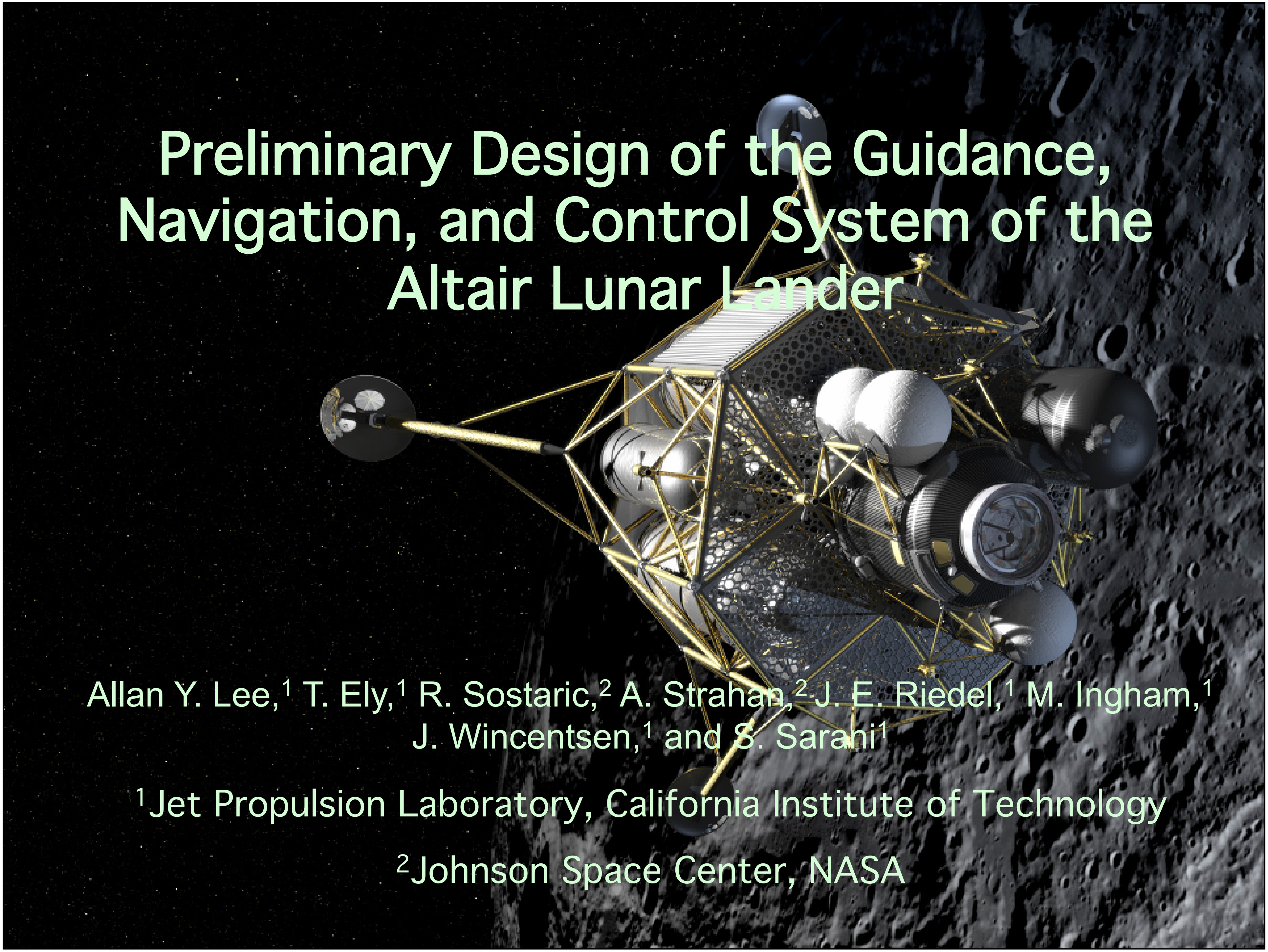


Preliminary Design of the Guidance, Navigation, and Control System of the Altair Lunar Lander

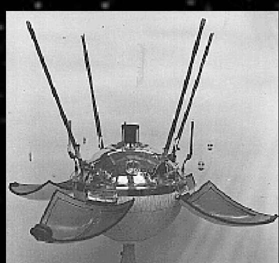
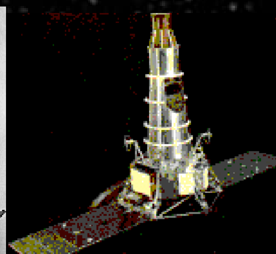
Allan Y. Lee,[1] T. Ely,[1] R. Sostaric,[2] A. Strahan,[2] J. E. Riedel,[1] M. Ingham,[1] J. Wincentsen,[1] and S. Sarani[1]

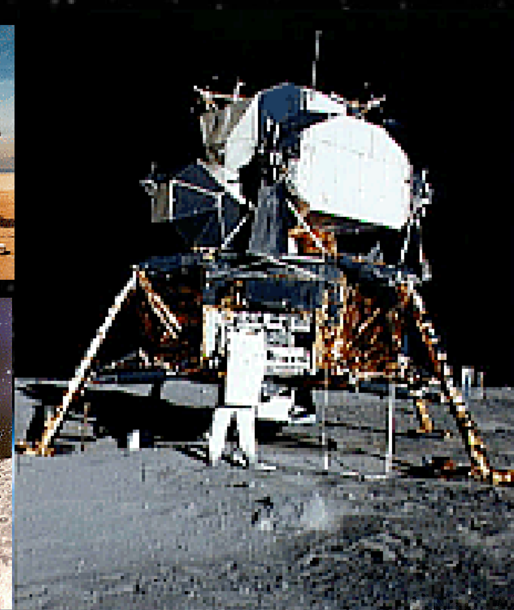
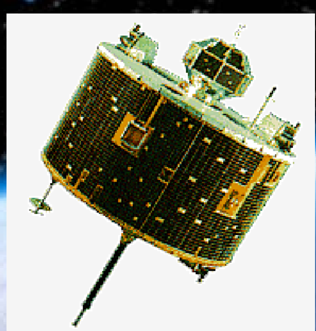
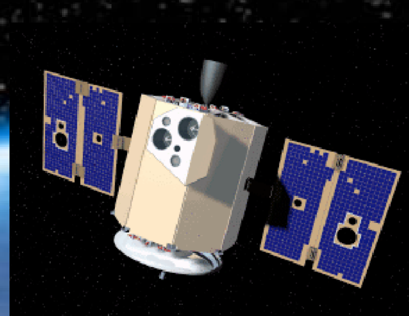
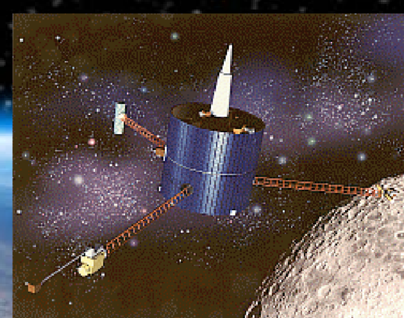
[1]Jet Propulsion Laboratory, California Institute of Technology

[2]Johnson Space Center, NASA

Lunar Visitors in the 20th Centaury

1959-76	Lunik 1-26 (18/26 successful)	USSR
1961-65	Ranger 1-9 (3/9 successful)	JPL, NASA, US
1966-67	Lunar Orbiter 1-5 (All successful)	JPL, NASA, US
1966-68	Surveyor 1-7 (5/7 successful)	JPL, NASA, US
1969-72	Apollo 11-17 (6/7 successful)	JSC, NASA, US
1990	Hiten (Muses-C) (Successful)	Tokyo U., Japan
1994	Clementine (partial success)	DoD/NASA, US
1998	Lunar Prospector	NASA, US

The "Return-to-the-Moon" Fever in the 21th Centaury

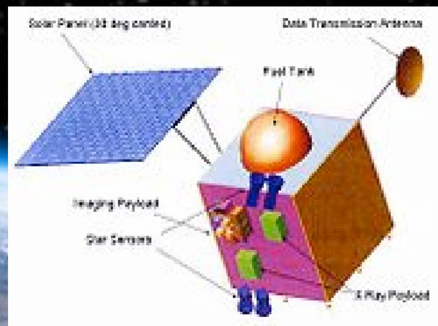
- There is a robust international interest in lunar exploration:
  - ESA's Smart-1(03), Japan's Kaguya (07), China's Chang'e-1 (07), and India's Chandrayaan-1 (08)
    - Kaguya-2 (2015), Chang'e-2 (2010, 2012, 2017), and Chandrayaan-2 (2015) are being planned
- This global interest in lunar research has been tapped by NASA:
  - An agreement with Canada, France, India, Germany, Britain, Italy, Japan, and South Korea has been signed to establish a network of automated science stations across the lunar surface
- A Google Lunar X prize has also been established ($30 million):
  - First privately funded team to send a robot to the Moon. Once there, it must traverse 500 m and transmit video, images, and data back to Earth

Smart-1

かぐや姫

嫦娥一号

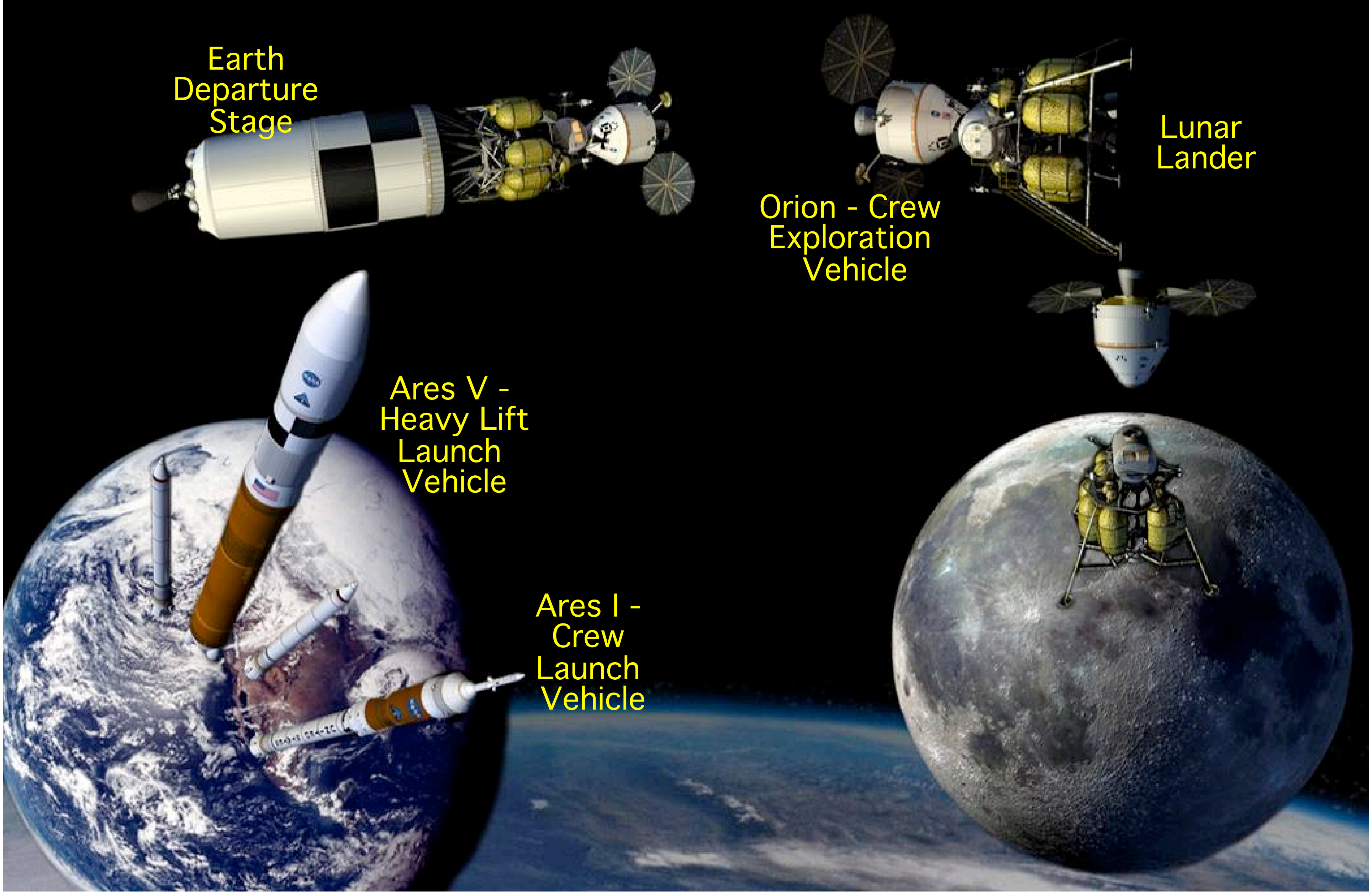
شاندرايان-1



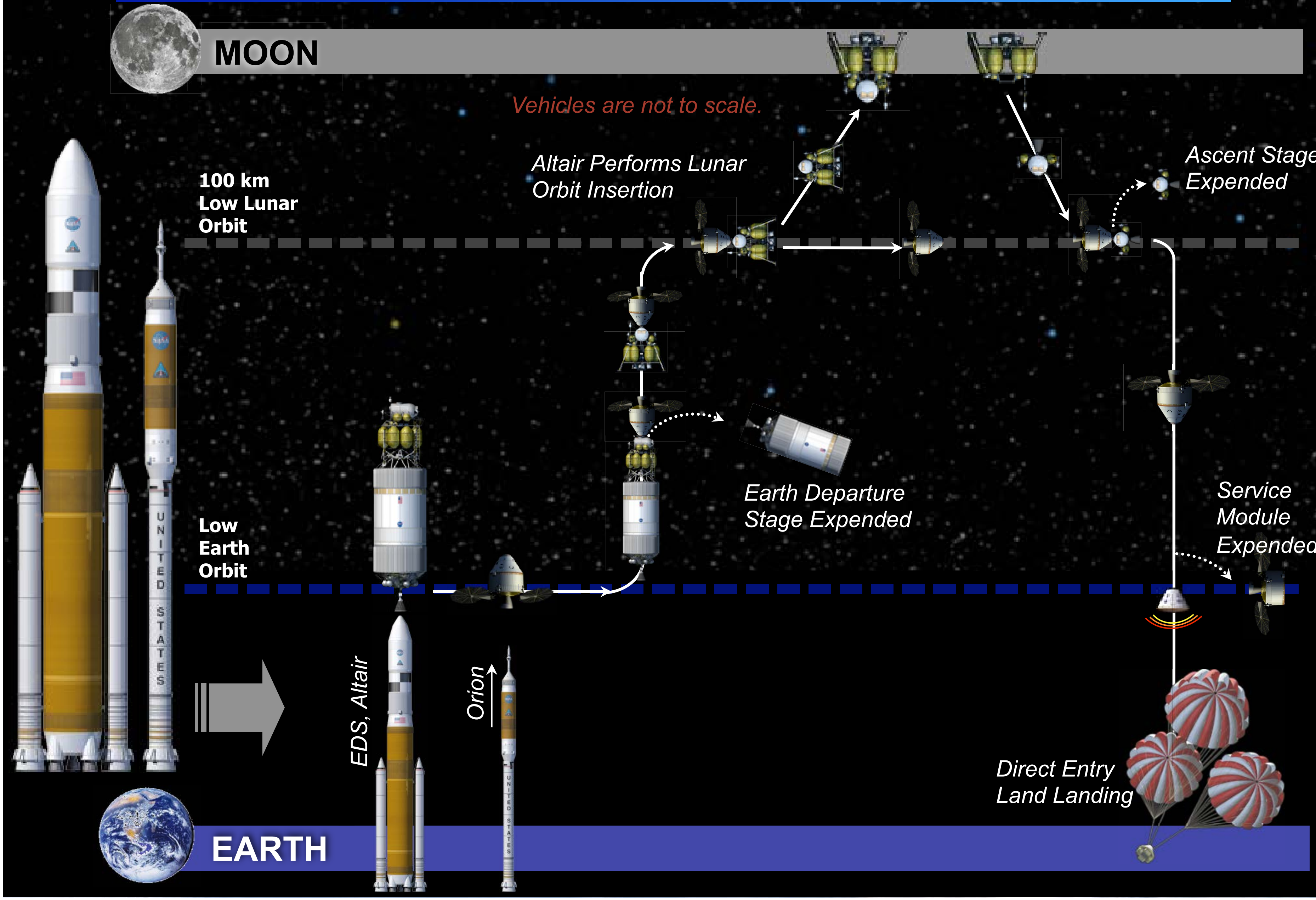
The Path Forward

- The future of the human space flight program, and thus the Constellation program, is currently being discussed at the highest levels of the U.S. government
- For the purposes of documenting the Altair GN&C design, this set of presentations are made without consideration of any forthcoming changes in the direction (or even existence) of the program.

Components of the Constellation Program Transportation Architecture

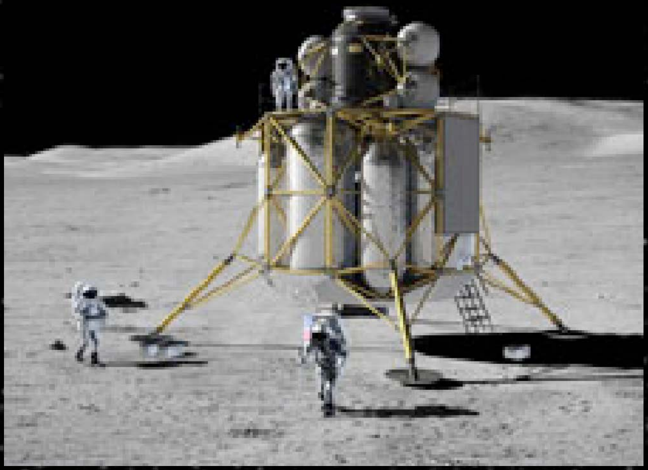


A Design Reference Mission



Lunar Lander Altair

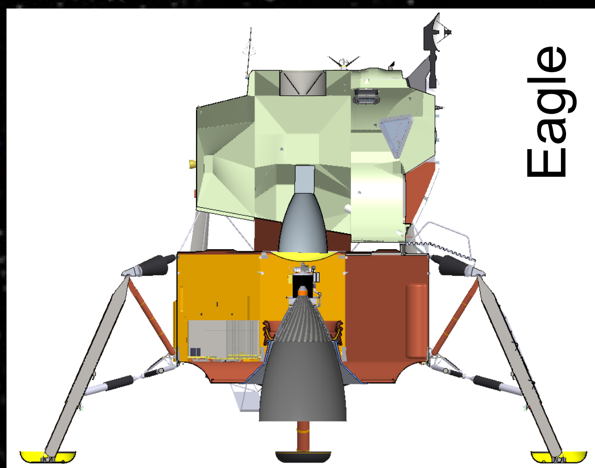
- A two-stage landing craft capable of bringing the entire crew to the surface
- High-level requirements:
  - Global access ("to land anywhere")
  - Any lighting condition ("to land anytime")
  - Maximize landed "payload" mass
  - Crew of four
  - 7 day minimum sortie surface stay
  - Return home at any time
  - Crew has an ABORT capability throughout the descent profile



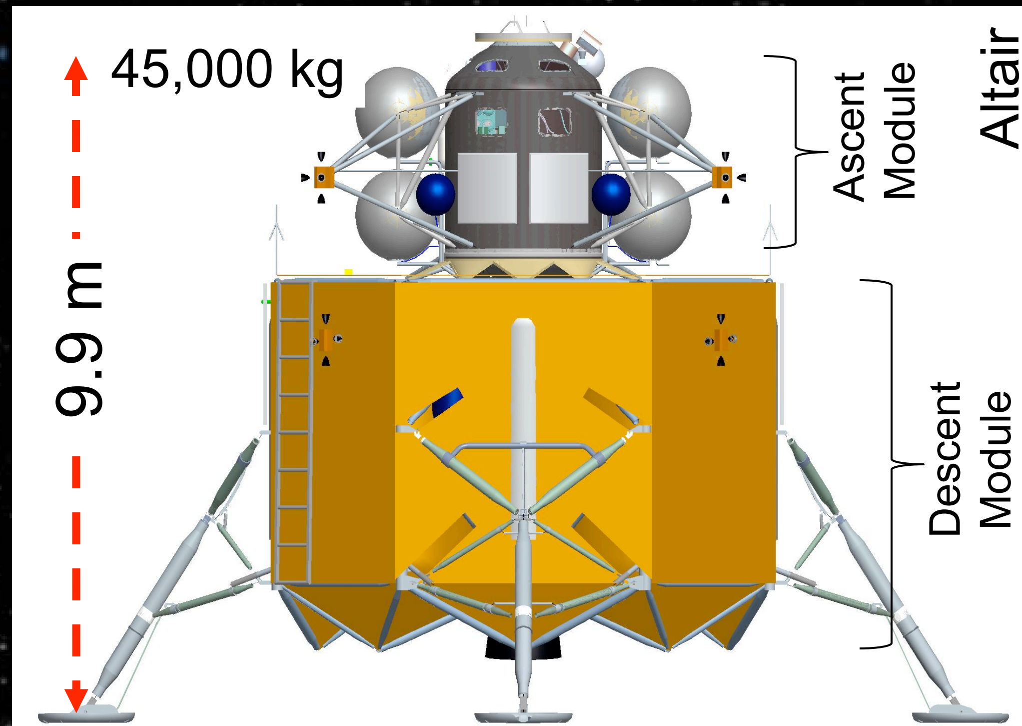
Comparison of Past and Future Lunar Landers

15,000 kg

6.7 m



9.5 m



14.9 m

More Crew
More Cargo
Execution of the Lunar Orbit Insertion ΔV

Lunar Lander Guidance, Navigation, and Control Functions

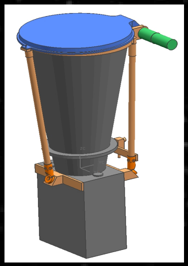
- Estimate and control the inertial attitude (and attitude rate) of the mated Orion/Altair vehicle
- Estimate the vehicle's state vector (position and velocity vectors)
- Perform flight path control via ΔV burns
- Compute and execute maneuvers associated with descent and landing
- Land Altair at a selected site satisfying specified landing accuracy and touch-down condition
  - Detects terrain hazards and recommends safe landing sites
- Generate telemetry data for Mission controls and for display to Crews
- With flexible hardware and software configurations, support the measurements and maneuver necessary for aborts

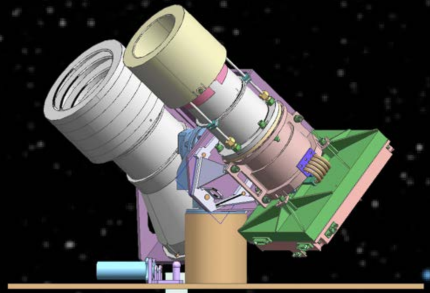
Notional Altair GN&C Sensors and Equipment†


MIMU


SIRU [backup IMU]


Star Tracker


Dust Cover

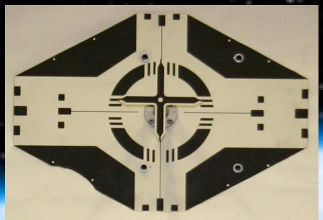

Optical navigation system (with B/U tracker on gimbal)

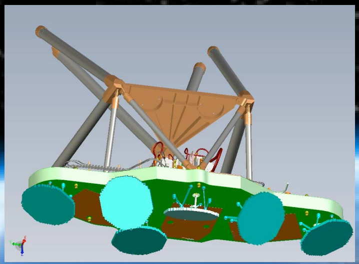

Laser range Finder


Docking camera


LIDAR


Terrain Hazard detection sensor System (on gimbal)

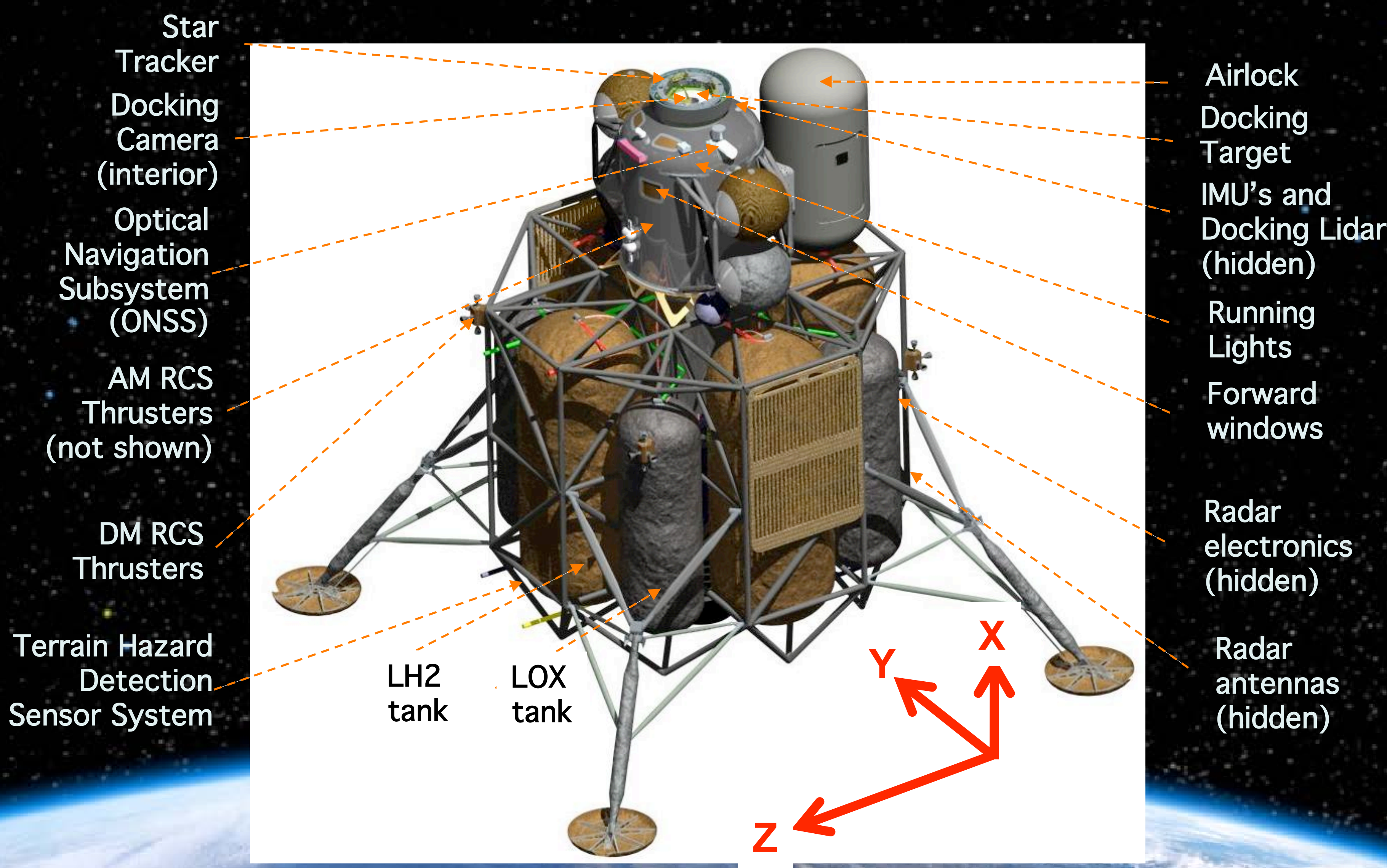

Docking Target


Descent Radar


DSN

†The intent in making this selection was not to promote Any particular vendor's sensor or rule out possible use of different sensors in the ultimate spacecraft design, but rather to specify a representative set of sensors that can provide the requisite functionality, based on currently-available technology.

Notional GN&C Sensors and their Placements

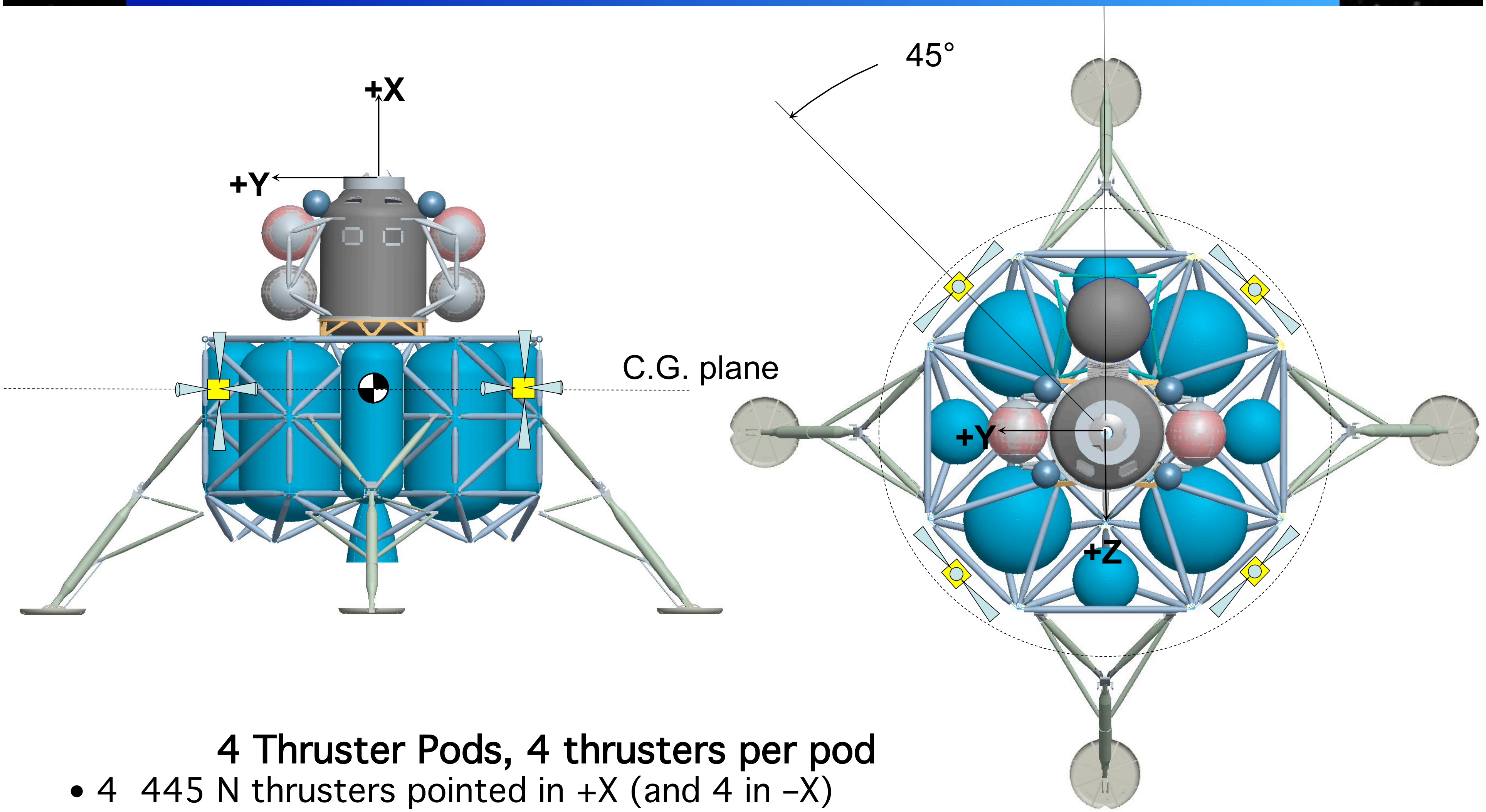


Overview: Effectors

- Descent engine
  - The Common Extensible Cryogenic Engine, or CECE, is fueled by a mixture of liquid O_2 and liquid H_2 chilled to sub-zero temperatures

- Reaction control thrusters on both the Descent and Ascent Modules provide:
  - Attitude control during powered descent and ascent
  - Trajectory Correction ΔV's during trans-lunar coast
  - Post-ascent rendezvous burns, proximity operations and docking control
  - MMH/NTO (fuel/oxidizer) thrusters

Descent Module RCS Thruster Configuration

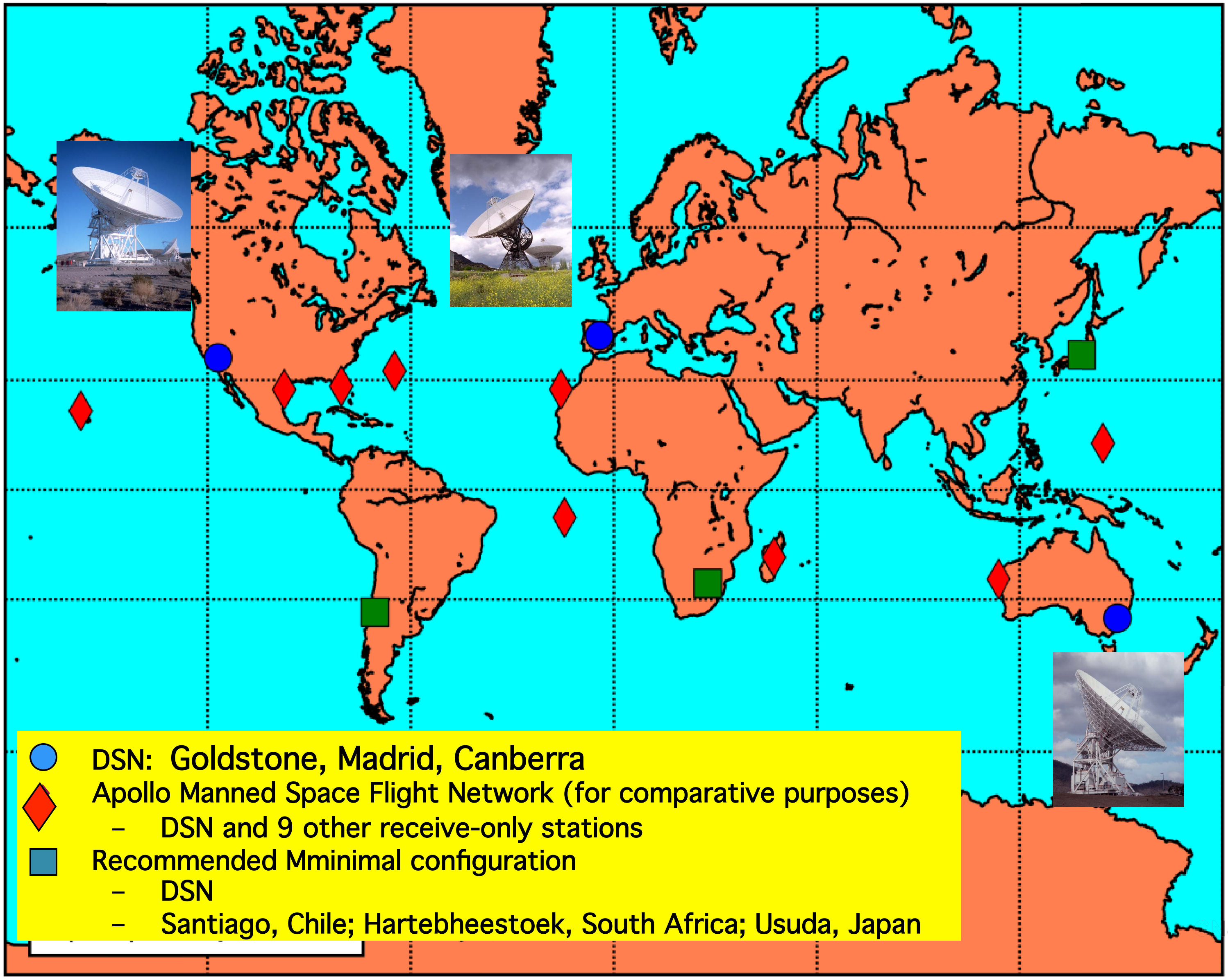


4 Thruster Pods, 4 thrusters per pod

- 4 445 N thrusters pointed in +X (and 4 in –X)
- 2 445 N thrusters pointed in +Y+45° (and 2 in -Y-45°)
- 2 445 N thrusters pointed in +Z+45° (and 2 in -Z-45°)

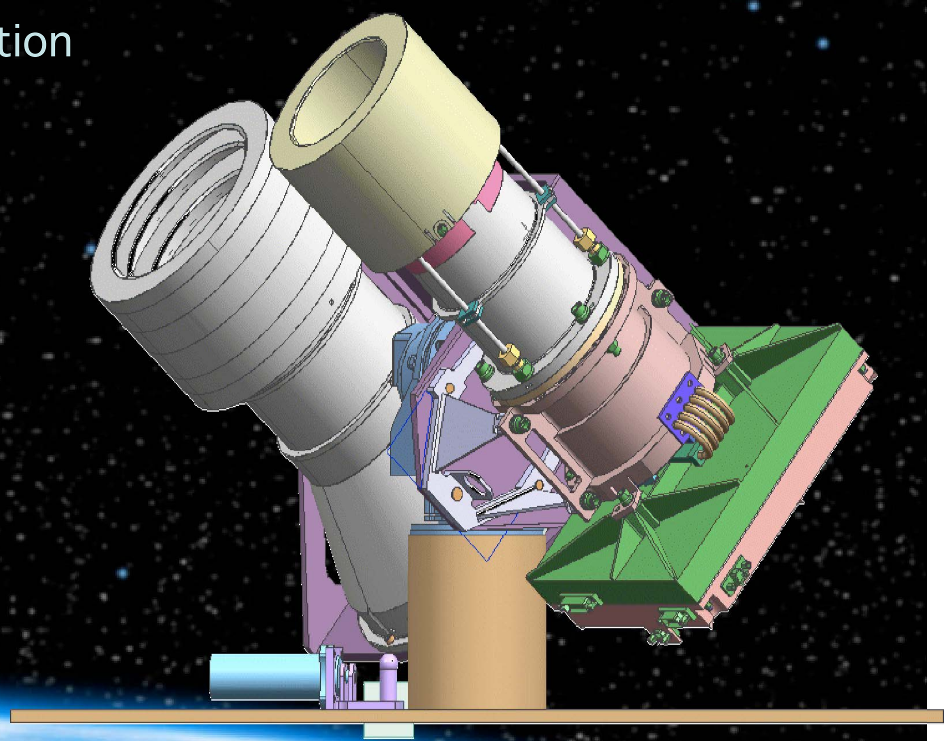
Earth-Based Ground Network

EBGS Locations

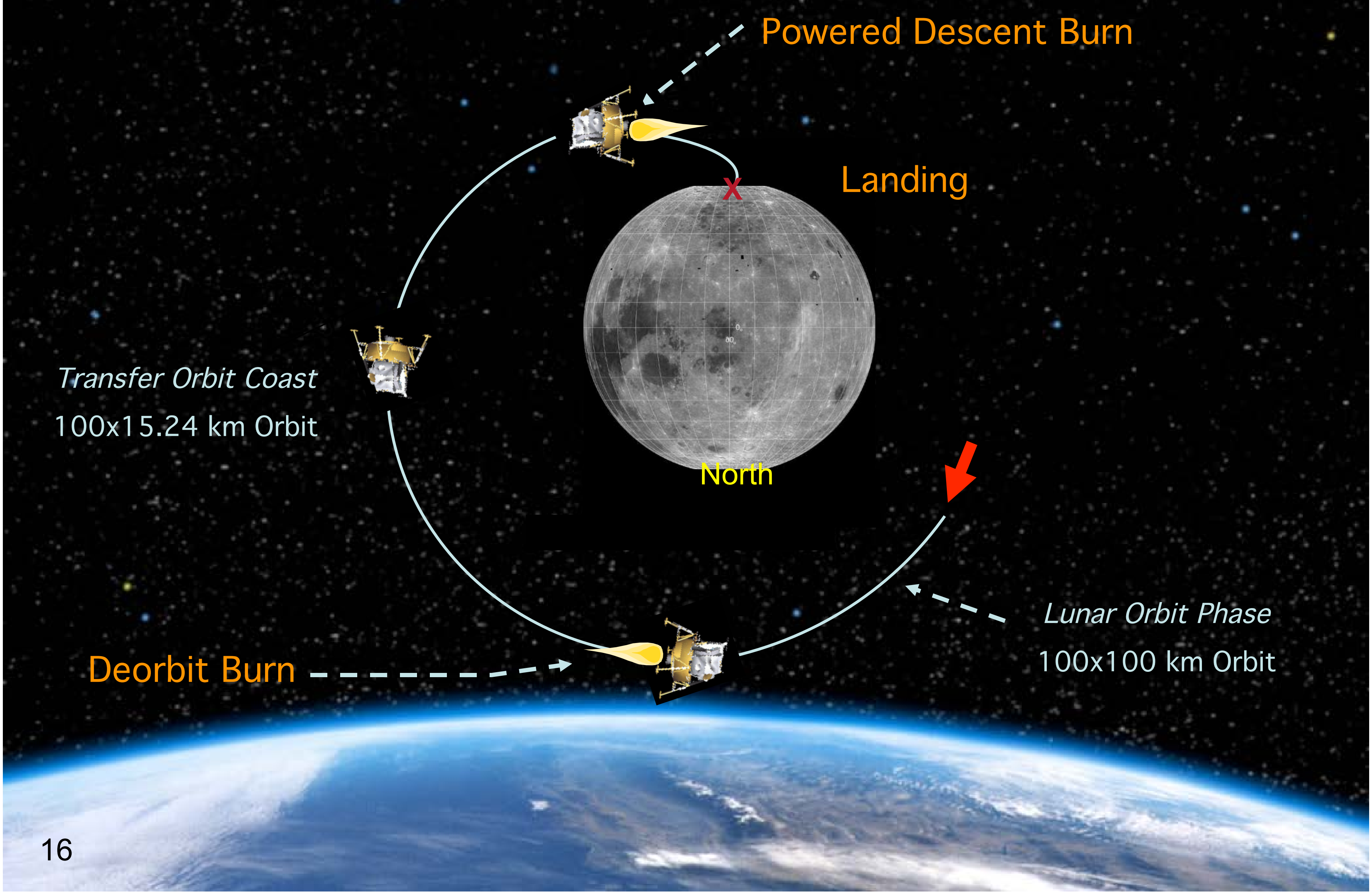


Optical Navigation

- All Constellation elements are required to “get the crew home” even when communications links are down or degraded:
  - To ensure the safety of the crew by allowing the Constellation systems to still function adequately if there were permanent or unplanned intermittent communication service outages preventing or limiting the ability of Mission Systems to interface with the vehicles
  - Without state vector updates, optical navigation is the only way to estimate the vehicle’s state vector



Deorbit and Descent ΔV



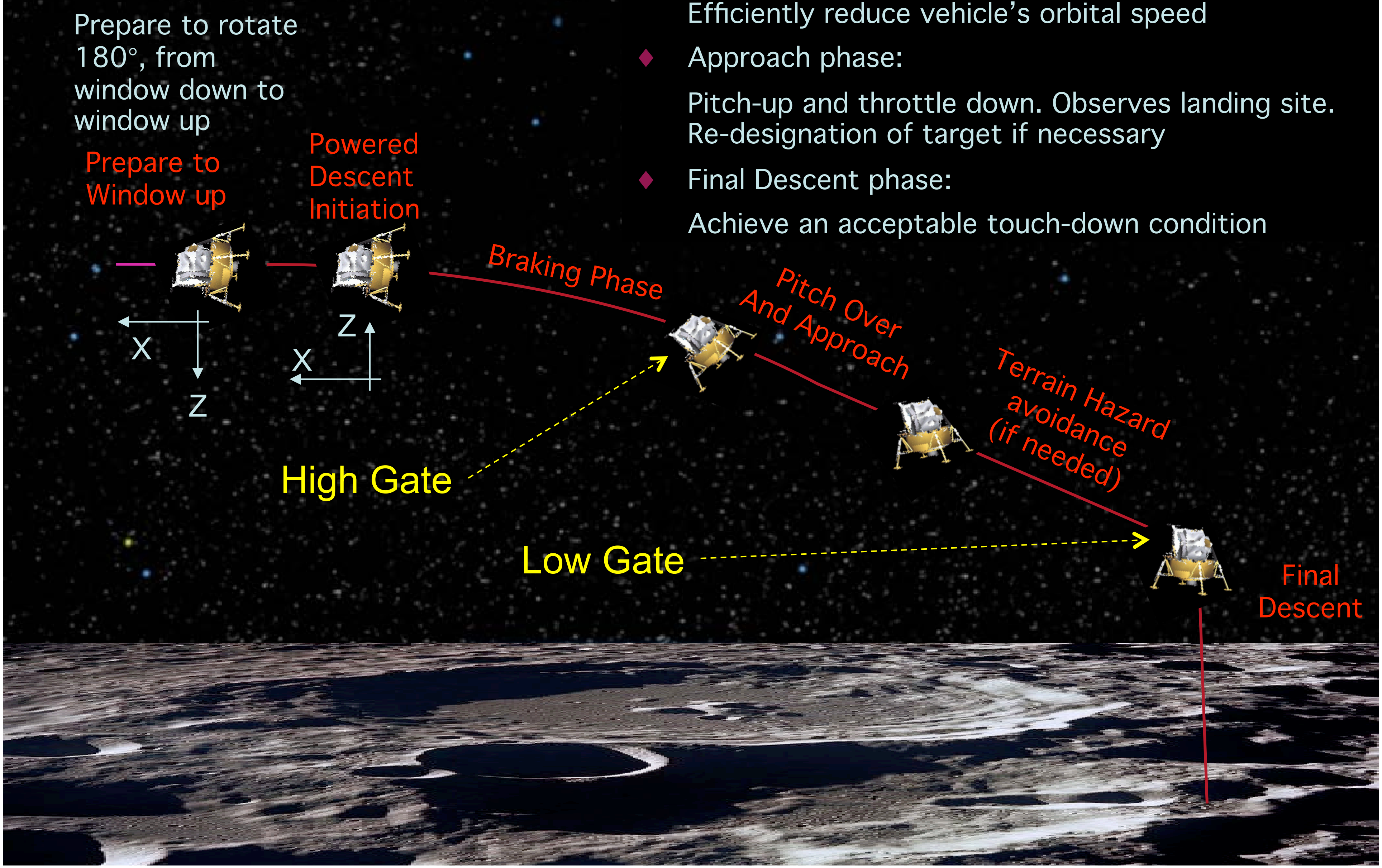
Notional Descent Guidance Trajectory Design

- Braking Phase:

  Efficiently reduce vehicle's orbital speed
- Approach phase:

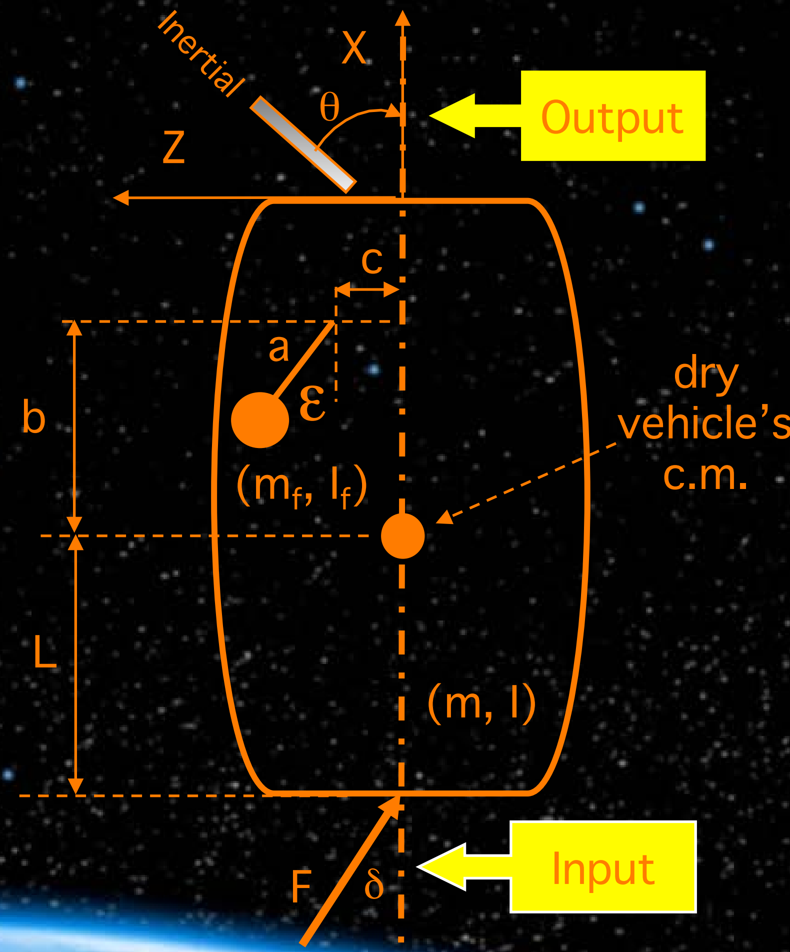
  Pitch-up and throttle down. Observes landing site. Re-designation of target if necessary
- Final Descent phase:

  Achieve an acceptable touch-down condition

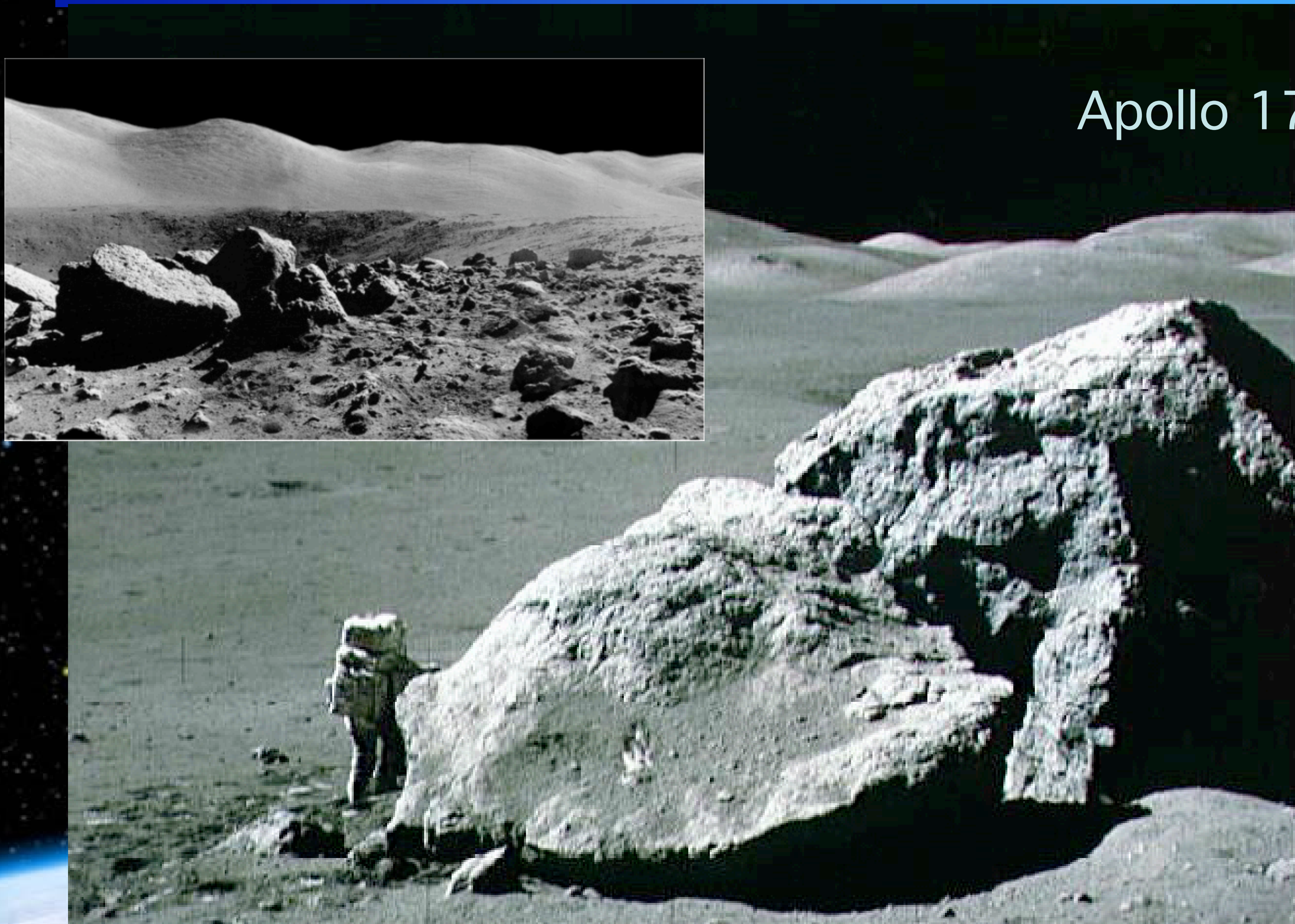


Unstable Interactions between TVC and Fuel Slosh Mode

- Lessons learned from past missions:
  - Loss of the ATS-V spacecraft in 1969
  - Loss of Intelsat IV in 1977
  - NEAR (Near Earth Asteroid Rendezvous, launched on 2/17/96):
    - During a critical orbital correction maneuver on 12/20/98, the spacecraft experienced unexpected motion one second after ignition and was “safed” by Fault Protection
  - Apollo-11 experienced TVC/Slosh interaction during powered descent and the entire duration of the trans-Earth injection burn



Landing Hazard: Rocks, Boulders, and Slopes

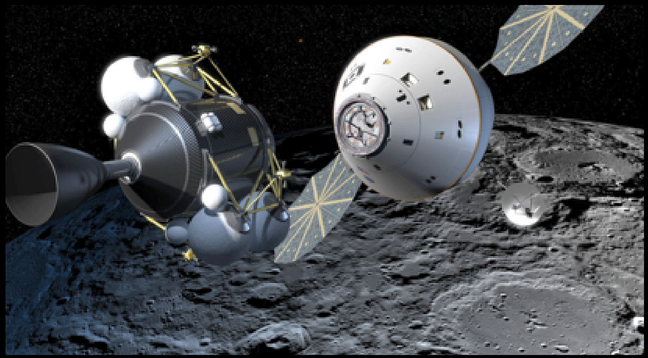


Ascent Guidance Trajectory

- Trajectory Phases:
  - Vertical rise
  - Single axis rotation (SAR)
  - Powered Explicit Guidance (PEG, Space Shuttle heritage) to engine cutoff
- Constraints:
  - Apoapse = 75 km at burnout
  - Periapse ≥ 15.24 km at burnout

Docking of Altair with Orion

- Background:
  - Orion is in a 100-km LLO
  - Altair will be the Active vehicle
- Docking sensors:
  - Far field (800 km to 5 km)
    - S-band 2-way radiometric data to provide range and range rate
    - Star tracker to provide bearing angles to Orion
    - Optical navigation sensor system will also provide estimates of range and bearing
  - Near field (5 km to <150 m)
    - Lidar to provide both range and bearing angle measurements
  - Close range (<150 m):
    - Lidar will provide relative attitude data ("pose"), to be supplemented by docking camera
    - Pilot-in-loop control (visual target will be mounted on Orion)



Other NASA Missions Head Moonward

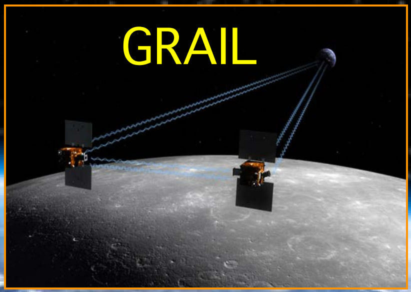
- Lunar Reconnaissance Orbiter (LRO), 6/18/09
  - Map the surface of the Moon. Find suitable landing sites

Done

- Lunar Crater Observation and Sensing Satellite (LCROSS), 6/18/09
  - Find answers to the question: “Are there raw materials that might be harvested and processed into rocket fuel, breathable air, and drinkable water?”
    - You cannot always bring everything you need on the Moon from Earth

Done

- Gravity Recovery and Interior Laboratory (GRAIL), 2011
  - Use gravity field mapping techniques to determine the Moon’s interior structure
  - Data collected will improve the current Moon gravity model: Improve landing accuracy
- Lunar Atmosphere and Dust Environment Explorer (LADEE), 2011



Altair GN&C Challenges

Other Topics to Cover In This Session

Challenges	Presenter	Time
Altair **Navigation** during Trans-Lunar Cruise, Lunar Orbit, Descent and Landing	Ely	2:30-3:00
Optical Navigation Plan and Strategy for the Lunar Lander Altair	Riedel	3:00-3:30
Altair Descent and Ascent **Reference Trajectory** Design and Initial Dispersion Analyses	Kos	3:30-4:00
Preliminary Characterization of Altair Lunar Lander **Slosh Dynamics** and Some Implications for the Thrust Vector Control Design	Lee	4:00-4:30
Terrain Hazard Detection and Avoidance during the Descent and Landing Phase of the Lunar Lander Altair Mission	Strahan (TBD)	4:30-5:00
Rendezvous and Docking Sensor and Effector System Designs for the Lunar Lander Altair	Lee	5:00-5:30