PL&HA
Precision Landing and Hazard Avoidance

SPLICE
Safe and Precise Landing – Integrated Capabilities Evolution

STMD-GCD / HEOMD-AES / STMD-FO

PL&HA and SPLICE Overview

Project Overview and ties into the NASA PL&HA Domain Implementation Plan

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Presentation Agenda

- PL&HA Domain and SPLICE Overview
- SPLICE Elements
- PL&HA Domain and SPLICE Project Summary

PL&HA Domain and SPLICE Project Overview

PL&HA

What is the NASA PL&HA domain?

SPLICE

- **Agency development, testing and infusion of GN&C technologies for controlled, precise and safe landing**
- Investments have come from **multiple HQ Directorates** (HEO, STMD, SMD) and included **cross-center collaborations** and many past & present projects:
  - SPLICE (Safe & Precise Landing - Integrated Capabilities Evolution)
  - ALHAT (Autonomous precision Landing and Hazard Avoidance Technology)
  - COBALT (CoOperative Blending of Autonomous Landing Technologies)
  - LVS (Lander Vision System)
  - Lander Technologies (LT)
  - ILS (Intelligent Landing System)
- Includes sensors, algorithms, avionics, software & techniques for missions (**robotic or human**) with various Concepts of Operation (ConOps) and various terrain illumination (light/shadow/dark)

Johnson Space Center
Houston, Texas

Langley Research Center
Hampton, Virginia

Jet Propulsion Laboratory
California Institute of Technology

Goddard Spaceflight Center
Greenbelt, Maryland

Marshall Spaceflight Center
Huntsville, Alabama

Armstrong Flight Research Center
Edwards, California

The Motivation for Precision Landing and Hazard Avoidance (PL&HA) Technology

Objective

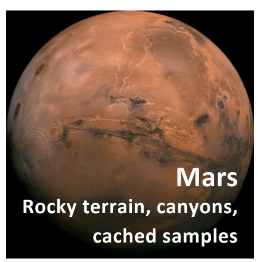
- Enable landing at locations that pose significant risk to vehicle touchdown or payload deployment (including near pre-positioned surface assets)
- Technology has been deemed critical in NASA and NRC Space Technology Roadmaps and architecture studies for future human and robotic missions

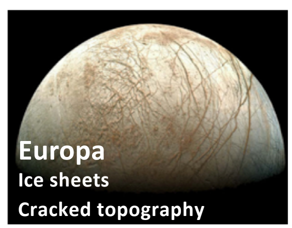
Goal

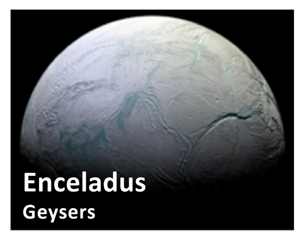
- Develop multi-mission technologies that become part of the standard suite of GN&C capabilities

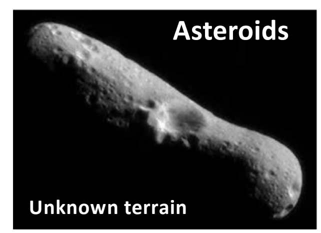
Approach

- Develop and maintain a PL&HA knowledge base that captures robotic and human mission needs
- Prioritize technologies that promote multiple robotic missions and align to human mission needs
- Maintain a multi-directorate development and investment strategy and leverage multi-center partnerships

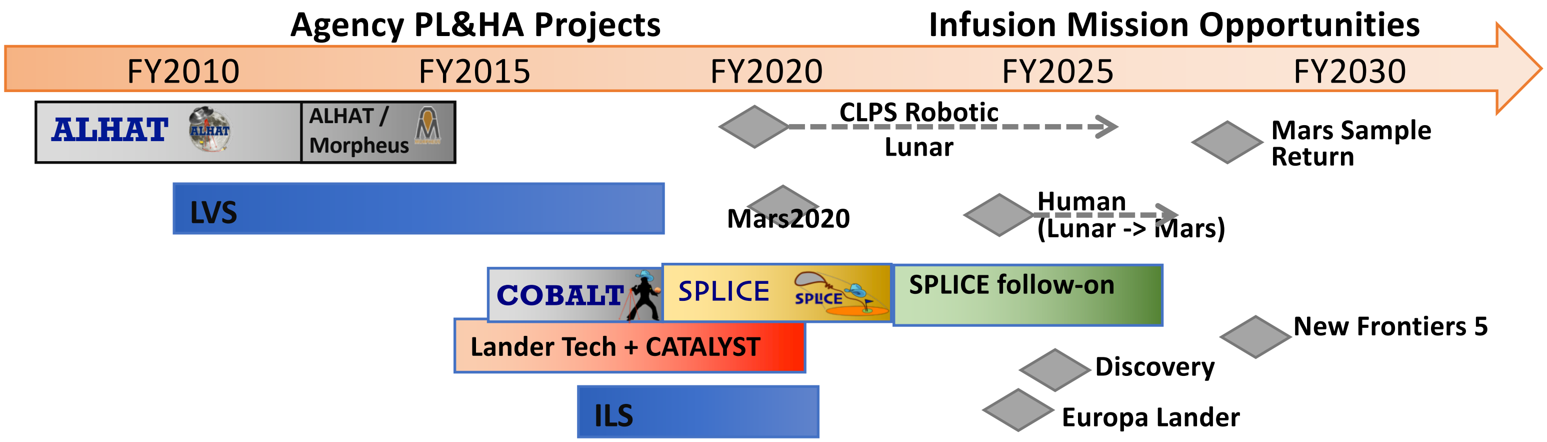




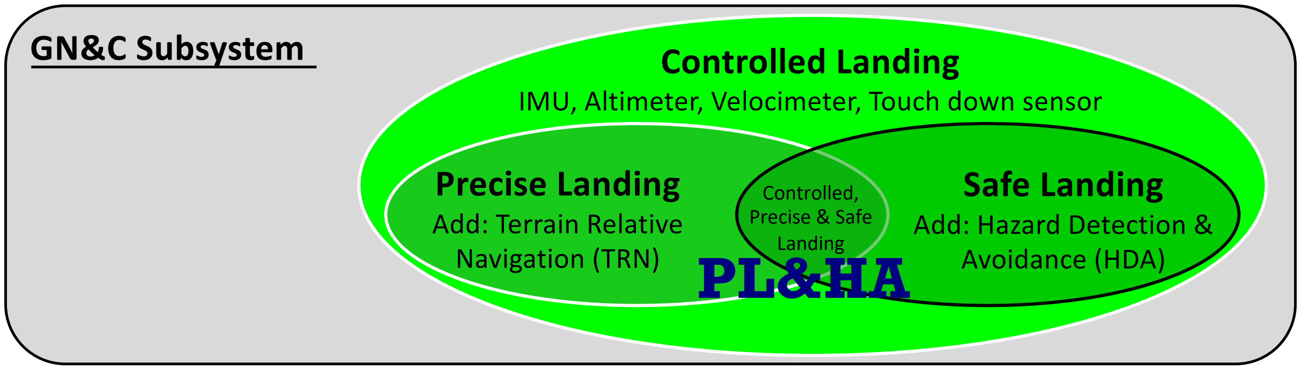




Infusion Strategy



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



Controlled Landing

- Minimize vertical descent rate and lateral velocity to ensure a soft (or controlled) touchdown
- No knowledge of global position – "blind" landing

Precise landing – Terrain Relative Navigation (TRN)

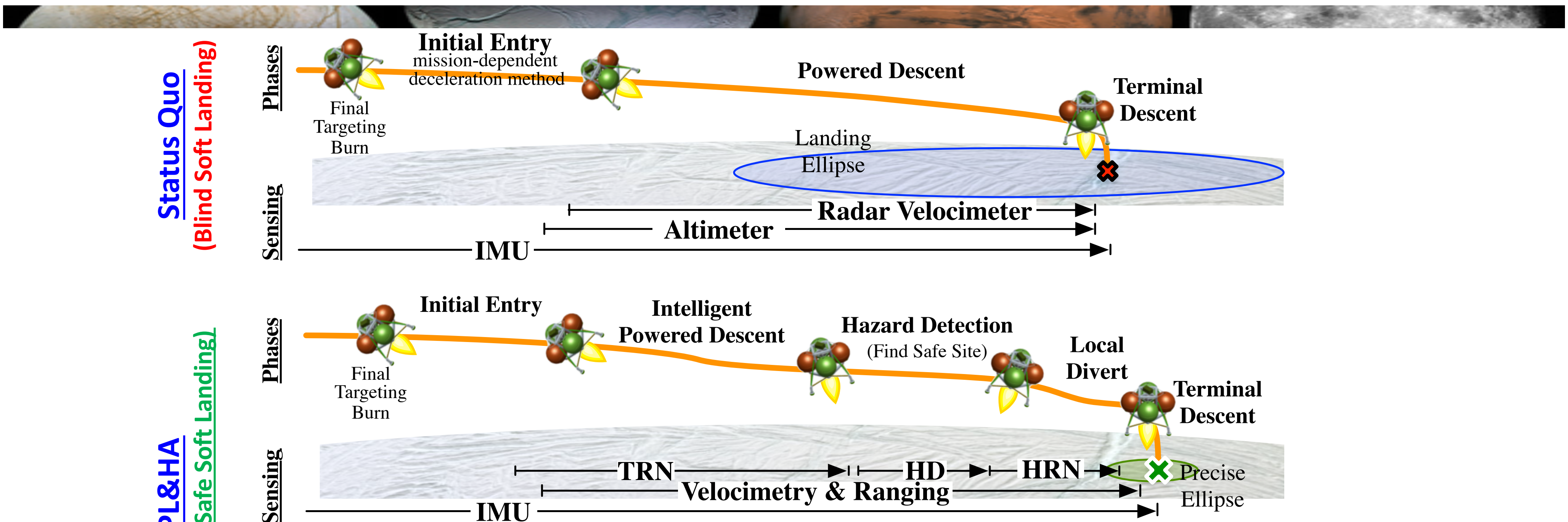
- Global navigation through onboard matching of real-time terrain sensing data with *a priori* reconnaissance data
- Enables efficient maneuvering to minimize landing error and avoid large hazards identified in *a priori* analyses

Safe Landing – Hazard Detection & Avoidance (HDA)

- Real-time terrain sensing to identify sites safe from lander-sized hazards that are undetectable in *a priori* data
- Enables a hazard avoidance maneuver to the identified safe site
- Can be leveraged for subsequent Hazard Relative Navigation (HRN) – similar to TRN

GN&C for Landing: Status Quo Vs. PL&HA

Mission landing needs & risk posture define which PL&HA capabilities to use



TRN: global position knowledge
Minimizes landing ellipse & avoids large hazards seen in reconnaissance maps

HD & HRN: local terrain knowledge
avoid small hazards & minimize local landing error

Velocimetry & Ranging: precise soft landing
Significantly improves navigation precision

Advanced GN&C Algorithms
provide precise state knowledge and intelligent maneuvering commands

TRN	Terrain Relative Navigation
HD	Hazard Detection
HRN	Hazard Relative Navigation

Overview of NASA SPLICE Project
(FY2018-FY2020)

- Multi-Directorate, Multi-Center PL&HA project
  - Centers: JSC, LaRC, GSFC, JPL, AFRC
  - Directorates: STMD-GCD, STMD-FO, SMD-PSD, HEOMD-AES
- Project Components (Elements)
  - DLC: Develop an **HPSC-surrogate DLC (Descent & Landing Computer) to TRL 5** for future suborbital flight tests and spaceflight infusion missions
  - NDL: Implement an **NDL (Navigation Doppler Lidar) Engineering Test Unit (ETU) & Achieve TRL6** in FY2019
  - HD: Design, develop, and test a new **HD (Hazard Detection) Lidar to TRL 5** that has relevance to future robotic & human missions
  - HWIL Sim/SW: Evolve **HWIL sim/test capabilities and PL&HA flight software** to foster PL&HA infusion into NASA & US commercial missions
  - ConOps: Develop a **multi-mission PL&HA requirements matrix** for relevant robotic science & human exploration destinations (to drive PL&HA infusion & investment)
  - Field Test: conduct NDL environmental tests, validate NDL & HD Lidar performance on ground and/or airborne vehicles, and perform **suborbital rocket flight tests of integrated SPLICE technologies**

Portfolio of NASA PL&HA Technologies

PL&HA

SPLICE

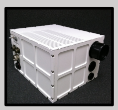
Controlled (Soft) Landing
Velocity and/or Range Sensing

SPLICE →

HEO/STMD/SMD

Navigation Doppler Lidar (NDL) TRL 5+ (6 in FY19)
Line-of-site velocity of 200 m/s (±1.7-cm/sec, 1σ)
Line-of-site range of 4+ km (±2.2m, 1σ)
dev & test in ALHAT/Morpheus, COBALT, & SPLICE

HEO/STMD



Long-range Laser Altimeter (LAlt) TRL 4
Range in vacuum, 50+ km (5 cm, 1σ)
dev & tested in ALHAT/Morpheus

SMD/ other

Optical Velocimetry (many in development) TRL 3+
Estimates from image-based feature tracking and optical flow

Precise Landing
Terrain Relative Navigation (TRN)

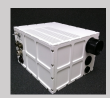
SMD/STMD/other

Passive-Optical/Camera-Based
(requires illuminated terrain: applicable to most missions)

- **JPL Lander Vision System** (LVS): camera + IMU + dedicated computing to be TRL 9 with Mars2020
- **TRN solutions also available from APL, Draper & elsewhere** in dev for multiple mission concepts
- **JPL Intelligent Lander System** (ILS) in dev for Europa Lander concept

← SPLICE

HEO/STMD



Active/Lidar-based TRL 3-4
(dark/shadowed or illuminated terrain)
dev & tested in ALHAT

PL&HA Computing

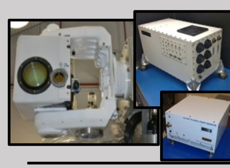
SPLICE →

STMD

Descent & Landing Computer (DLC)
HPSC (High Performance Spaceflight Computing) multicore A53 (extendable) + FPGAs (extendable) + PL&HA sensor interfaces
(in dev & test within SPLICE) TRL 3 (5 in FY2020)

Safe Landing
Hazard Detection (HD) and Hazard Relative Nav (HRN)

HEO/STMD



Hazard Detection System (HDS) prototype TRL 4
flash lidar + gimbal + dedicated IMU + dedicated computing
Range, 1 km (±8cm, 1σ). Generates 100mX100m map & safe landing sites within 10-12 sec dev & tested in ALHAT/Morpheus

STMD/ SMD

Hazard Detection Lidar (HDL) in dev & test within SPLICE TRL 4 (5 in FY2020) uses many flight heritage parts
Scan array lidar + FPGA. Provides long-range altimetry and rapid medium- & short-range high-resolution terrain maps

← SPLICE

SMD

JPL Intelligent Lander System (ILS) in dev for Europa Lander concept

PL&HA + HPSC Infusion Strategy

PL&HA

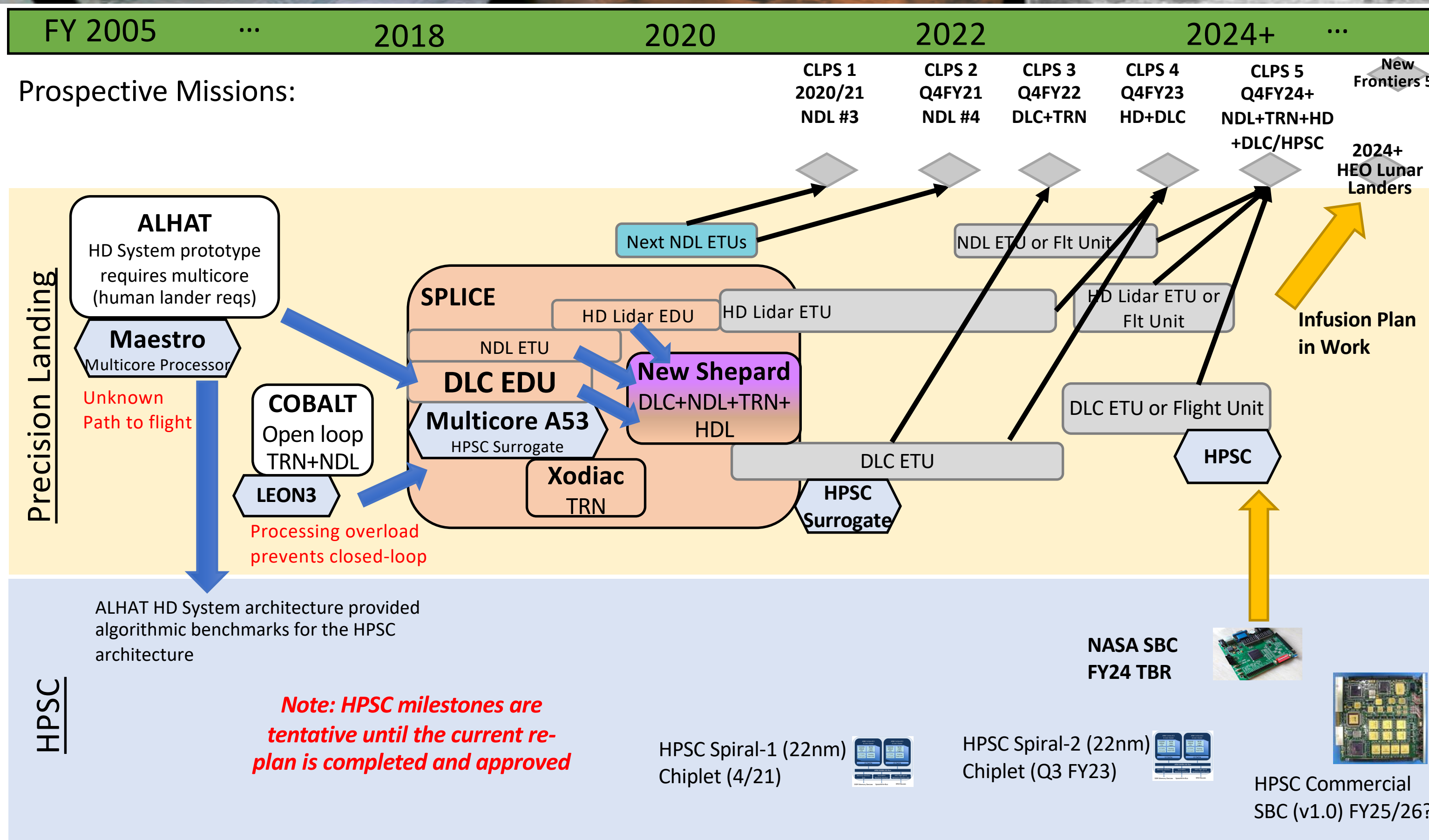
SPLICE

Legend

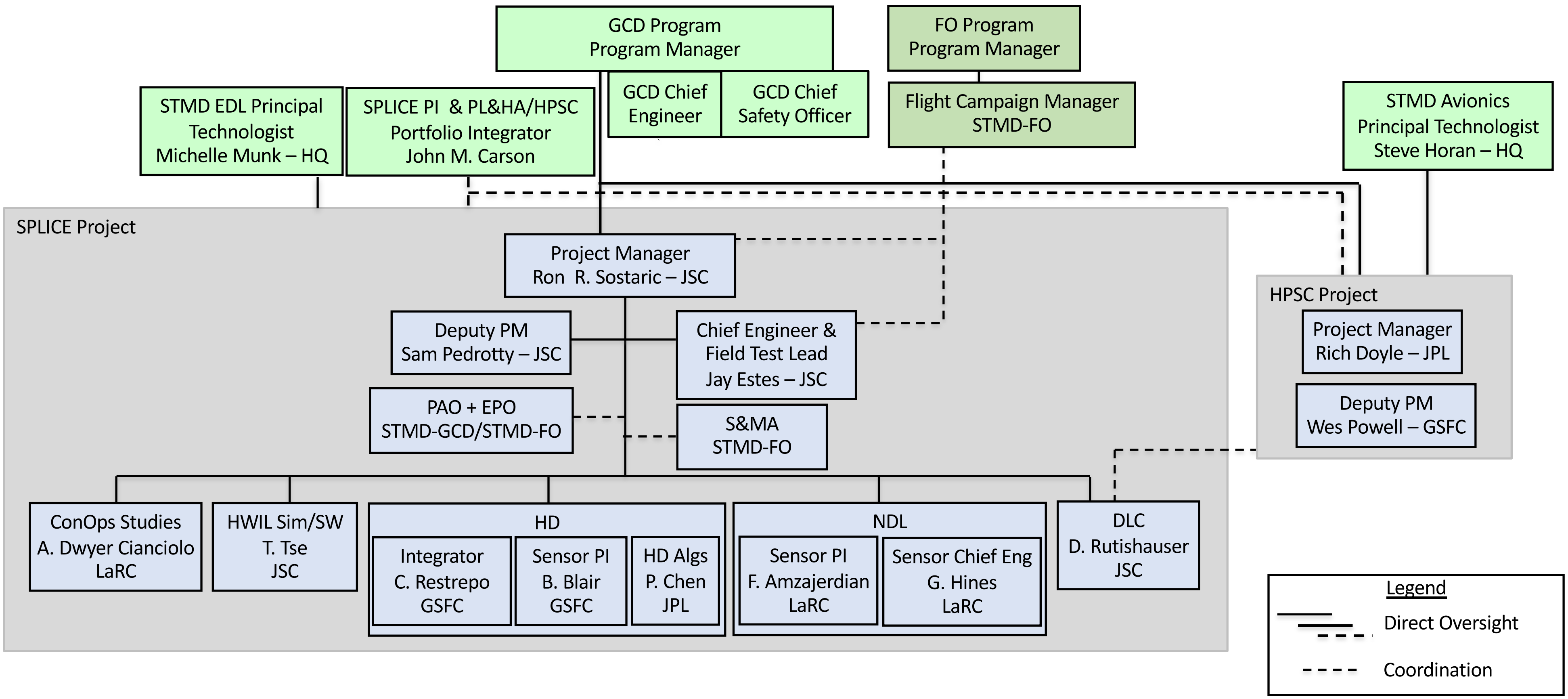
- Past Project
- SPLICE
- Processor
- Blue Origin TP
- SMD NPLP
- Future Activity

Acronyms

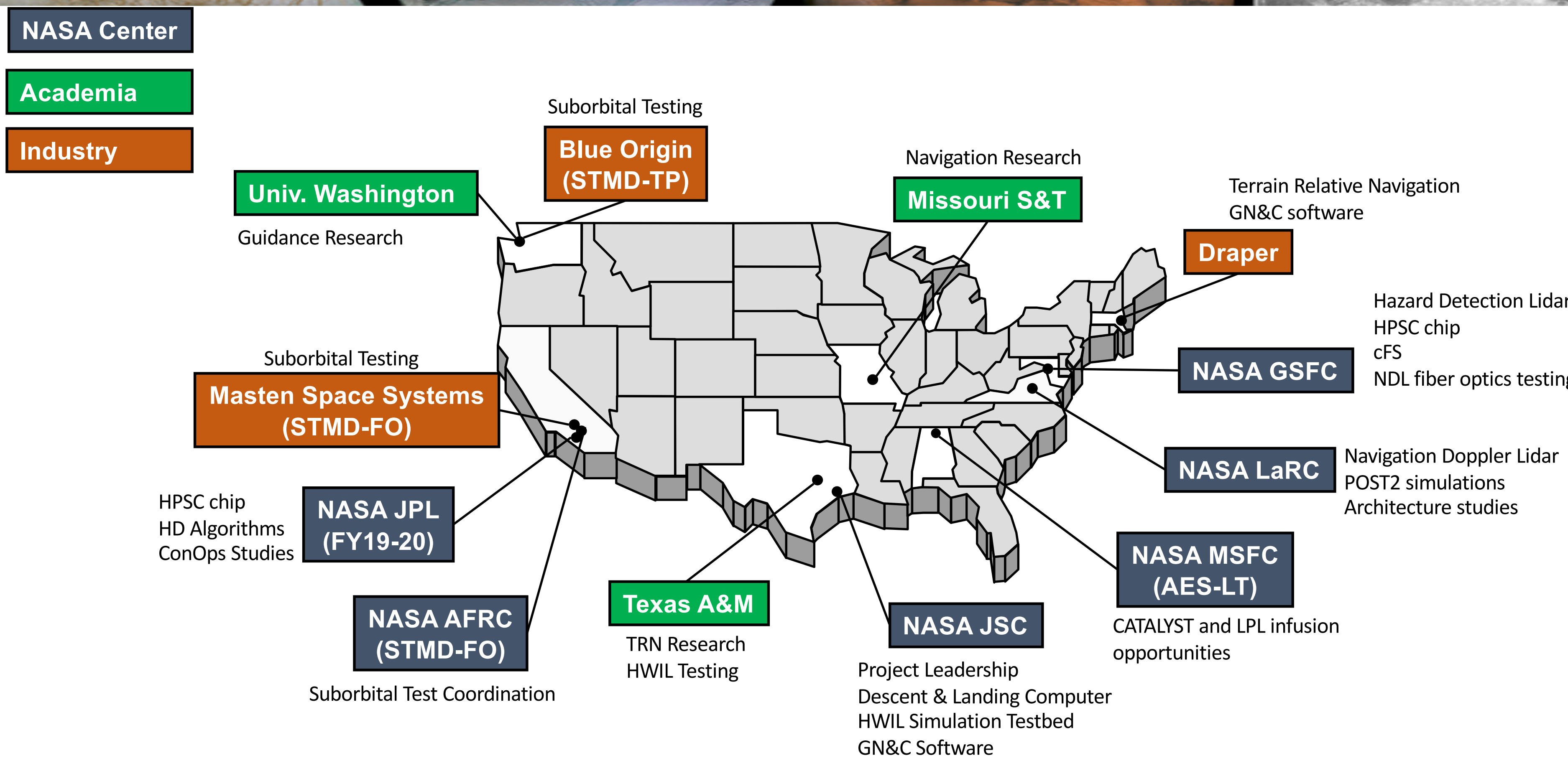
SPLICE	Safe & Precise Landing – Integrated Capabilities Evolution
ALHAT	Autonomous precision Landing & Hazard Avoidance Technology
cFS/E	core Flight Software/Executive
DLC	Descent & Landing Computer
EDU	Engineering Development Unit
ETU	Engineering Test Unit
HD	Hazard Detection
NDL	Navigation Doppler Lidar
TRN	Terrain Relative Navigation
SBC	Single Board Computer
CLPS	Commercial Lunar Payload Services
HEO	Human Exploration and Operations (Mission Directorate)
TDM	Technology Demonstration Mission



SPLICE Organizational Chart



SPLICE Contributing Organizations



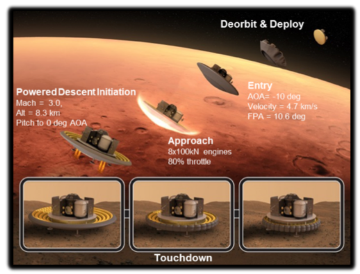
SPLICE Project Elements

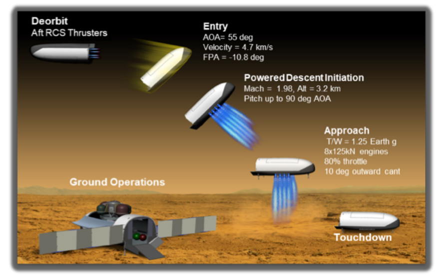
ConOps Studies

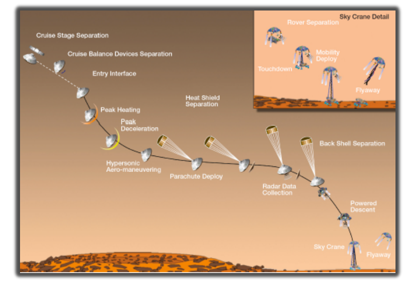
(Langley POST2 and JSC LinCov)

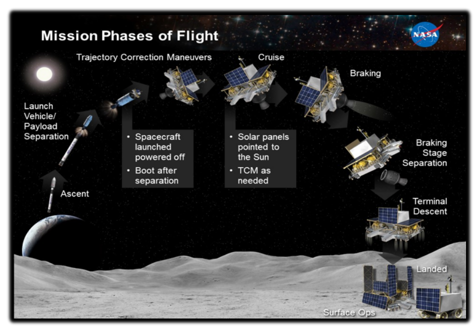
Goal: Identify the GN&C/PL&HA technology investments that are of maximum benefit to future missions

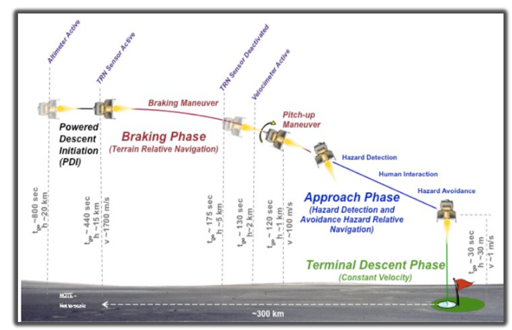
1. **Define reference trajectories and dispersions for all con ops**
2. **Define top level requirements (Trajectory, Navigation, and Sensor)**
3. **Determine approach to evaluate the various sensor suites**
4. **Perform sensor evaluation**
5. **Determine if any sensors/suites are common to all con ops**







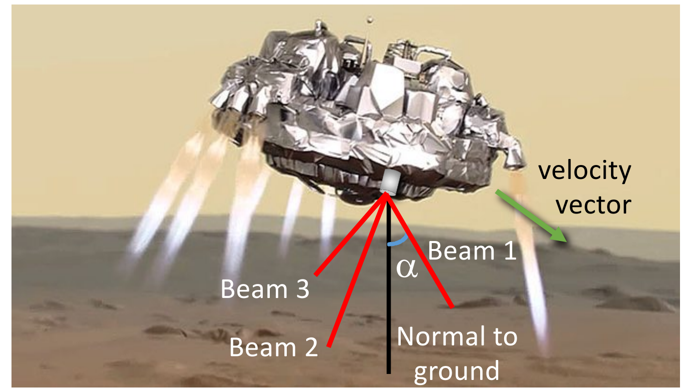




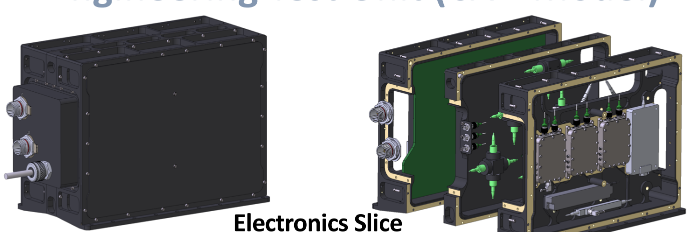
Navigation Doppler Lidar

(NASA LaRC)

- Engineering Testing Unit (ETU) that will be environmentally, functionally, and dynamically tested to TRL 6 in CY2019
- NDL is a laser-based sensor that provides vector velocity and range measurements for use in precise navigation for landing
- Sensor measures velocity and range along three different laser beams
- Anticipate 7.3km per-beam range performance for Moon



Engineering Test Unit (CAD Model)



Conductively Cooled
Chassis design mitigates EMI
Space and space-equivalent components

Chassis	< 10 kg (13.8”x9.7”x6.2”)
Optical Head	< 5 kg (2” lenses)
Power	~85W

GEN3 NDL
(pre-ETU)

Parameter	Value
Maximum LOS Velocity	200 m/sec
Maximum LOS Range	~4 km (Earth)[1]
LOS Velocity Error[2]	1.7 cm/sec
LOS Range Error[2]	2.2 m
Data Rate	20 Hz

1. **Anticipate 7.3 km Moon** and 5.5 km Mars
2. Measured with GEN2 on Morpheus -- Errors dominated by vehicle vibration and angular motion

Hazard Detection Lidar

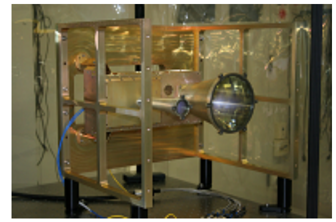
(NASA GSFC)

Design Overview of HD Lidar, LELLI (Lunar and Exploration Lander Lidar Imager)

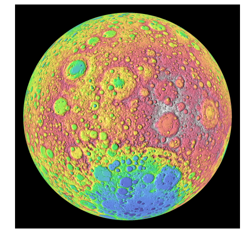
- Design is a hybrid scanning-imaging lidar consisting of an optical head (Risley-prism scanner mechanism) fiber coupled to an electronics box/vault (detectors and laser)
- Leverages numerous GSFC geodetic-quality Lidar designs and flight builds
  - ICESat-1, MOLA, LOLA, MLA, SLA and the recently launched ICESAT-2 and GEDI
  - Produced wide-swath topographic images with ~cm precision from a high-altitude (10-20km)
- Major components have flight heritage, sub-cm ranging performance, high radiation tolerance, and compatibility with a range of landing approaches

Performance Goals

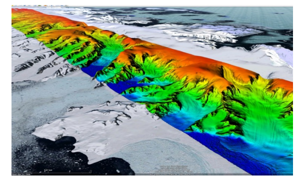
- Rapid 3-D landing site imaging and Digital Element Map (DEM) generation
  - Surface Imaging and DEM produced in 2 seconds with centimeter-level precision
  - Nominal operational altitude of 500 m (Imaging from longer ranges possible with lower resolution)
  - Sampling pattern is robust to motion and attitude changes during imaging
  - DEM has 4 Mpixels over a 100m diameter area with 5-cm spatial resolution and 4X oversampling (8 M pixels/sec). Meets range precision without averaging, has oversampling for robustness to motion, high sampling reliability.
- Single beam altimetry starting at 10 km altitude with < 10 cm range precision. Longer ranges possible.



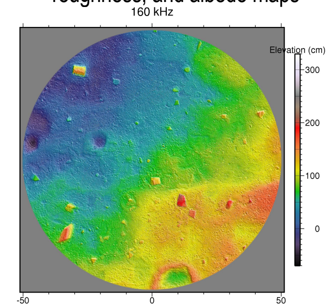
Lunar Orbiter Laser Altimeter (LOLA), on LRO



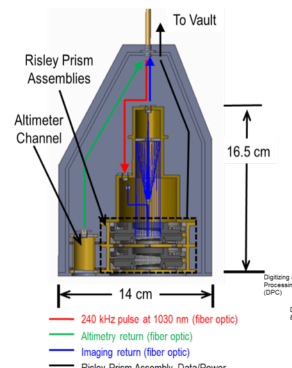
LOLA Lunar elevation, roughness, and albedo maps

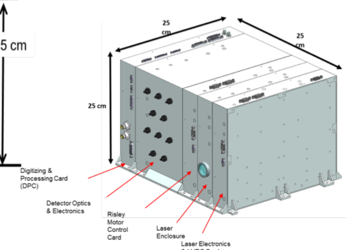


Antarctic Peninsula mapped with LVIS from 12 km altitude



Simulated HDL performance - 2k x 2k scan of asteroid surface





HDL LELLI Design - GSFC

Descent & Landing Computer

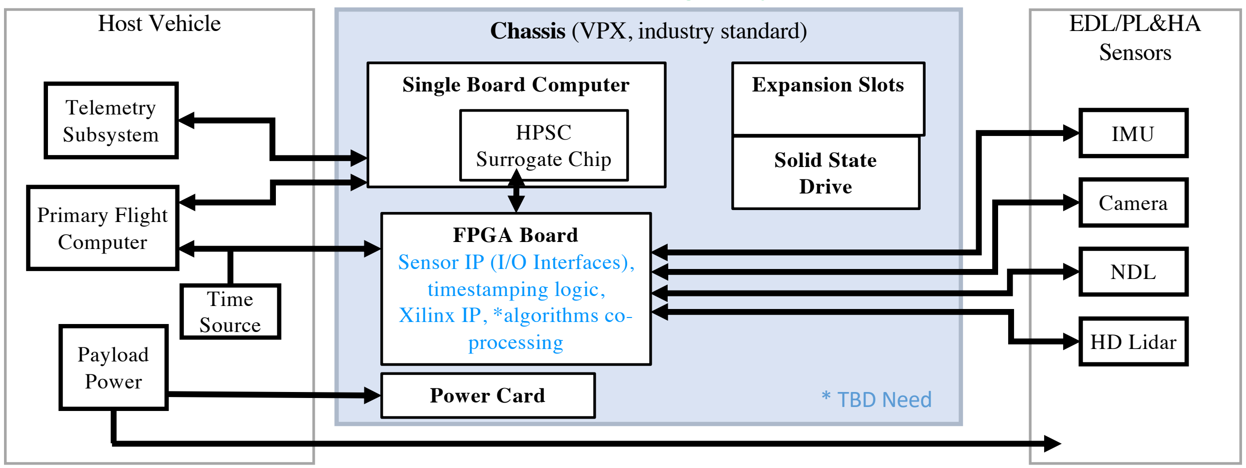
(NASA JSC with HPSC team at JPL and GSFC)

PL&HA

SPLICE

- SPLICE developing an EDU flight computer for PL&HA and GN&C that leverages a surrogate for the multicore High Performance Spaceflight Computing (HPSC) processor
- SPLICE will take DLC to TRL 5 with flight infusion is targeted for 2022/23

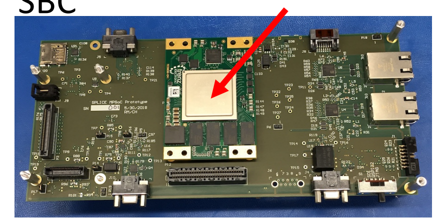
Descent and Landing Computer



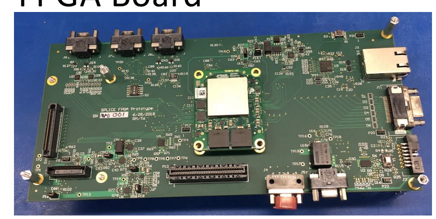
JSC-developed DLC boards

SBC

HPSC-surrogate chip



FPGA Board



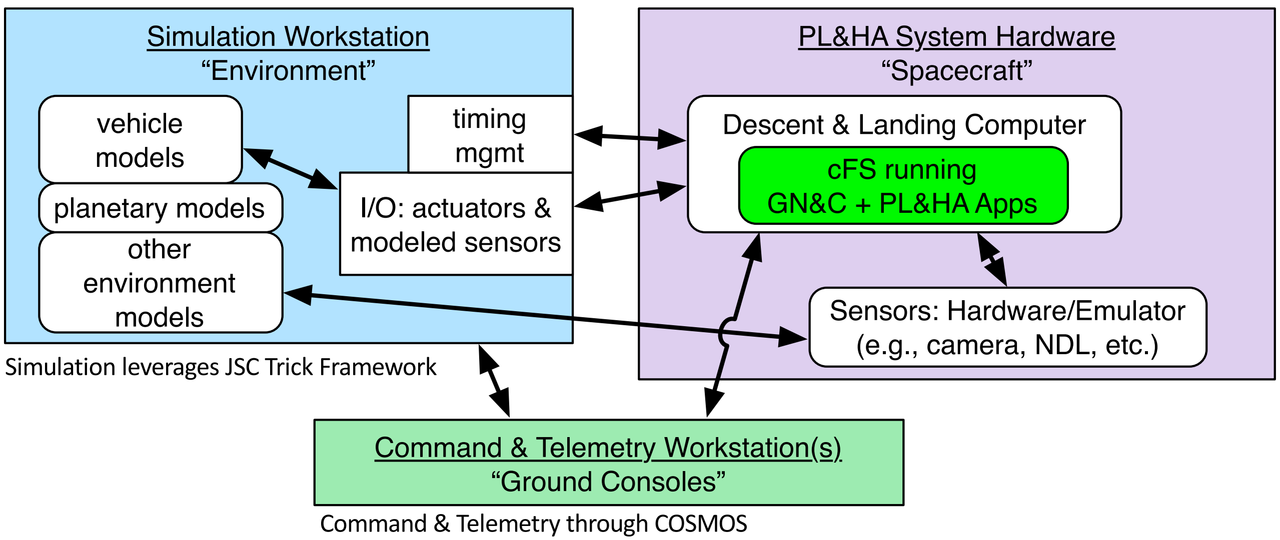
SPLICE DLC Engineering Development Unit components

- VPX chassis
- HSPC-surrogate Single Board Computer (SBC)
- Xilinx FPGA board
- Power board
- Solid state drive board
- Expansion slot for additional FPGA or HPSC-surrogate SBC

DLC Engineering Test Unit (spaceflight path)

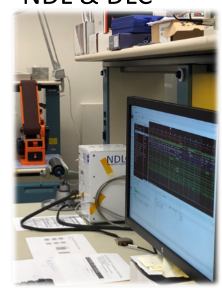
- An industry standard for space (VPX/spaceVPX)
- Path to space (HPSC SBC) or robustified surrogate
- Path to space (Kintex) or existing space (Virtex5)
- Multiple for space in VPX form factor
- Multiple for space in VPX form factor

SPLICE HWIL Simulation Testbed
(NASA JSC)

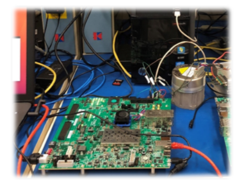


HWIL Integrated Components

NDL & DLC



Simulation Workstation & DLC

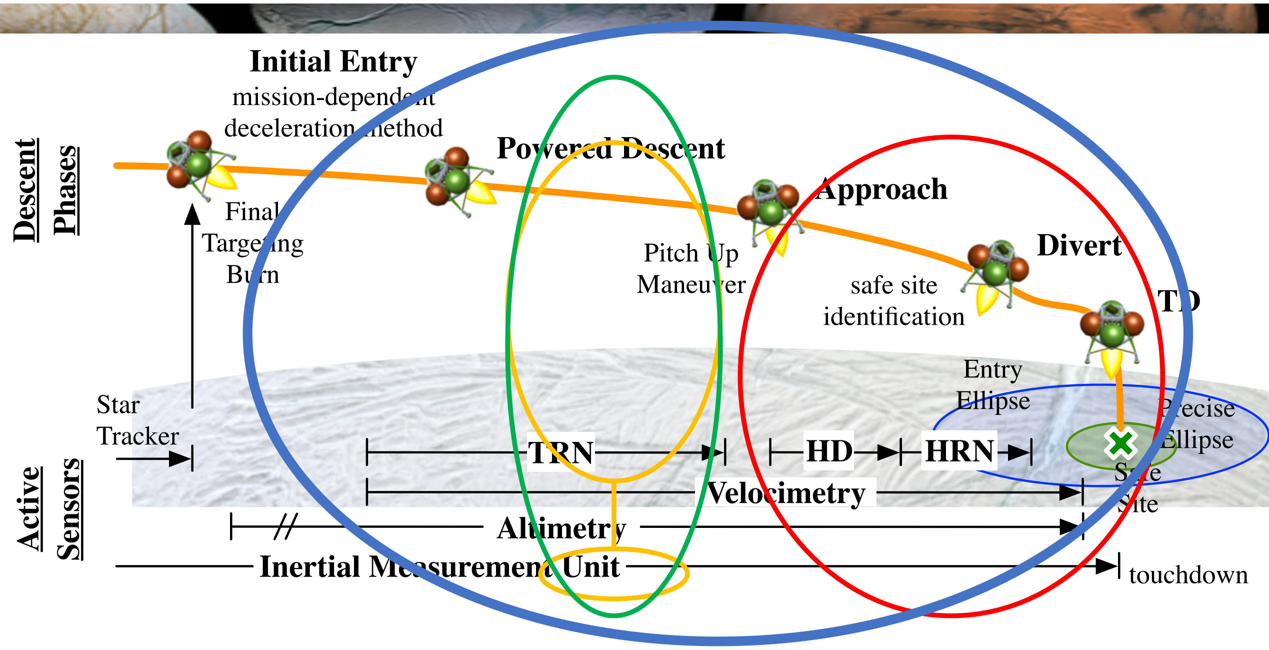


IMU & DLC

- Testbed provides test and validation capabilities for the integrated PL&HA Subsystem: DLC+TRN+NDL+HDL+IMU
- The Simulation software has been developed and tested to interface and real-time interact with the flight computer
- The DLC FPGA firmware enables the hardware event signals that lock-step the Simulation, DLC and PL&HA sensors
- The Simulation outputs simulated PL&HA sensor data in the expected sensor ICD and DLC formats
- The Testbed can also incorporate physical PL&HA sensors or emulators for testing with the Simulation and DLC
- Alternate flight processors and compute elements could be incorporated into the Testbed

Extensive NASA Portfolio of PL&HA Technology Development & Testing (through many projects)

Suborbital Testing of PL&HA Technologies



SPLICE/New Shepard 2020
COBALT/Xodiac 2017
ADAPT/Xombie 2014 & SPLICE/Xodiac 2019
ALHAT/Morpheus 2014

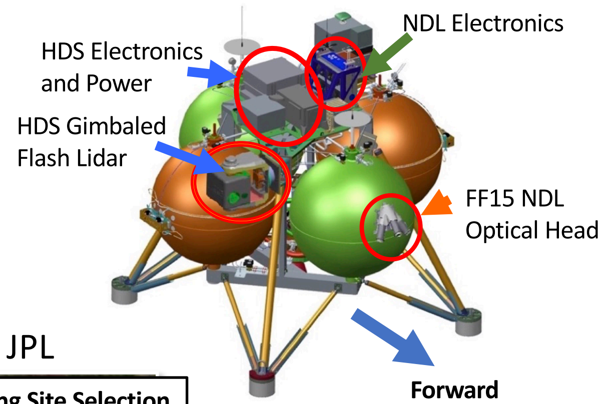
Acronyms	
TRN	Terrain Relative Navigation
HD	Hazard Detection
HRN	Hazard Relative Navigation
TD	Terminal Descent
ConOps	Concept of Operations

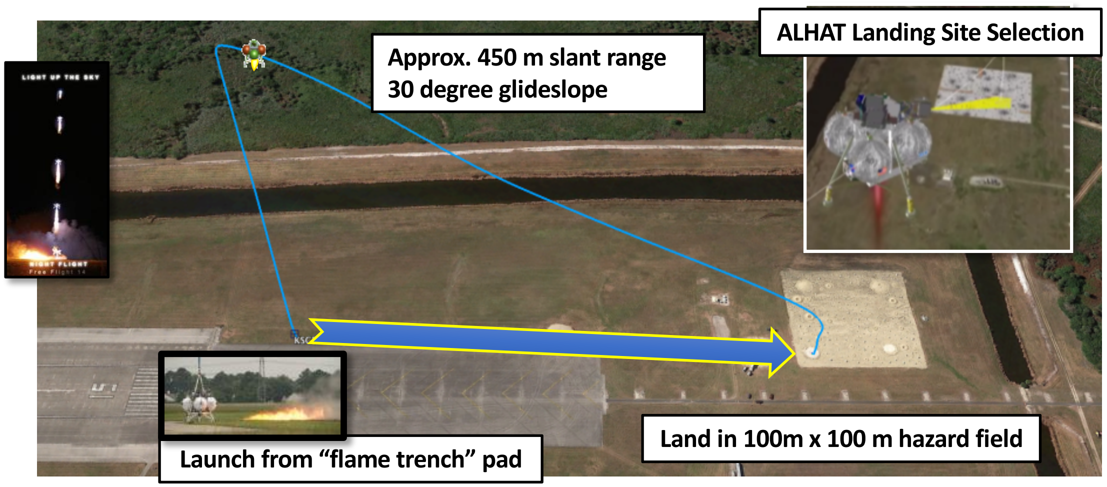
- The 2014-2019 PL&HA testing focused on elements of an integrated PL&HA ConOps
- 2020 plans to test a fully integrated PL&HA suite to higher altitudes, relevant dynamics, and more spaceflight-relevant environments – path to achieving TRL 7

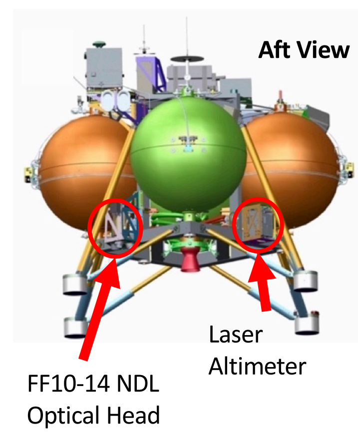
2014 ALHAT on Morpheus 1.5B

PL&HA

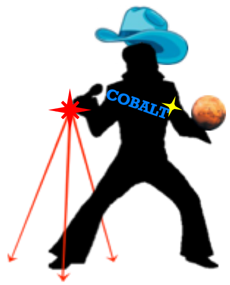
- Six flights: three open-loop & three closed-loop
- Tested safe and precise landing technologies
  - NDL (Gen-2), HDS (Gen-1), Laser Altimeter
  - TRN was not a part of the Morpheus tests
- Demonstrated integration and flight testing of ALHAT for Approach Phase of descent and landing (including hazard detection)
- Performed one flight test in darkness
- Supported by HEOMD and multi-center collaboration: JSC, Langley, JPL



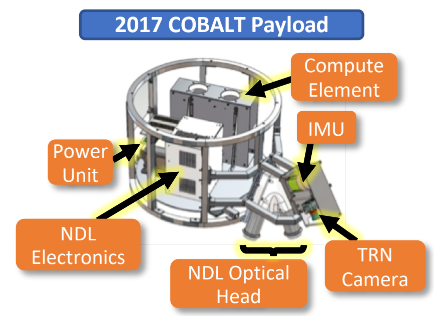


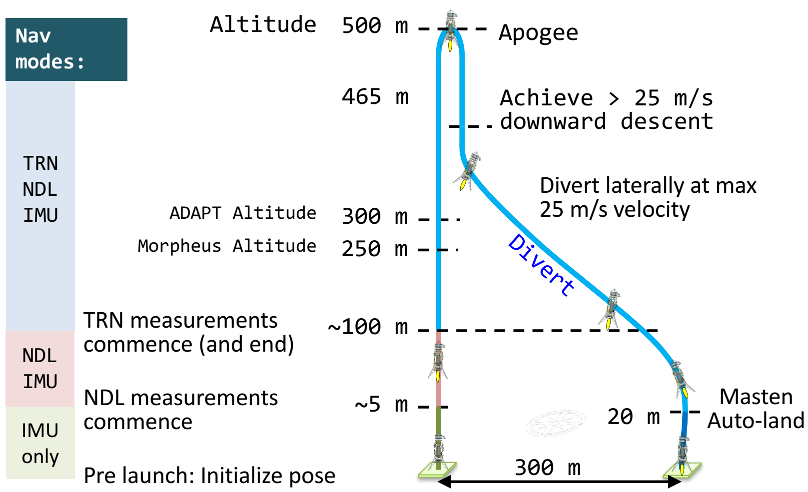


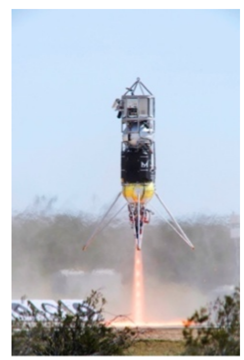
2017 COBALT Flights on Xodiac



- COBALT: CoOperative Blending of Autonomous Landing Technologies
- Platform matured TRL of NDL and Navigation filter
- Multi-center collaboration: JSC, Langley, JPL
- Multi-directorate partnership: STMD & HEOMD







PL&HA Domain and SPLICE Project Summary

Summary

- SPLICE maintains multi-center PL&HA partnerships and cross-directorate investments that have been critical for advancement in PL&HA
- Technology development is spread across all partner centers
  - JSC – Descent & Landing Computer, HWIL Simulation, GN&C Algorithms
  - LaRC – Navigation Doppler Lidar
  - GSFC – Hazard Detection Lidar, cFS, HPSC
  - JPL – HPSC, HD algorithms
- Targeting infusion of all SPLICE technologies into CLPS and other lunar missions in early 2020's and human landers in mid 2020's
  - PL&HA promotes new mission concepts and enlarges the trade space of landing locations for surface exploration
  - SPLICE steers the advancement of capabilities critical for future human missions to Moon and Mars