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Design, Development, and Use of a Lunar Lander Simulation for NASA's Artemis Program

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***Abstract*—This paper describes the design, development, and initial use of a generalized and configurable lunar lander simulation to support NASA's Artemis Program. This simulation is being developed for the Crew Compartment Office (CrewCo) in the Human Landing Systems (HLS) program and is called the HLS CrewCo Lander Simulation (HCLS). The HCLS provides insight into the challenges associated with returning humans to the Moon and the particular difficulties of operating at the Lunar South Pole. A generalized lunar landing spacecraft based on a government reference design has been modeled but the simulation can be modified and adapted to model vendor designs as well. The simulation architecture and toolsets provide a flexible framework that allows for quickly prototyping and evaluating various aspects of a piloted lunar landing system. This includes the modeling of all principal human controlled flight phases: rendezvous and docking with crew transfer systems; docked orbital outpost operations; undocking and lunar transfer; lunar orbital operations; lunar deorbit, descent, and landing (DDL); lunar surface operations; lunar ascent; and return to the orbital outpost. The flexibility of the simulation allows for the integrated evaluation of potential vehicle subsystems, crew displays, guidance and control modes, and trajectory designs. The purpose of the HCLS is not to design the ideal lunar lander, but rather to understand the strengths and weaknesses of vehicle design choices.**

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1. INTRODUCTION

The HCLS was originally developed to support early Gateway demonstrations and flight software integration and testing concepts. It has since evolved to support studies related to handling qualities, crew displays and controls, and Guidance, Navigation, and Control (GNC) in support of NASA's Crewed HLS Interfaces for Piloting Working Group (CHIP-WG). It has been a valuable tool which has been used to give insight into some of the major areas of concern the Crew Compartment Office has related to crew interactions with the vehicle.

The purpose of the HCLS is to provide a Human-In-The-Loop (HITL) simulation to familiarize the crew and other National Aeronautics and Space Administration (NASA) organizations with the challenges of returning humans to the lunar surface. It has been over half a century since humans last set foot on the lunar surface, and the Lunar South Pole (LSP) presents new challenges and unknowns that were not present during the Apollo missions. The HCLS has been an invaluable asset to better understand the lunar environment and the flight characteristics of a lunar lander since the majority of the people with that knowledge and experience base are no longer with the agency.

The HCLS is not the authoritative source for the final HLS design choices but rather provides an environment which can be used to evaluate their integrated effect and gives additional insight into lunar lander systems. It serves as a sandbox where new ideas for displays, guidance and control modes, or vehicle subsystems can be quickly prototyped for early evaluation before higher fidelity models and tool sets are available.

The simulation has primarily been used for assessing manual control of a lunar lander during the Deorbit, Descent, and Landing (DDL) phase of flight up to this point but has potential for a number of use cases beyond this. It also supports modeling a variety of physics-based subsystem models including power, thermal, and environmental controls. The fully integrated simulation can be used to provide insight into the effects of subsystem design choices on the overall vehicle design.

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Overview

- Introduction
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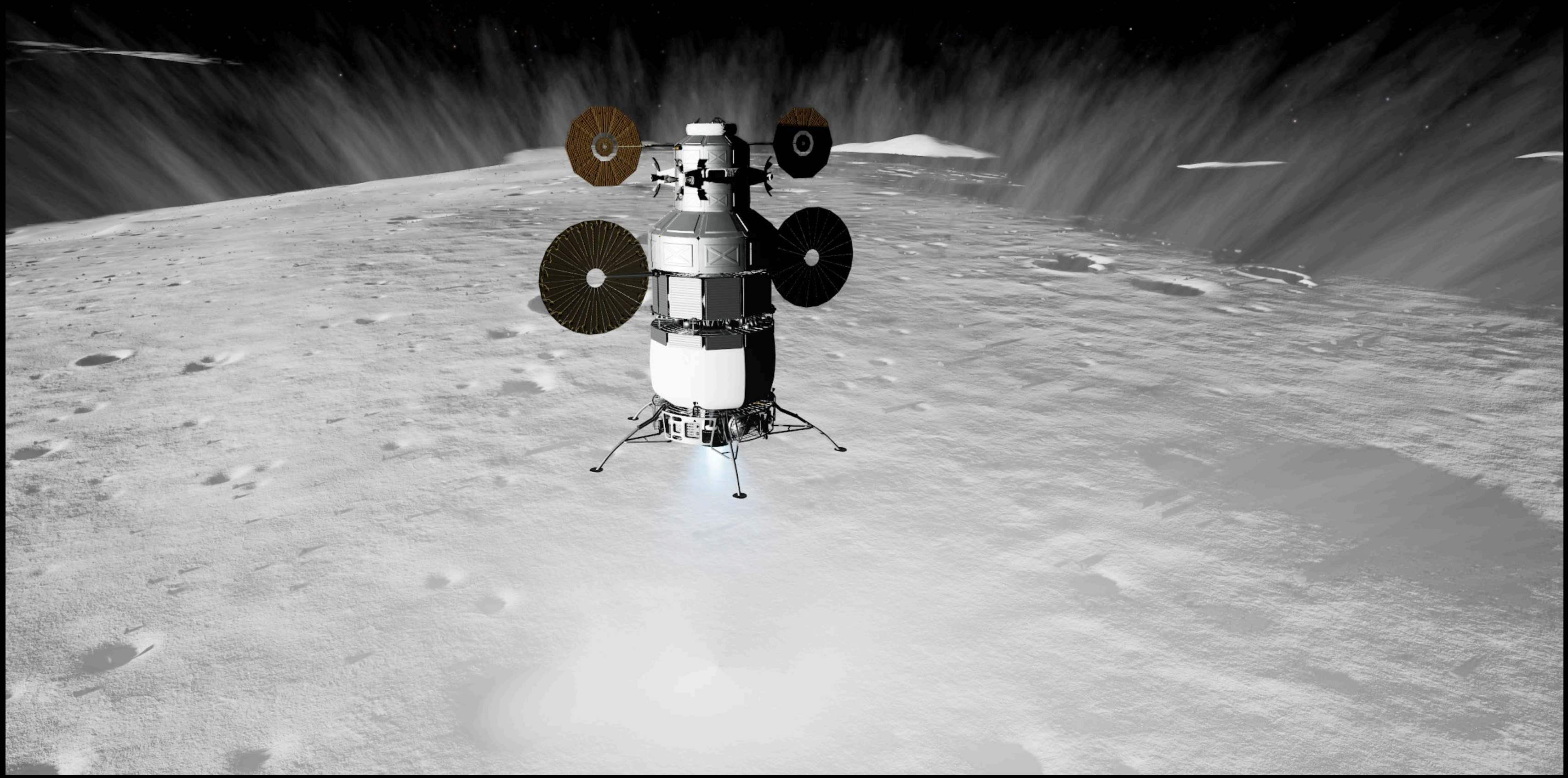
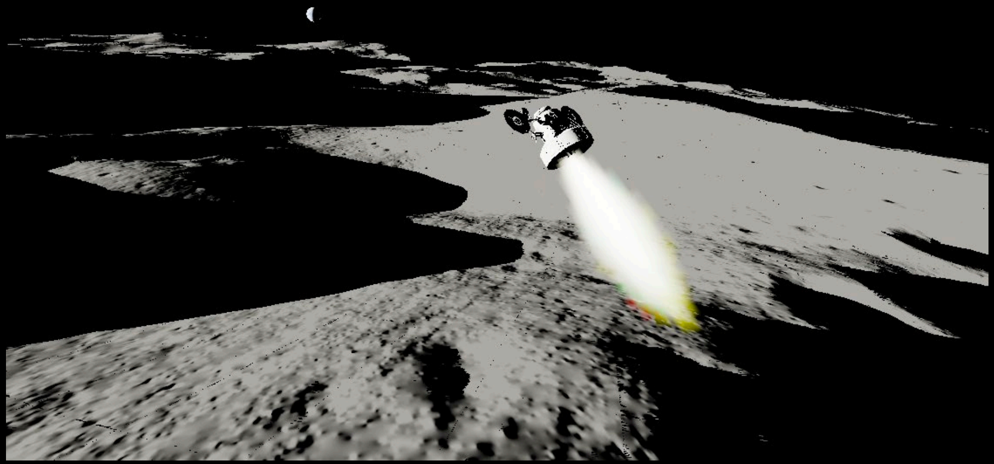
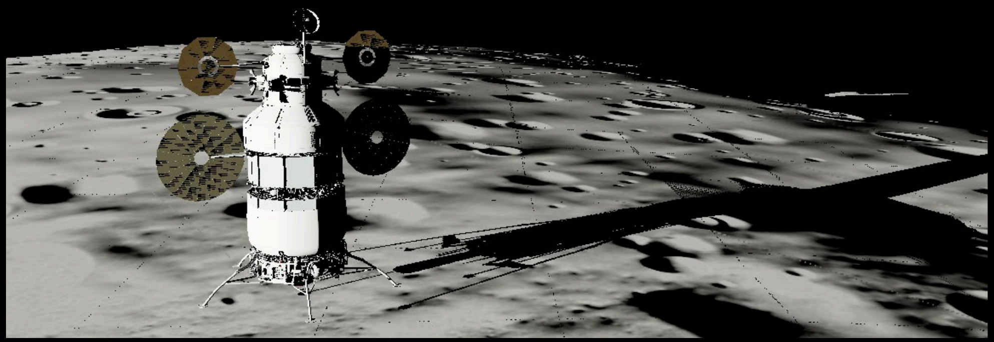


Introduction

- The Artemis program will rely heavily on simulations because the environments that the spacecraft will be operating in are difficult or impossible to recreate on Earth
- It has been over 50 years since humans have set foot on the Lunar surface so many of the tasks will need to be relearned
- The Human Landing System (HLS) CrewCo Lander Simulation (HCLS) provides insight into the challenges associated with returning humans to the Lunar surface, particularly at the Lunar South Pole





What is the HCLS?

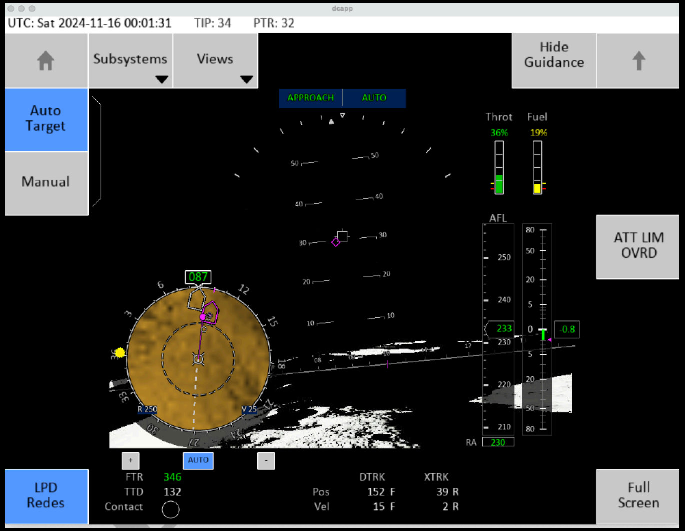
- An integrated simulation of a generalized and configurable lunar lander simulation
  - Based on a NASA HLS government reference design but can be easily adapted to model vendor specific vehicle designs
  - Supports principal human-controlled flight phases
  - Primarily used to quickly prototype and evaluate various aspects of a piloted lunar lander system
  - Includes models for the vehicle dynamics, Guidance, Navigation, and Control (GNC), and vehicle subsystems for integrated systems analysis
  - Supports simulation interoperability (distributed simulation): HLA and SpaceFOM
  - Can be run in a desktop environment and is also deployed at multiple facilities at the Johnson Space Center (JSC)
- Supports both real-time and non-real-time
  - Real-time for Human-In-The-Loop (HITL) operations
  - Non-real-time for analysis

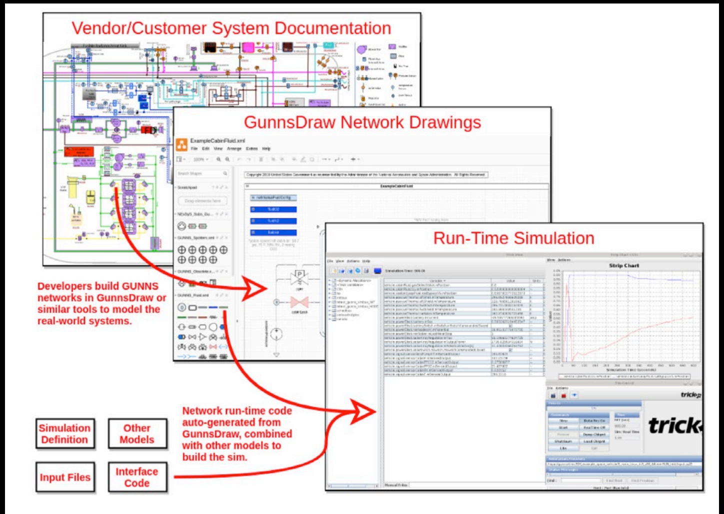
Simulation Architecture

- Uses the NASA Exploration Systems Simulation (NExSyS) simulation architecture and the associated collection of open source and proprietary computer simulation model sets
- Trick Simulation Environment provides a common framework for defining the content of the simulation
- Majority of NExSyS models use object-oriented programming practices and are coded in C++
- Trick-based simulation architecture allows for runtime configurability using Python-based input files
- Where applicable, the NExSyS team adheres to NASA standards and adopts appropriate voluntary consensus standards
  - NASA Software Engineering Requirements (NPR 7150.2D)
  - NASA Standards for Models and Simulations (NASA-STD-7009)
  - Space Reference Federation Object Model (SpaceFOM) (SISO-STD-018-2020)

Open-Source Simulation Toolsets

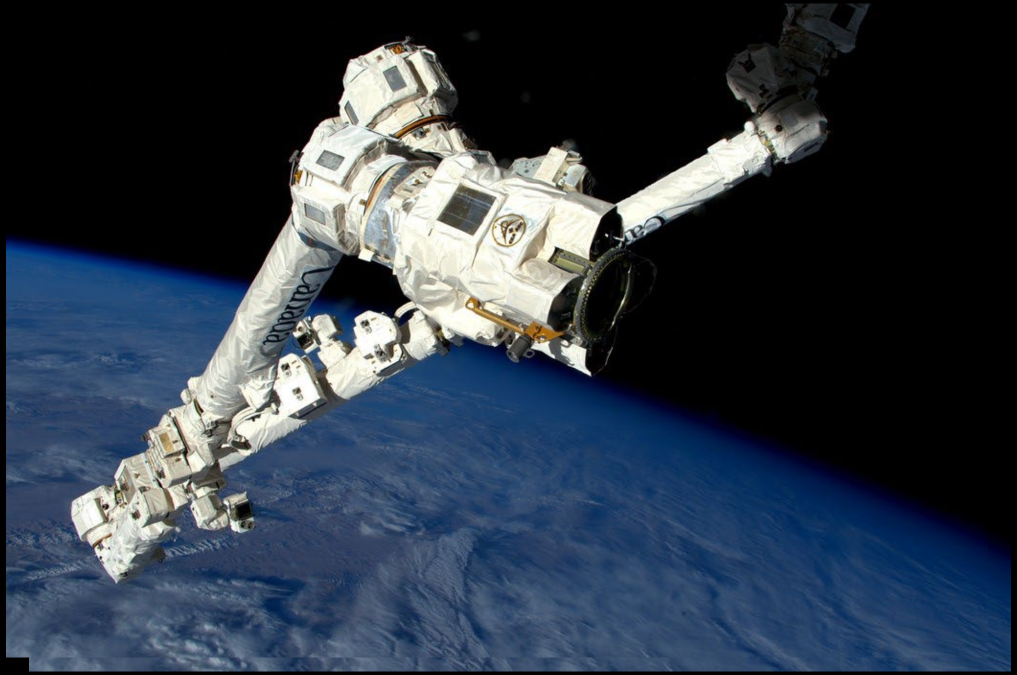
- **Trick:** simulation environment for model execution ordering, input processing, data recording, and post processing capabilities
- **Displays and Controls Application (DCApp):** provides simple interface for rapidly prototyping display concepts
- **Integrated Device Framework (IDF):** provides sim interfaces for hand controllers
- **JSC Engineering Orbital Dynamics (JEOD):** provides environment models and 6-DOF vehicle dynamics
- **General Use Nodal Network Solver (GUNNS):** provides physics-based, nodal network models of power fluidic, and thermal subsystems
- **TrickHLA:** provides IEEE 1516 High Level Architecture (HLA) interface mechanism for all Trick simulations





Proprietary Simulation Toolsets

- **Multibody dynamics (MBDyn) and MBJEOD:** provide rigid and flexible-body dynamics modeling for surface and orbital environments
- **Pong:** provides contact modeling of terrain and mechanical systems based on solid modeling
- **Valkyrie:** generalized suite of space systems models which includes models for GNC, communications, spacecraft subsystems, etc.
- **EDGE:** NASA developed graphics engine rendering package
- **Unreal Engine 5 (UE5):** commercially available graphics engine rendering package adapted for NExSyS specific use cases



Vehicle Models and Subsystems

Vehicle Models

- Base set of tools and generic models allow for easy configuration of the simulation to match design data (mass properties, effectors, sensors, etc.)
- Generic GNC framework allows for quickly prototyping and evaluating guidance and control strategies

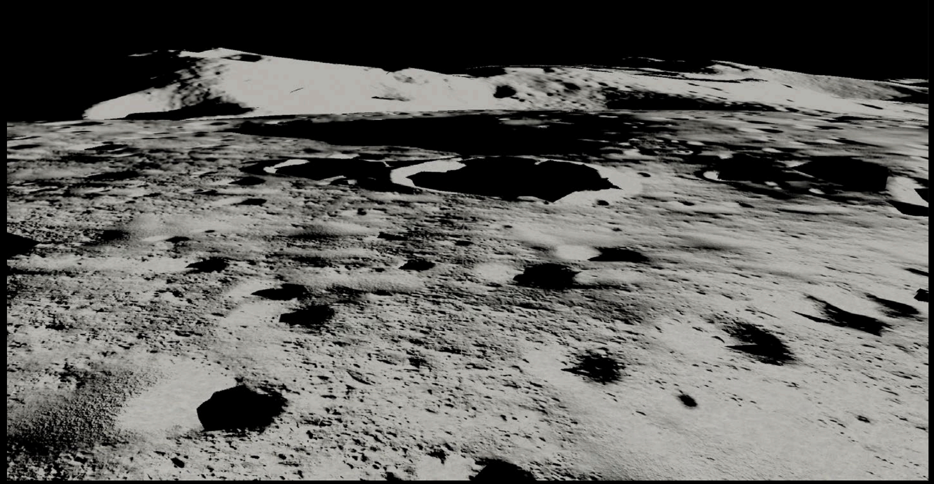
Subsystems

- Supports modeling a variety of physics-based spacecraft subsystems to provide a fully integrated view of the vehicle
- Subsystem models strive to employ re-usable common approach using data components (pumps, valves, batteries, etc.)
- Supports multiple subsystem models
  - Electrical (generation, distribution, loads)
  - Thermal (structure temperatures, solar heating, etc.)
  - Fluidic (plumbing, life support systems, coolant loops, etc.)
  - Mechanisms (solar array articulation, docking system contact modeling, etc.)

Visualization Products

- Accurately models the complex lighting environment at the Lunar South Pole
- Primarily used to to simulate the out-the-window and camera views
- Currently using EDGE which is a NASA developed graphics package
- Transitioning to higher fidelity graphics using Unreal Engine 5
- Virtual Reality (VR) provides an immersive experience to experience landing on the Moon

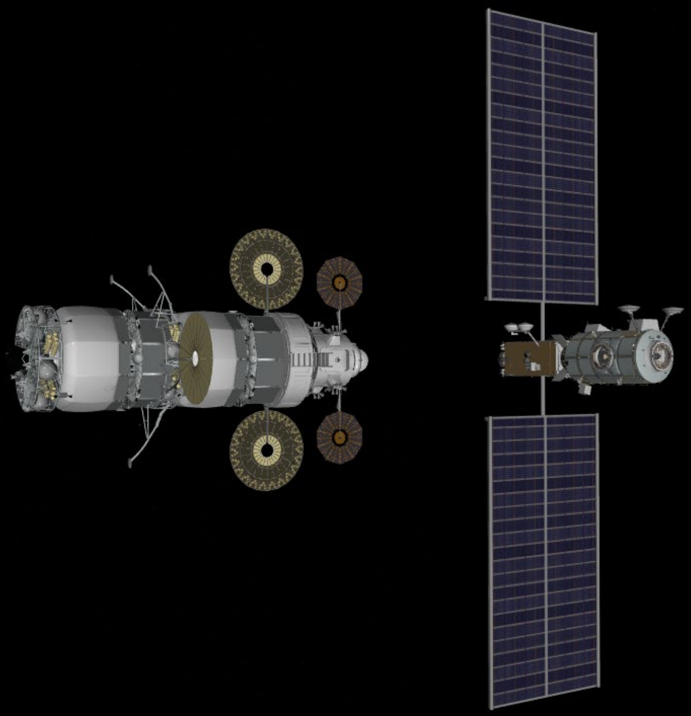
EDGE



Unreal Engine 5

Mission Segments

- Supports multiple flight phases associated with a lunar mission
  - Rendezvous, Proximity Operations, Docking, and Undocking (RPODU)
  - Connected
  - Transit
  - Deorbit, Descent, and Landing (DDL)
  - Ascent
- Goal is to provide a comprehensive simulation framework for all the critical mission phases that involve crew interaction



Facilities

- The HCLS can be run locally and is deployed at multiple facilities at JSC
  - Desktop Environment
  - Simulation Exploration and Lab (SEAL)
  - Systems Engineering Simulation (SES)
    - Mini Dome (Motion Table)
    - Videowall
- Can be deployed on more modern Linux and Macintosh Systems

Simulation Exploration and Analysis Lab

- Simulation facility at JSC used to support crew and NASA organizational demonstrations to evaluate manual control of the Human Landing System (HLS)
- Lab has been set up with flexibility in mind to provide as many options as possible for evaluating landing systems
  - Two crew stations which can be run independently or together
  - Multiple hand controllers
  - Workstation and hand controller positions can be adjusted
  - Operator station for facility operations personnel
  - Capability to stream video and audio to remote participants via Microsoft Teams

Systems Engineering Simulator

- Simulation facility at JSC that houses multiple real-time, crew-in-the-loop engineering simulators
  - International Space Station (ISS)
  - Orion
  - Lunar surface mobility
  - Lunar landing systems
  - Other advanced concepts
- Video Wall
  - Comprised of 15 large monitors which allow for a more immersive environment
  - Multiple display and control inputs
- Mini Dome
  - Six-DOF motion table
  - Virtual reality provides visual cues

Preliminary Use of the HCLS

- Used to gather input from several trained test pilot evaluators from the Department of Defense (DoD) and civilian flight test organizations
- Informal evaluation sessions are used to drive the development of the simulation and gain insight into various aspects associated with piloting a lunar lander
  - Displays and guidance cues
  - Control laws
  - Flying techniques
  - etc.
- Support several crew and organizational demonstrations to provide insight into the challenges of landing at the Lunar South Pole
  - Handling qualities
  - Effects of trajectory design on the piloting task
  - Lighting conditions
  - Out-the-window versus camera views

Conclusions and Future Work

- The HCLS has proven to be an invaluable asset to better understand the lunar environment and flight characteristics of a lunar lander
- Provides engineers, program managers, and crew the opportunity to evaluate the effect of various design and architecture options early in the design phase
- Provides a platform for personnel to experience some of the challenges of landing on the Moon that cannot be easily conveyed through presentations and documentation
- Continual improvements, upgrades, and features are in work for the HCLS
  - Hazard Maps
  - Transit Phase to NHRO
  - Displays and Manual Control for Ascent
  - etc.

Questions?