: Hazard Detection
- Summary Remarks & ALHAT Contacts

Disclaimer – This disclosure of ALHAT technologies does not imply applicability to a particular NF4 mission or represent a resource commitment by any of the participating organizations to support or collaborate in the development of NF4 mission proposals

ALHAT Domain

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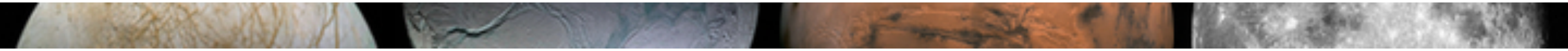

- An EDL domain area chartered by NASA HQ in 2006 that addresses GN&C technologies supporting autonomous, precise, and safe landing for robotic and human-scale vehicles
- ALHAT capabilities are funded through multiple NASA projects and directorates. ALHAT development and testing involves multiple centers and institutions.
- Capabilities include sensors, software and techniques supporting missions/destinations:
  - Where accurate/pinpoint landing relative to a map-based target is critical
  - Where terrain poses significant risks to safe vehicle touch down or payload deployment
  - With a variety of ambient surface illumination conditions (light/shadow/dark)
- The incorporation of ALHAT technologies reduces landing risks and increases surface accessibility and science opportunities for a variety of New Frontiers 4 destinations

Progression of GN&C Landing System Capabilities
Controlled – Precise – Safe

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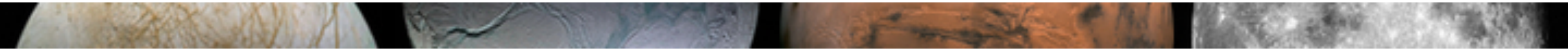
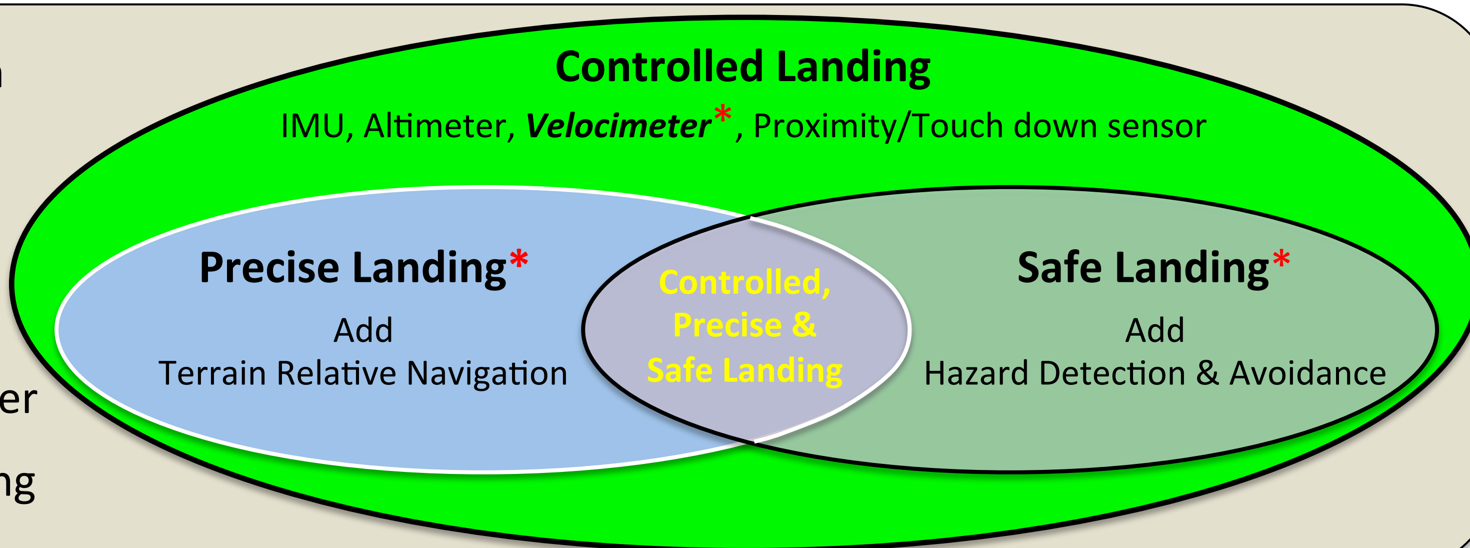


GN&C Subsystem

- Sensors
- Software
- Processing
- Navigation Filter
- Network/Timing



* **Navigation Doppler Lidar (NDL)**

Highly accurate line-of-sight velocity and range measurements

* **Terrain Relative Navigation (TRN)**

Global navigation through onboard correlation of real-time terrain sensing data with *a priori* reconnaissance data

Enables early and efficient maneuvering to minimize landing error and avoid large terrain hazards identified through the analysis of *a priori* reconnaissance data

* **Hazard Detection (HD)**

Real-time, onboard lidar survey to rapidly develop a high-resolution terrain map and identify sub-meter hazards

Identify and rank safe landing sites and perform a hazard avoidance maneuver to the selected safe site

Generic EDL Operations Concept

Mission landing needs and risk posture drive the landing system configuration

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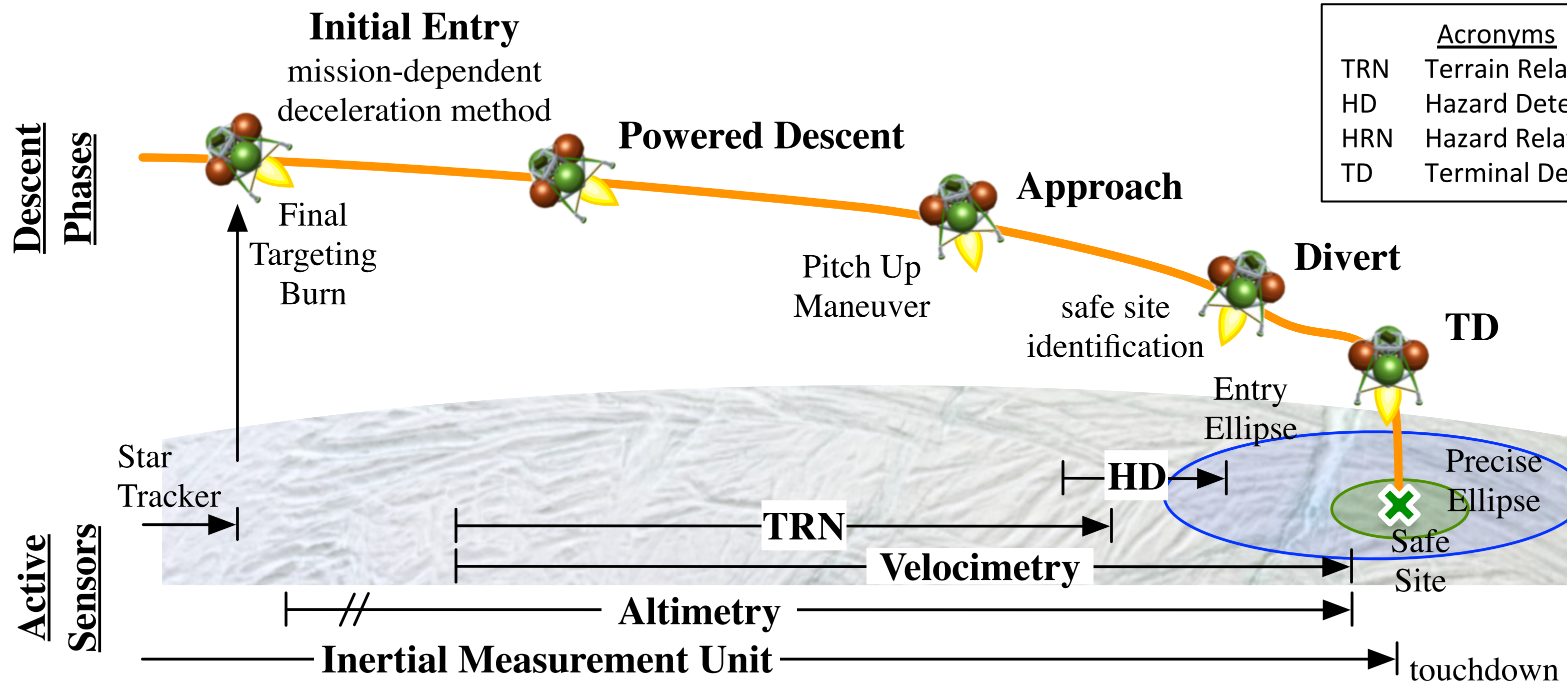

Acronyms	
TRN	Terrain Relative Navigation
HD	Hazard Detection
HRN	Hazard Relative Navigation
TD	Terminal Descent

- Comments on Operations Concept:
  - EDL begins with an accurate inertial state established prior to entry interface
  - TRN is used to update the vehicle global position and enable precision landing relative to a map-based target. TRN utilizes reconnaissance data at set resolution(s) which drives its maximum/minimum range of operation.
  - Surface-relative altitude and velocity measurements improve the accuracy of the vehicle navigation state and facilitate a soft and controlled landing. Highly accurate velocimetry also helps to minimize navigation error growth following TRN.
  - Generate a high resolution terrain map during approach, identify the safe landing site(s), and execute a divert maneuver
  - Dead reckon on the IMU during terminal descent to avoid sensor noise generated from dust kicked up by the rocket plume/surface interaction, or invest in additional sensor development and testing to address the dust environment.

Highlighted ALHAT Technologies

A brief overview of NDL, TRN and HD

Navigation Doppler Lidar (NDL) Overview

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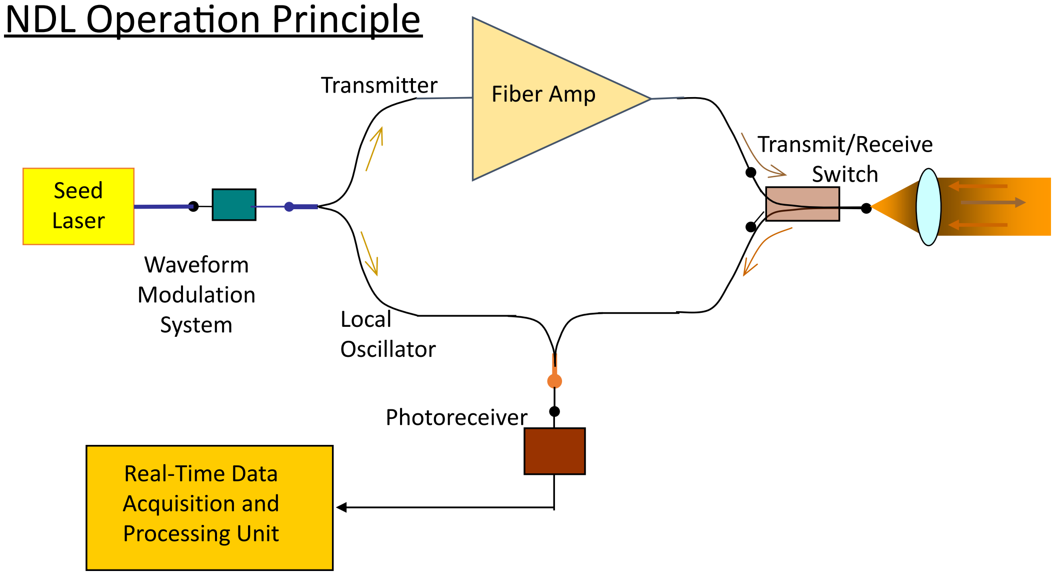
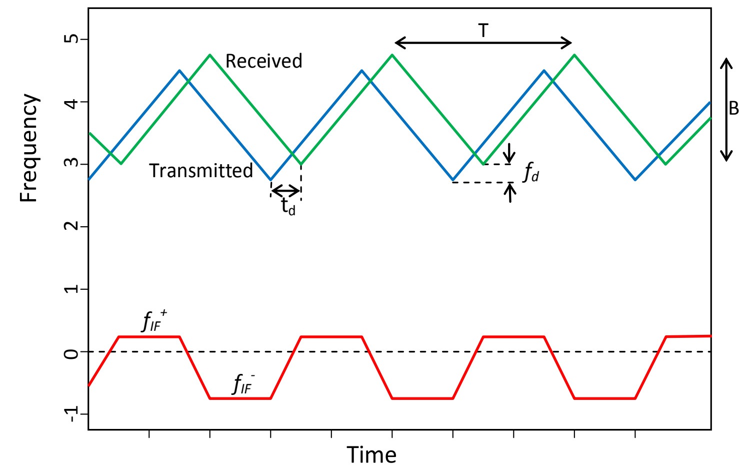
- NDL provides both a direct velocity and a range measurement
  - Directly measures velocity from the Doppler shift of a continuous-wave laser beam
  - Time shift of the custom waveform enables range estimate
- Direct velocity measurement enables GN&C to minimize lateral velocities and tightly control vertical velocity for a controlled soft landing

<u>NDL Operation Principle</u>



- Target velocity causes up and down beat frequencies to separate
- Time delay is a measure of target range



Langley NDL Highlights

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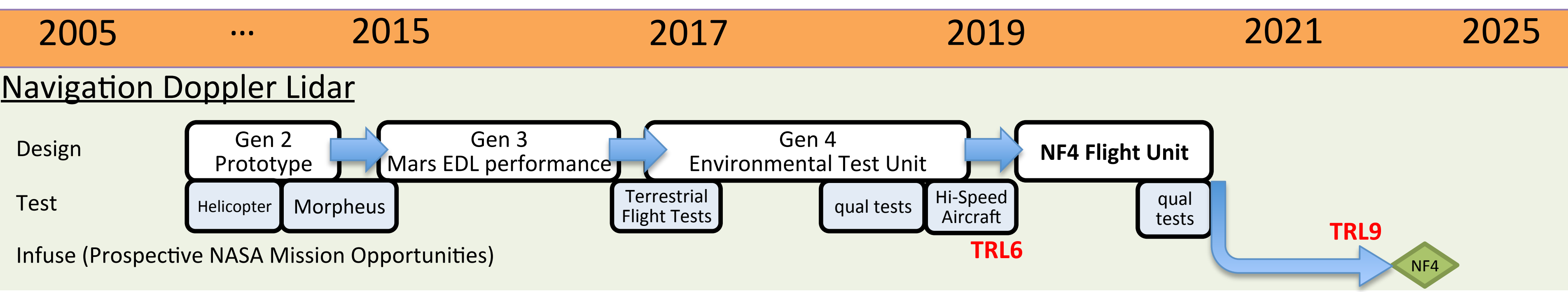
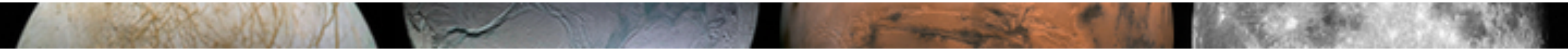
- Gen 3 Environmental Test Unit (ETU) is currently being assembled. Plan is to progress to Gen 4 maturation to TRL6 by 2019 to support NF4 PDR
- NDL includes a custom electronics unit and optical head
  - Performance can be tailored through changes to electronics, laser, and optics
  - Packaging can be tailored for vehicle integration; optics can be separated and/or remote mounted
- Nominal Performance: Line-of-Site (LOS) velocities up to 200 m/s; LOS ranges > 4 km
- Nominal Mass: 10 kg electronics unit and 5 kg optics
- Nominal Power: 90W
- Nominal Dimensions: 29 x 23 x 20 cm (electronics unit) and 34 x 33 x 21 cm (optics)
- Accuracy and Precision (as measured in 2014 Morpheus flight tests of Gen 2 NDL)
  - LOS Velocity: < 2 mm/sec (accuracy) and 1.7 cm/sec (1σ precision)
  - LOS Range: 30 cm (accuracy) and 2.1 m (1σ precision)
  - NDL measurement precision is governed by vehicle vibration

Development Schedule (Overview)

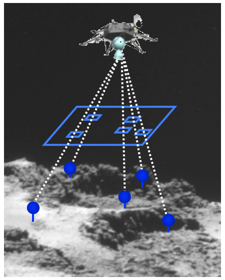


Terrain Relative Navigation (TRN) Overview



- TRN is an enabling technology for precision landing
  - Provides global navigation data to enable GN&C to plan efficient maneuvers for accurate/pinpoint landing
  - Improves probability of landing success by enabling avoidance of large terrain hazards identified (on the ground) through analysis of *a priori* reconnaissance imagery
- Extensive terrestrial TRN applications since the 1970's (e.g., TERCOM, DSMAC)
- Landing position error can be reduced to tens of meters
  - Requires reconnaissance map with fine resolution
  - Requires lander maneuverability to execute divert
  - improves access to targets of scientific interest located in proximity to hazardous terrain
- For missions to new destinations without *a priori* reconnaissance maps (or low resolution maps)
  - Map data can be collected using onboard instruments while orbiting the body (e.g., Europa, Enceladus). Map is then generated and uploaded to spacecraft
  - Stored map can then be employed for TRN and to support precision landing
- Space qualified cameras and optics are commercially available – low size, weight, and power (SWaP)

Passive Optical TRN



Match distinctive image features to geo-registered map

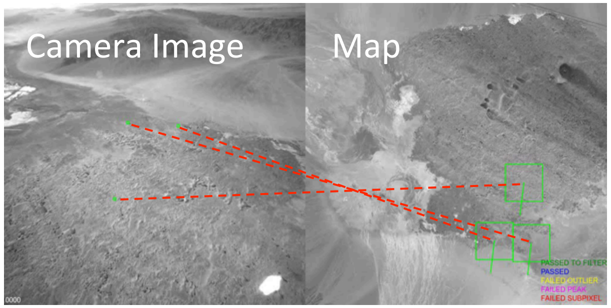


Image Source: JPL LVS helicopter field test, Death Valley, Feb 2014

JPL TRN Highlights: Lander Vision System (LVS)

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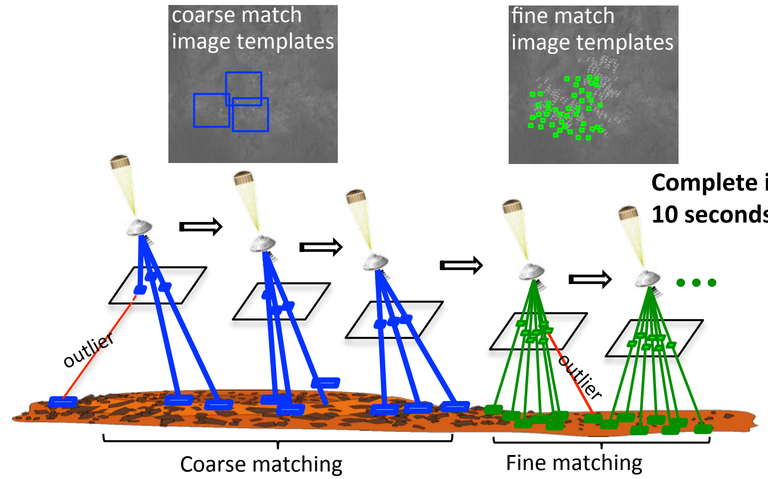
- LVS TRN is baselined on Mars 2020
  - LVS technology will be TRL 6 by NF4 PDR
  - LVS will be space qualified prior to NF4 launch
- LVS utilizes IMU data, a passive optical camera (LCAM), a dedicated TRN processor (VCE), and a stored reconnaissance map
- LVS estimates spacecraft global position based on comparison of sensed images to *a priori* reconnaissance maps stored onboard the spacecraft
- LVS conducts coarse feature matching to remove initial position uncertainty, which can be several kilometers following Mars entry
- LVS then transitions to fine feature matching to develop high precision position estimates



Current Best Estimates

Mass	5.4kg
Power	47W
Volume	9 x 28 x 20cm (VCE) 6 x 6 x 10cm (LCAM)

APL TRN Highlights: APLNav

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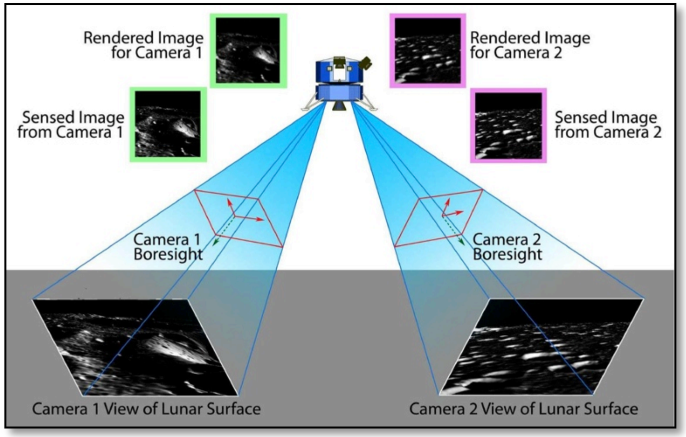
- APLNav is baselined on the Resource Prospector mission
- APLNav utilizes IMU data, one or more passive optical cameras, and the primary spacecraft processor
- At higher altitudes, position (and optionally, attitude) estimates are generated by comparing sensed images to rendered images from *a priori* onboard maps
- During terminal descent, sequential images are compared to provide velocity estimates without the need for an *a priori* map (requires an independent range measurement for scale)



- APLNav is designed to enable execution in parallel with GN&C code on a flight processor comparable to a 133 MHz RAD 750. Performance optimization is ongoing.
  - Benchmark tests on RAD750 analog performed to estimate performance using four 64x64 pixel image patches
    - 0.63 seconds for position estimation / 6 MB statically allocated memory
    - 1.54 seconds for velocity estimate / 12 MB statically allocated memory
- APLNav can also be executed on a dedicated processor on the order of an ~80 MHz Leon 3 processor
  - ~4 W and 0.5 kg for additional processor card in existing avionics
  - ~6W and 1.0 - 1.5 kg for a stand alone avionics box
- APLNav algorithm can utilize a variety of commercial wide angle cameras (~30-60 deg FOV)
  - Examples include the Malin ECAM (OSIRIS-Rex), ROLIS (Philae), and Mars MER Cam
  - Malin ECAM is 256 g / 2.5 W (peak) per optical head and 1.1 kg / 13.5 W (peak) for electronics

Hazard Detection (HD) Overview – Safe Landing –

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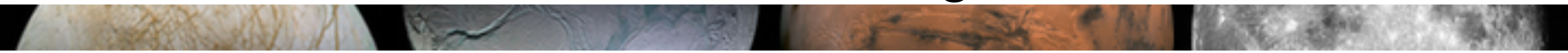

- Onboard HD expands the range of landing targets that are viable for science missions
- Uses real-time terrain sensing onboard the lander to identify sites free of surface roughness and slope hazards that are undetectable in the orbital reconnaissance data
- Enables GN&C to retarget & execute a hazard avoidance maneuver to land at the selected safe site
- ALHAT HD prototype demonstrated in closed loop flight on Morpheus flights in 2014 used gimbaled 3D flash lidar (128x128 focal plane array) for real-time terrain imaging. Scanning lidar is also an option.
  - Lidar sensor generates a range map with 7 cm / 1σ precision from up to ~1 km slant range
  - ~120 image frames collected, assembled into a 60x60 meter map with 10 cm GSD, and processed in ~13.5 sec
  - Active lidar-based HD system functions independent of the ambient lighting conditions at the target area
- HD algorithm takes into account the vehicle hazard tolerances (allowable terrain slopes and roughness), vehicle geometry (footpad locations and sizes), landing orientation, and sensor characteristics (measurement uncertainty)

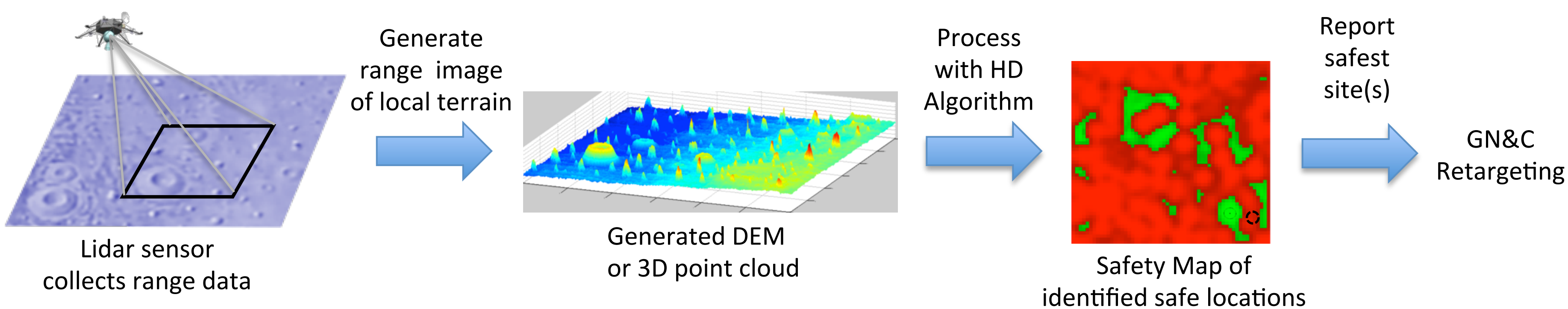

Image Sources: JPL

JPL HD Highlights

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- A prototype ALHAT HD system for large landers was terrestrially flight tested in 2014 on Morpheus
- Smaller, simplified prototype concepts have been developed for small, robotic-scale landers
  - Utilize fixed 3D lidar sensor (flash or scanning) and a dedicated current generation flight processor (e.g., RAD750 or LEON-3)
  - Can identify safe landing sites within 5 seconds
  - Concepts to date have been focused on lunar & Mars landing missions
- Autonomous, real-time HD is a new technology and additional development, integration, and testing remains to reach TRL 6 by 2019 to support the NF4 PDR
- Infusion of HD into a NF4 mission will require involvement between the proposal team and NASA/JPL to scope design applicability and feasibility to the mission concept

Summary Remarks
and
ALHAT Contacts

Summary Remarks

- The ALHAT domain includes a diverse suite of NASA technologies for autonomous, precise, and safe landing that enable new exploration destinations and expand the feasible range of landing sites
- Mission landing needs and risk posture drive the landing system configuration
- Technologies within the ALHAT domain have been developed and matured to their current state through ten years of investments across multiple NASA directorates as well as collaboration among multiple centers and organizations
  – FY2017 COBALT flight tests will demonstrate integrated LVS and NDL operation
- Gen 3 NDL sensor is currently being assembled to support the COBALT flights
- The NDL has a development path to TRL 6 by FY2019 to support the NF4 PDR
- TRN will reach TRL 6 in FY2019. TRN is baselined on both Mars 2020 and the 2022 Resource Prospector mission
- Prototype HD systems for robotic landers have been developed, but will require additional development to reach TRL 6 by FY2019 to support the NF4 PDR
- ALHAT NDL, TRN, and HD technologies were submitted for NF4 risk bye and financial incentives. The available incentives, if any, will be defined in the NF4 AO.

ALHAT Contacts

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