National Aeronautics and Space Administration

Space Technology Mission Directorate

Game Changing Development Program

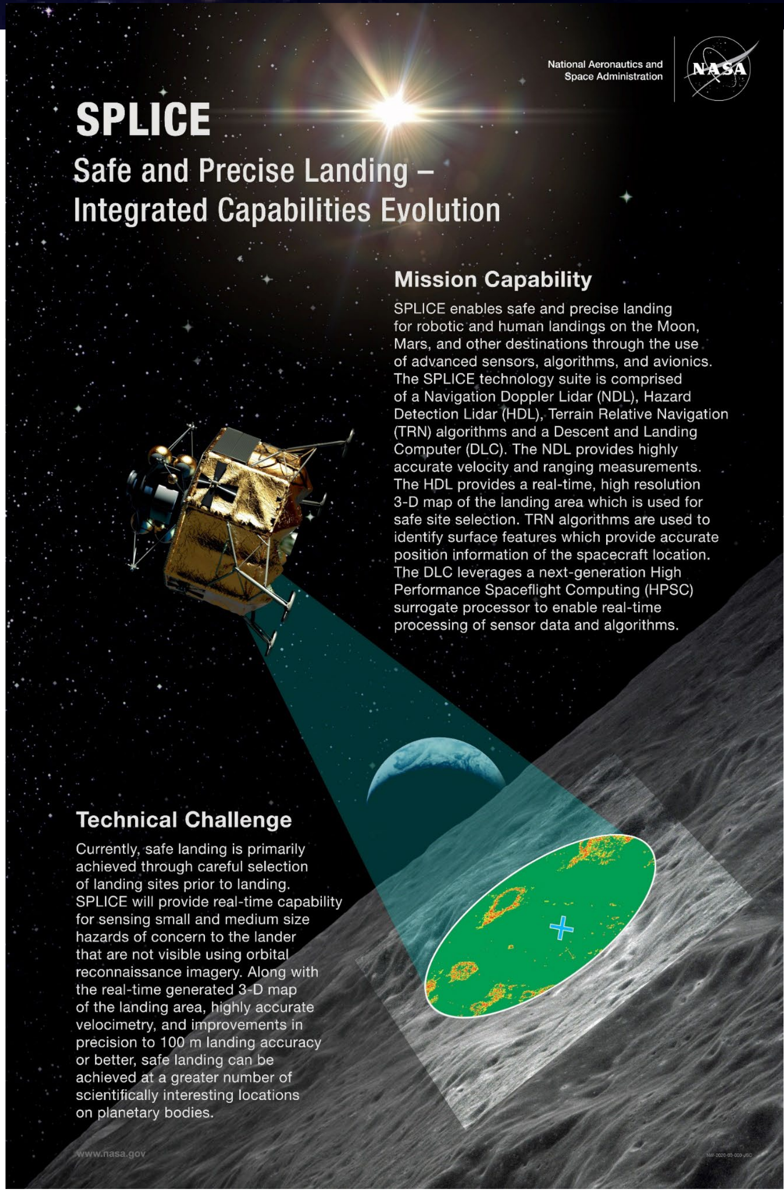
Gavin Mendeck | Wade May | FY23 SPLICE Annual Review Presentation | 08.21.2023
gavin.f.mendeck@nasa.gov

Project Overview

- **Technology Products Capability**
  - SPLICE Precision Landing and Hazard Avoidance (PL&HA) technologies will improve landing precision by an order of magnitude and enable high-resolution real-time 3-D mapping for hazard detection and avoidance during descent.

- **Technical Capabilities**
  - Portfolio of sensors, avionics and algorithms for PL&HA appropriate to be infused as individual technologies, or can be fully integrated
    - Hazard Detection (HD) Lidar - high resolution terrain mapping
    - GN&C/PL&HA Algorithms improving integrated functions and real-time performance
    - Descent and Landing Computer (DLC) with COTS HPSC surrogate for PL&HA+GN&C computing
  - Analysis and Test capabilities to mature PL&HA and GN&C technologies
    - Hardware-in-the-loop (HWIL) Simulation Testbed for development, low-cost V&V, and integrated testing (prior to costly field tests)
    - Flight Testbeds (terrestrial and suborbital) for component or integrated systems testing in relevant environments (risk mitigation and TRL maturation toward mission infusion)

- **Exploration & Science Applicability**
  - Technologies enable precise, safe, and soft landing in close proximity to targeted surface locations (hazardous terrain, pre-positioned cargo, cached samples, etc.) on the Moon, Mars, or other solar system destinations
  - Technologies have commercial space applications for companies interested in landing payloads (and eventually people) on the Moon or Mars



Project Needs & Goals

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Technology Development Needs Addressed by Project		
HLS, STMD	***How do we safely land near where we intend to?*** Develop precision landing & hazard avoidance sensor and software components for landers at Moon, Mars, and other destinations.	EDL & Precision Landing
HPSC	***How do we leverage high performance computing development?*** Utilize a high performance space computing prototype for processing sensor data and algorithms to flight demonstration precision landing and hazard avoidance.	Advanced Avionics

Project Goals	
Goal #1	Design, integrate, and flight demonstrate a portfolio of sensor and software components that together or independently enable precision landings within 50m while avoiding landing hazards. The portfolio consists of: • A descent guidance trajectory-planning software library that generates trajectory solutions within 3 seconds that achieve constraints on sensor pointing, position, and thrust bounds while minimizing propellant use. • A Hazard Detection Lidar to scan and provide within 2 seconds a 1 MP digital elevation map of 100x100m area at 1.5cm (1σ) elevation precision. • A hazard detection software library that processes a 1 MP DEM within 2 seconds, then provides a prioritized list of safe landing sites meeting lander-specific parameters. • A Navigation & FSW architecture using these technologies fused with traditional Navigation sensors to achieve onboard position accuracy of 3m (3σ) relative to a safe site within the DEM.
Goal #2	Design, integrate, and suborbital-flight demonstrate this portfolio of capabilities leveraging an HPSC-class terrestrial prototype computer.
Goal #3	Achieve TRL 6 and SRL 6 for the portfolio components.

Project Objectives

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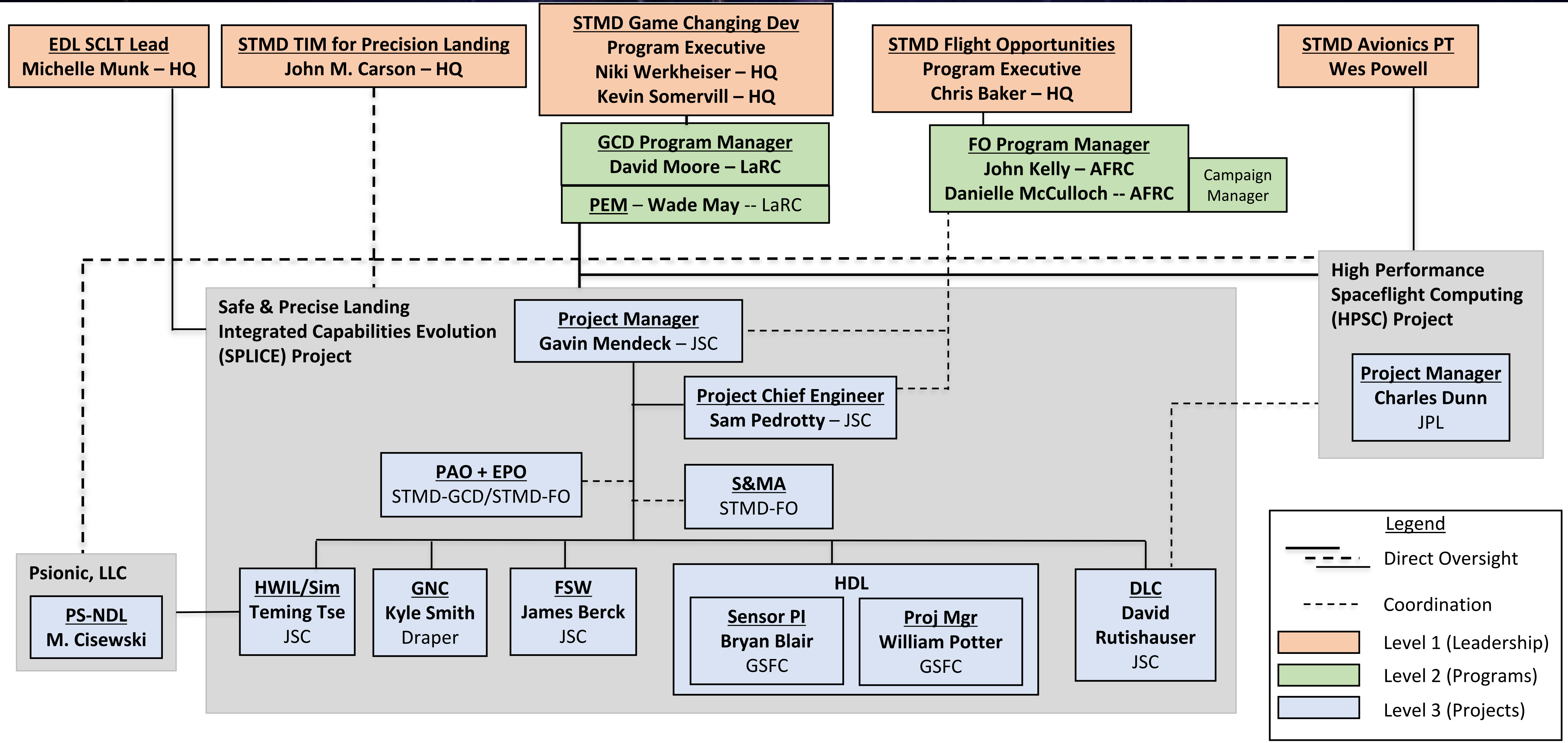
Project Objectives	
Objective #1	Design and implement a Descent and Landing Computer (DLC) Engineering Test Unit (ETU) capable of spaceflight that performs sensor fusion, runs GN&C computing applications, and can transfer, process, and store data at high speeds
Objective #2	Complete a full set of flight software and firmware applications using cFS that includes navigation and guidance algorithmic technology advancements, navigation filter for sensor fusion, data processing, i/o, and storage
Objective #3	Develop and implement a Hazard Detection Lidar that rapidly collects measurements to generate a digital elevation map (DEM) of the landing area.
Objective #4	Develop and implement a long-range altimeter channel within the Hazard Detection Lidar, usable for active terrain relative navigation.
Objective #5	Develop and implement software on DLC that processes the DEM, identifies a ranked list of safe sites, chooses a new landing target, and calculates and updated trajectory to the new landing target within modeled vehicle constraints
Objective #6	Develop both guidance and hazard detection algorithm technologies as software C/C++ libraries that meet at least NASA Class C FSW standards, to ease infusion into flight projects.
Objective #7	HWIL integration and testing of all SPLICE system components
Objective #8	Flight test of the integrated SPLICE system and system components

SPLICE Project Organization



Collaborations & Partnerships

NASA Center

Academia

Industry

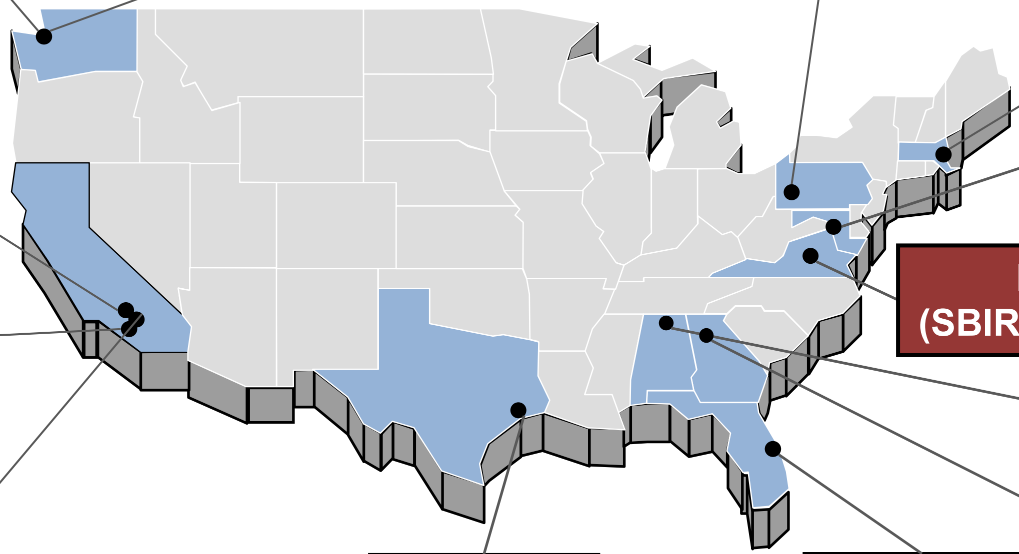
Guidance Research
Univ. Washington

Suborbital Testing 2020/1
SAA Adv. Guidance
Blue Origin (STMD-TP)

Terrain Relative Navigation demo
(V&V leverages SPLICE Trick Simulation)
Astrobotic (STMD-TP, A-TRN)

Terrain Relative Navigation
GN&C software
Draper

Suborbital Testing 2025
Astrobotic Space Systems (STMD-TP, *Xogdor*)



NASA GSFC
Hazard Detection Lidar (HDL)
cFS

Hazard Detection algorithms
High Performance Space Computing (HPSC)
NASA JPL

Psionic (SBIR & STMD-TP)
SBIR Navigation Doppler Lidar (NDL)
TP NDL Demo 2024 *(potential)*

NASA MSFC
Inputs to Human Landing System (HLS) Oversight & Insight

NASA AFRC (STMD Flight Ops Program)
Suborbital Test Coordination

NASA JSC
Project Leadership
Descent & Landing Computer
HWIL Simulation Testbed
GN&C Software

NASA KSC
HDL Flight Testing

Georgia Tech
Review of ECF Hazard Detection algorithms that leverage Machine Learning

SPLICE TRL & SRL Progression

Project Milestone | GCD (Key) Milestone | Controlled Milestone | TRL Progression

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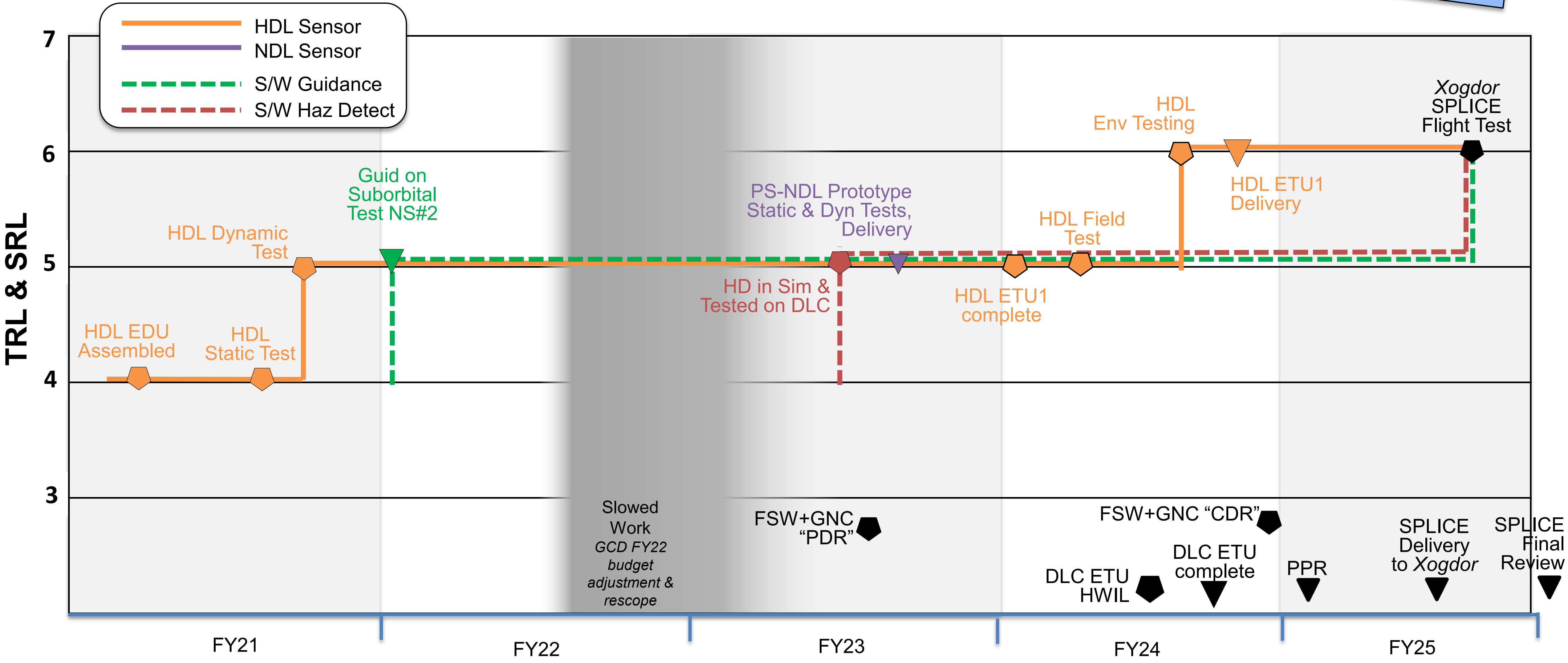
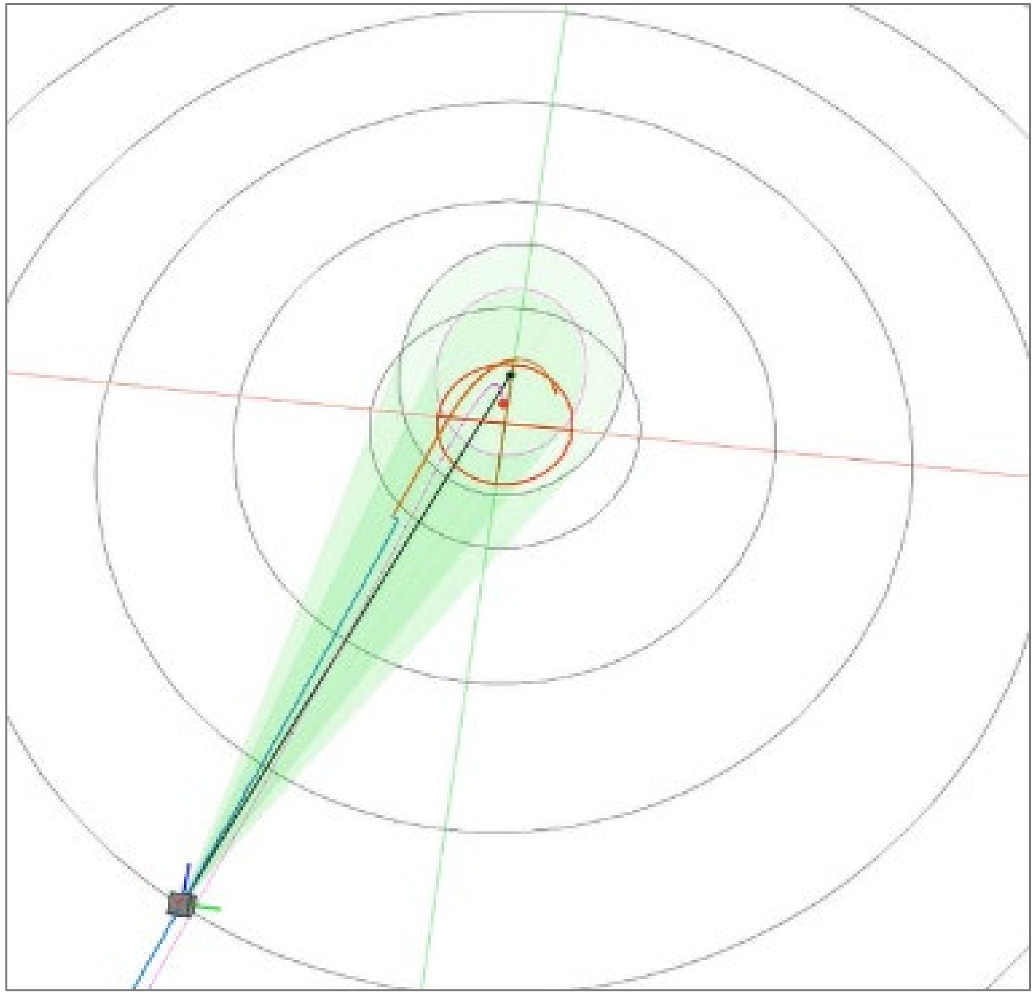


Accomplishments in FY23
Guidance Software

- Project has partnered with University of Washington on Dual Quaternion Guidance (DQG) to provide real-time trajectory solutions that meet multiple constraints, including sensor pointing, while minimizing propellant use.
- Initial implementation flew successfully as part of SPLICE “ride-along” payload on *New Shepard* flight in 2021.
  - Used UW custom second-order cone programming (SOCP) solver, with ~10k lines of code that were refactored into ~500k lines for run time efficiency.
  - Ran on single DLC ARM A53 processor with a simple constraint set, repeatedly providing valid solutions within 3 seconds each time.
  - UW SOCP generic software was never intended to meet spaceflight FSW standards. Software needed to be streamlined for review and reliability.
- UW developed first-order proportional integral projected gradient (PIPG) solver in FY22-23 to simplify the software and improve performance. FY23Q4 prototype benchmark testing on DLC ARM A53 shows PIPG is ~20% the run time of SOCP and with less than 1k lines of code.
- FY23 work added sensor constraints which, while successful, slowed down the SOCP solver beyond the project’s goal.
- Project is proceeding with implementing PIPG as a software library meeting FSW Class C to meet goals and objectives
- Project also supports Blue Origin SAA on advanced guidance development and implementation

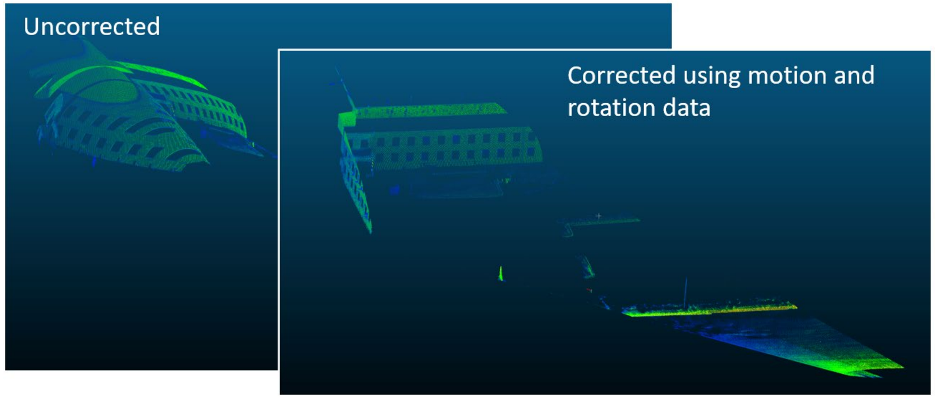


6DOF lander simulation illustrating SPLICE DQG successfully points the HDL sensor field-of-view (green) within 50m of the site (red circle) and diverts to an identified safe site (red dot).

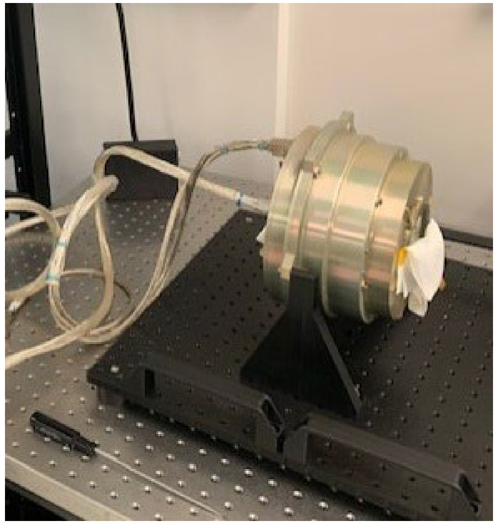
Accomplishments in FY23
Hazard Detection Lidar

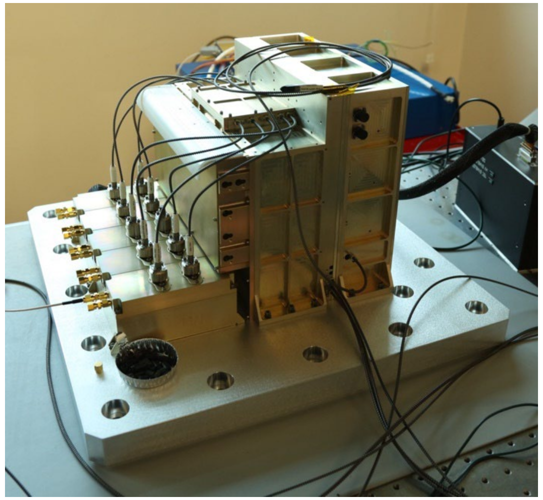
- Project partnered with GSFC to design, build, and test the Hazard Detection Lidar (HDL)
  - Design implements a scanning lidar with pointing controlled by two high-speed spinning Risley prisms to make millions of precise point measurements per second with <1.5 cm (1σ) range accuracy
  - HDL avionics compensate for motion while populating a 1 MP 100x100 m digital elevation map during the 2 sec scan, allowing hazards of 30cm diameter or larger to be identified
- FY23 has focused on assembly and testing of the ETU1 for both Hazard Detection Lidar and Long-Range Altimeter
  - All components assembled except for the altimeter telescope. Completed: Detector and its electronics, altimeter laser electronics, master electronics unit, HDL interface harnesses, motor & power chassis, scanner assembly, main power interface board, fiber lasers and harnesses
  - Begun vibration acceptance testing of major subassemblies
  - Begun FPGA programming to process DEM
- Planning underway for FY24 KSC helicopter flight tests, which reduces risk prior to *Xogdor* SPLICE flight in FY25Q3

HDL EDU Dynamic Testing w/ Truck (2021)
With Post-Processed Motion Compensation



HDL Scanner testing using Motor Controller Board (MCB) breadboard





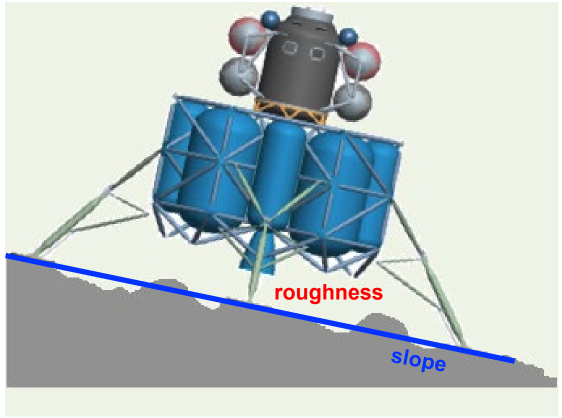
HDL ETU1 Detectors, Altimeter LEU Housing, Fiber Delay Box & Laser subassembly mounted to vibration plate

KSC helicopter flight concept for scanner mount

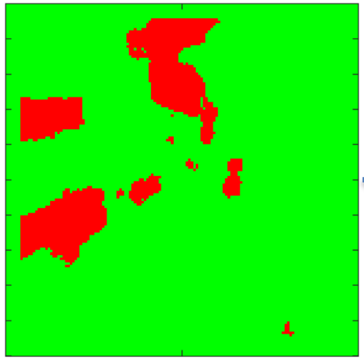
Accomplishments in FY23
Hazard Detection Software

- Project has partnered with JPL to refine the hazard detection software used on the *Morpheus* PL&HA demonstration flights in 2013-2014.
  - This software processes a DEM against defined lander characteristics to identify sites most likely to avoid slope and roughness (lander clearance) hazards.
  - 2013 implementation required parallelization on multiple CPUs to process within 6 seconds. Processor speed improvements (i.e., HPSC) since then have reduced the need to parallelize this algorithm.
  - FY22 work on algorithm development to improve performance (~60% of original execution time) and implement as a software library package.
- FY23 focused on HD library code review, analyses, & testing
  - Deep-dive library code and documentation review by FSW and GNC peers, collecting ~300 comments on code, ~100 comments on documentation and design. 99% of all comments now closed. Updated library delivered.
  - Quantifying technical and execution time performance with combinations of different algorithm parameters, including small to large lander sizes
  - Evaluating algorithm performance using simulated HDL DEMs from Blue Origin 2021 ACO to compare with published Blue results. Evaluating LuNaMaps DEMs.
  - Testing a 1 MP DEM on DLC ARM A53 achieved 2 second goal for a 5m diameter lander, with <0.1% false positive rates
- FY24 will include further analysis, flight test planning support, and testing this algorithm real-time on the HDL helicopter tests using the DLC

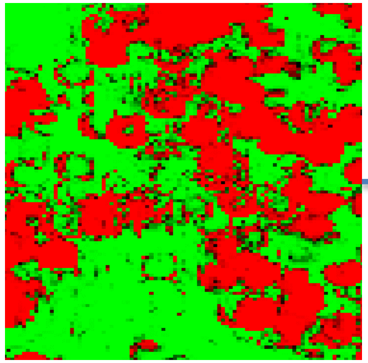
Depiction of Lander Hazards



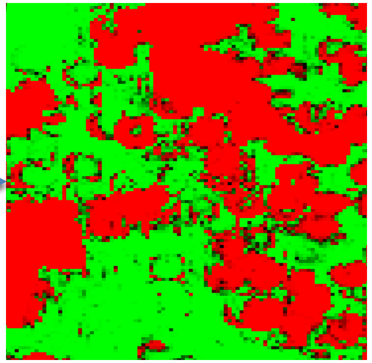
Hazard Detection Processing Steps of DEM



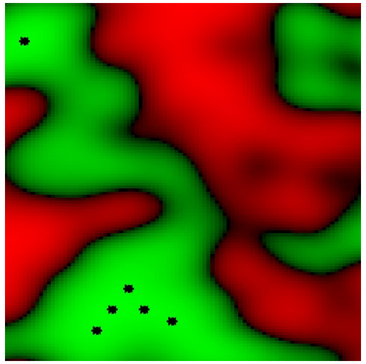
Slope Hazards



Roughness Hazards



Combined Hazards

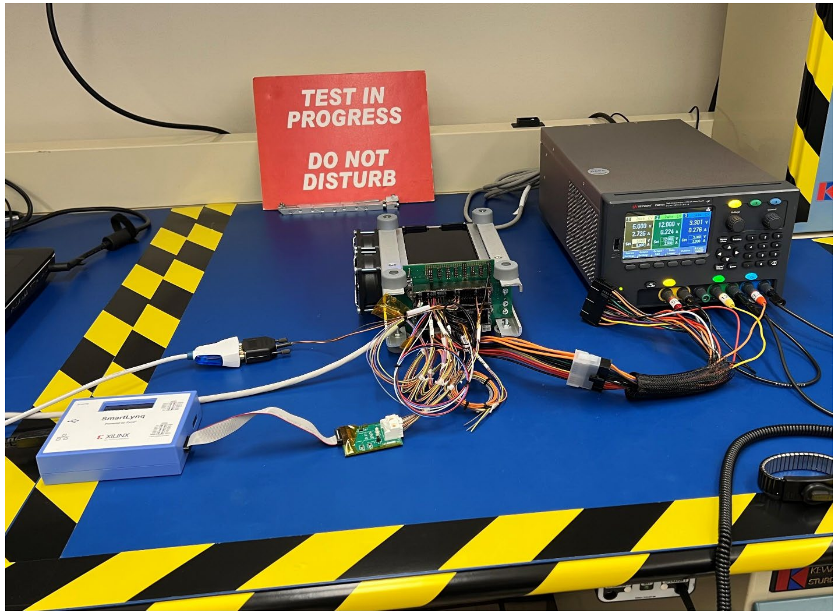


Combined Hazards w/ Landing Accuracy

Accomplishments in FY23
Descent Landing Computer

- Project previously developed and qual'd a Descent Landing Computer EDU for New Shepard flights
  - Four ARM A53 processors running 64-bit cFS on a Pentalinux OS
- FY23 has Descent and Landing Computer (DLC) ETU design in fabrication and testing
  - ETU design corrects time synchronization deficiencies that were accepted to ride-along on *New Shepard*. These deficiencies must be corrected for *Xogdor*, as that vehicle will respond to SPLICE guidance commands.
  - DLC main processor boards in second round of fabrication and evaluation. DLC FPGA board preparing for procurement. O/S and firmware updates for ETU. Mercury solid state data recorder (SSDR) interfacing in development.
  - Now participating in industry consortium to influence SpaceVPX development towards future NASA needs
- FY24 will complete assembly and testing of two DLC ETU assembly, and include applying ETU firmware updates to existing DLC EDU units to support HDL and potentially NDL flight tests

DLC SSDR Testing



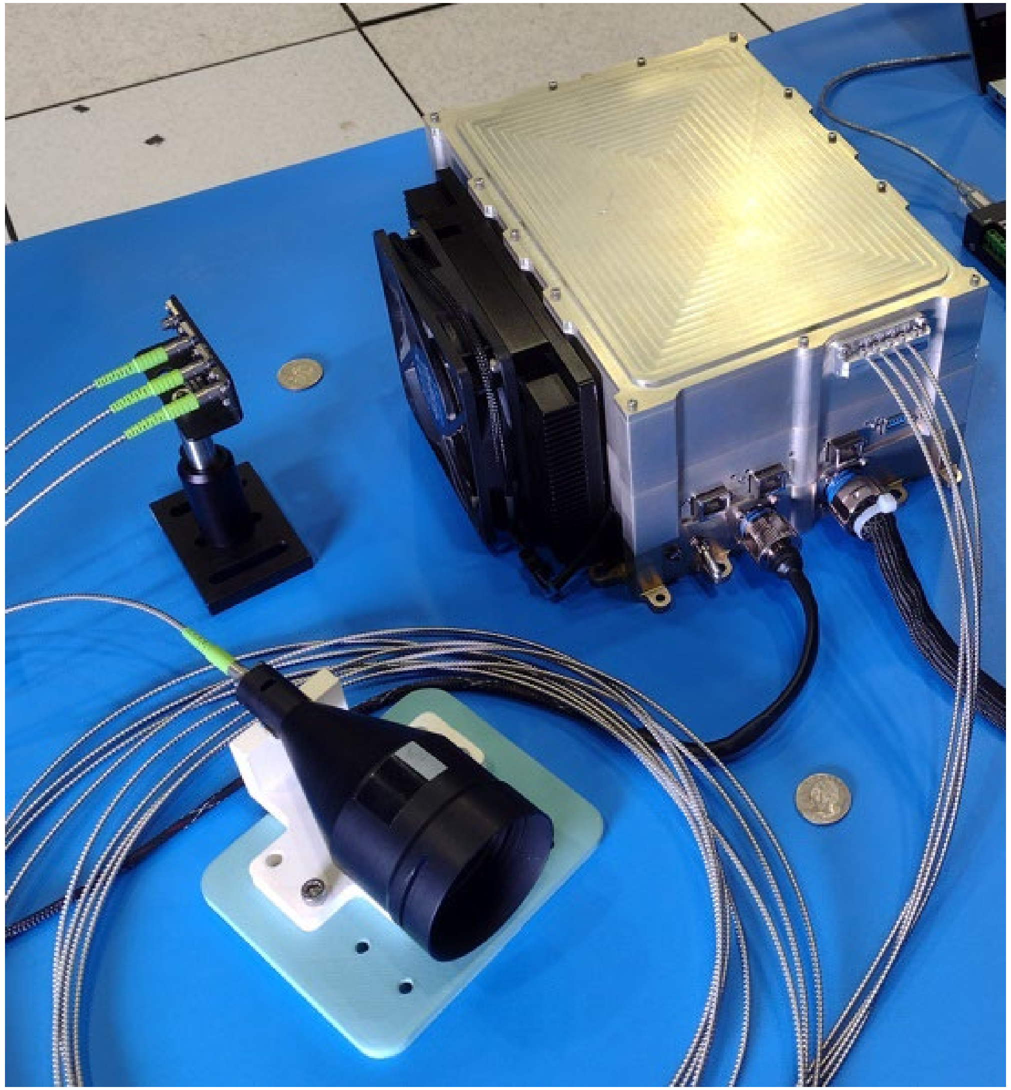
Accomplishments in FY23
Psionic NDL

- Project partnered with Psionic, LLC. to develop and deliver commercial Navigation Doppler Lidar unit
  - Sensor provides softer controlled touchdown with low lateral velocity and significantly reduced navigated position error, improving precision landing
  - SBIR Phase 3 to develop of two photonic integrated circuit (PIC) upgrades and build a 5th Generation NDL EDU, reducing mass by 70% from prototype and more redundancy. EDU mass target is 3 kg.

- FY23 accomplishments
  - Developed sensor software and early integrated testing
  - Prototype w/o PIC delivered in FY23Q4
  - Potential for project to minimally support Psionic Tipping Point flight testing in FY24. Utilizing project hardware previously flown on New Shepard.

- PPBE25 funding constraints descoped Psionic NDL from project. Expect its descope will negatively impact suborbital flight testing as onboard position knowledge will be degraded relative to identified safe sites.

Psionic NDL Prototype



Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year	G	Y	G	Y	Schedule – Projected ~3mo delays to HDL and DLC completion milestones Programmatic – GSFC and JSC workforce support reduced in late FY22 and has not recovered fully; competing with other projects.
Annual	G	Y	G	Y	Schedule – Mitigations to HDL delays in work. DLC completion milestone slipping ~3 mo due to both redesign after pathfinder testing and to critical resources supporting flight tests with DLC EDU for HDL; not critical path to *Xogdor* TP. Programmatic – GSFC and JSC workforce support reduced in late FY22 and has not recovered fully; competing with other projects. Budget for FY24-26 descoped Psionic NDL.

SPLICE Infusion & Partnerships

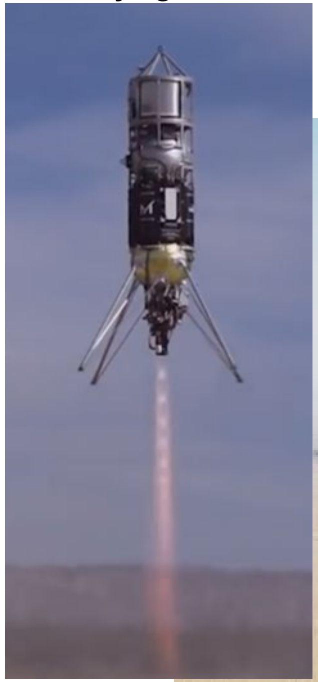
- EDL/PL&HA domain goal is to address capability gaps and promote infusion and commercialization by achieving TRL 9 for the following technologies via lunar flight demo. These technologies may be infused separately or collectively.

SPLICE Component	Component Description	Commercial/Mission Infusion Targets	Development Partnerships
Hazard Detection Lidar (HDL)	A scan-array lidar capable of short- and long-range mapping to support HD applicable to Moon, Mars, Icy Moons, Ocean Worlds, etc. Long-range altimeter to support active TRN.	Pursuing potential lunar demo. Several New Frontiers proposals. Interest with several companies regarding use or licensing.	One RSAA, GSFC SAA
Psionic Navigation Doppler Lidar (PS NDL)	An evolved commercial NDL with SBIR Photonic Integrated Circuits which provide ~70% reduction in mass & more redundancy	LaRC NDL on IM-1 & AB-1 CLPS. Psionic NDL on VIPER.	Army-PNT & Army-ERDC
Dual Quaternion Guidance (DQG) FSW	A 6-DOF trajectory planner software with integrated control & state constraints to perform hazard detection & precision landing.	Two RSAAs. Collaborating with HLS. Licensing available through partner.	Univ. of Washington
Hazard Detection FSW	ALHAT-evolved hazard detection software application and library	JPL/SMD (Europa Lander). Licensing available through partner.	JPL/Caltech
Navigation S/W	Incorporates NDL data and fault logic, TRN/AFP measurements, and hazard/site relative navigation (SRN)	Potential CLPS/HLS & Orion Artemis/OpNav. Blue RSAA. AFP TT patent.	Draper
Core Flight S/W (cFS)	Ported onto DLC to process all SPLICE sensor data and algorithms. SPLICE was early adopter of 64-bit cFS, which eases migration to HPSC.		GSFC
Descent Landing Computer (DLC)	A SpaceVPX architecture including internal redundancies, COTS multicore processor (with rad-tolerance provisions), and PL&HA I/O for sensor fusion and algorithms processing during EDL/DDL	Interest by two companies in tech transfer patents	HPSC

Xogdor Tipping Point

- **Astrobotic/Masten awarded a Flight Opportunities Tipping Point in 2021**
  - *"...to conduct flight tests demonstrating the capability to conduct testing of Precision Landing and Hazard Avoidance (PL&HA), plume surface interactions, and other technologies and phenomena."*
  - Masten has previously flown third-party GNC algorithms while employing an independent monitoring algorithm and vehicle GN&C that will override for vehicle and range safety
  - Technical and management team has ramped up after Astrobotic acquisition of Masten in late 2022
- **SPLICE Xogdor flight scheduled for late FY2025**
  - Closed-loop suborbital flight test of PL&HA sensors and software that include navigation, guidance, hazard detection
  - SPLICE provides the anchor payload for the Astrobotic/Masten *Xogdor* Tipping Point
- **The mutual benefits to NASA (GCD+FO) and Astrobotic of flight validating SPLICE on *Xogdor***
  - NASA PL&HA strategy closes several high-priority gaps: provides relevant & real sensor/software data and maps benefiting partners
  - Astrobotic showcases *Xogdor* closed-loop capabilities and relevance to EDL maturation
    - Provides performance data on *Xogdor* PL&HA-specific test profiles (2+km altitude & lunar-relevant trajectory)
    - Provides flight validation of *Xogdor* ability to inject third-party guidance and navigation inputs (i.e., closed loop)
    - Develops *Xogdor* payload interfaces (electrical, mechanical, telemetry, comm and onboard C&DH)
    - Identifies flight operations locations for PL&HA-relevant testing (i.e., terrains for good TRN & HD field testing)

Xodiac flying COBALT, 2017



Xogdor, 2025

Education/Public Outreach

EPO Involvement

- JPL Hazard Detection algorithm presented at 3rd Space Imaging Workshop @ Atlanta, GA, October 2022
- SPLICE poster and booth at the SMD Technology Showcase in January 2023
- SPLICE Guidance paper presented at AIAA SciTech in January 2023
  - *"Customized Real-Time First-Order Methods for Onboard Dual Quaternion-based 6-DoF Powered-Descent Guidance "*, Kamath, A.; Elango, P.; Kim, T.; Mceowen, S.; Meshabi, M.; Acikmese, B.; Yu, Y.; Carson, J.
- SPLICE DLC paper presented at IEEE Space Computing Conference @ Pasadena, CA, July 2023
  - *"A System to Provide Deterministic Flight Software Operation and Maximize Multicore Processing Performance: The Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE) Datapath"*, Rutishauser, D.; Prothro, J.; Fail, J

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead	
2024 AIAA SciTech Forum, Orlando, FL	Jan 8 – 12

- Upcoming Notable Events in FY24
  - HDL Helicopter Testing @ KSC, FY24Q2-3
  - (potential) Psionic Tipping Point Testing @ AFRC, FY24Q3
  - DLC ETU hardware-in-loop testing @ JSC, FY24Q4

Summary

- Major Accomplishments for the Year
  - Hazard Detection Lidar assembly nearly complete and testing well underway
  - Hazard Detection FSW meeting accuracy and time execution goals on target hardware, completed formal code review
  - Guidance FSW development on track to meet time execution goals
  - Navigation architecture maturation to support precision landing and hazard avoidance goals
  - DLC ETU components maturing
  - Psionic NDL prototype delivered
- SPLICE is building up to a suborbital, closed-loop test flight with the Astrobotic *Xogdor* vehicle, to demonstrate all technology components in real-time
  - SPLICE payload on track to be ready by FY25Q1 for functional fitchecks before FY25Q3 flight
  - HDL will close at TRL6 with environmental testing, with multiple infusions and transitions routes.
  - FSW Guidance and Hazard Detection technologies will close at TRL6, meeting at least NASA Class C FSW standards, and be available for licensing. Both have multiple infusion routes.
  - Project post-flight report and flight data will be released after the *Xogdor* flight.