National Aeronautics and Space Administration

ADVANCED EXPLORATION SYSTEMS

NASA Advisory Council HEO Committee • May 13, 2020

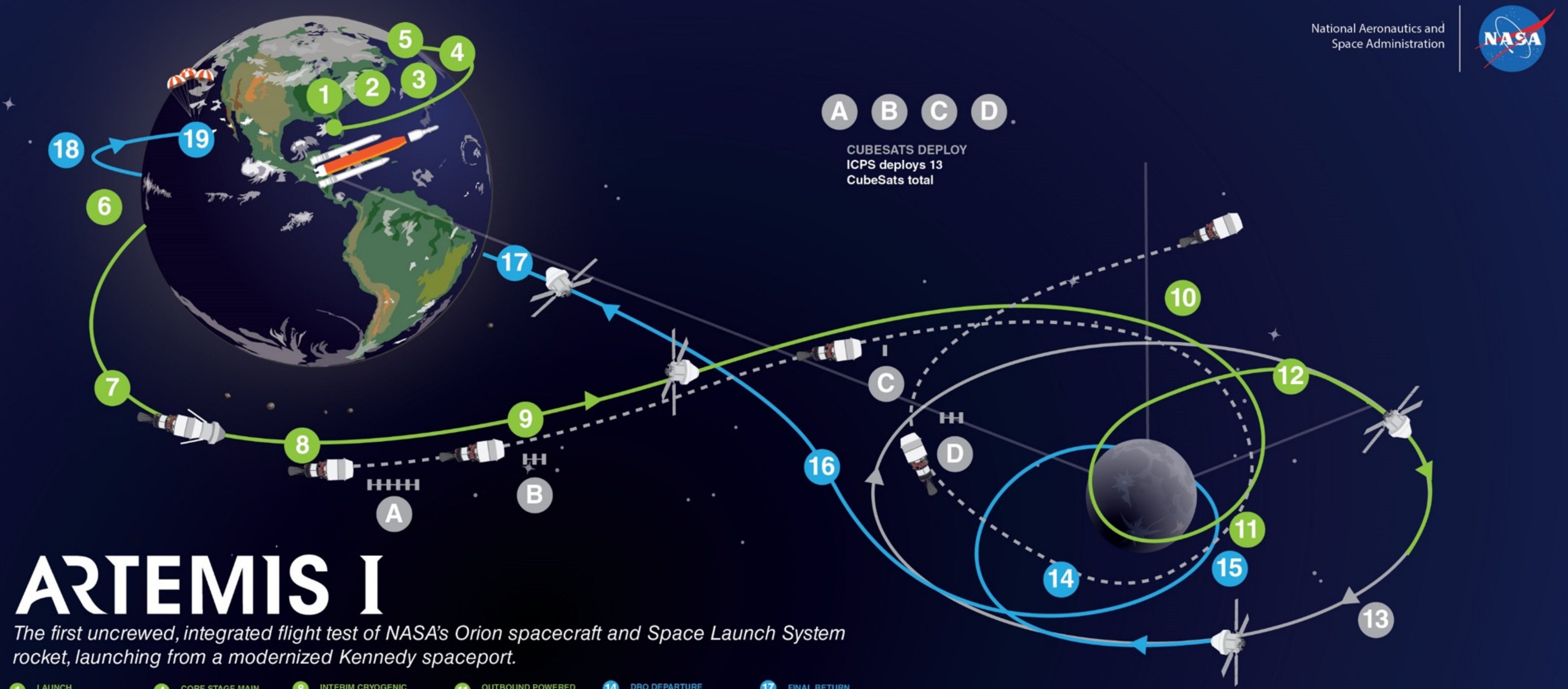
MARSHALL SMITH

DIRECTOR, HUMAN LUNAR EXPLORATION PROGRAMS

MISSION TRADES

Artemis Mission Trades

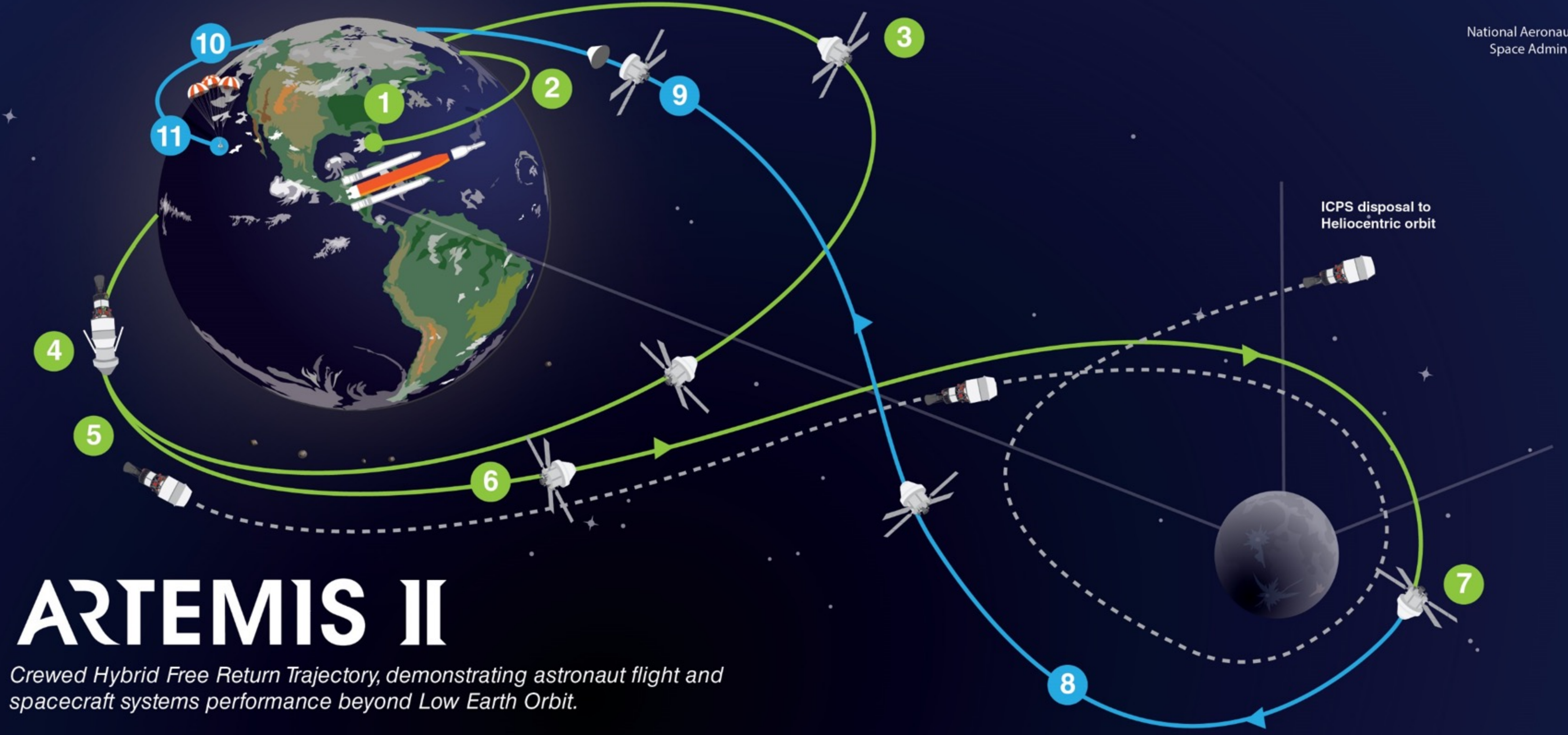
- Conducts mission trades across HEOMD to balance risk and ensure overall mission success
- Current activities include:
  - Orbits trades (NRHO vs. lunar polar orbits)
  - Balance of risk between Artemis I, II, and III, e.g., abort options
  - Options to demonstrate Rendezvous and Proximity Operations (RPO) on Artemis II



ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport.

1. **LAUNCH**
   SLS and Orion lift off from pad 39B at Kennedy Space Center
2. **JETTISON ROCKET BOOSTERS**
   Solid rocket boosters separate
3. **JETTISON LAUNCH ABORT SYSTEM (LAS)**
   The LAS is no longer needed, Orion could safety abort
4. **CORE STAGE MAIN ENGINE CUT OFF**
   With separation
5. **ENTER EARTH ORBIT**
   Perform the perigee raise maneuver
6. **EARTH ORBIT**
   Systems check and solar panel adjustments
7. **TRANS LUNAR INJECTION (TLI) BURN**
   Manuver lasts for approximately 20 minutes
8. **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION**
   The ICPS has committed Orion to TLI
9. **OUTBOUND TRANSIT**
   Requires several attitude maneuvers
10. **OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS**
    As necessary adjust trajectory for Lunar flyby to Distant Retrograde Orbit (DRO)
11. **OUTBOUND POWERED FLYBY (OPF)**
    62 miles from the Moon; targets DRO insertion
12. **LUNAR ORBIT INSERTION**
    Enter Distant Retrograde Orbit for next 6-23 days
13. **DISTANT RETROGRADE ORBIT**
    Orbit Maintenance burns and solar panel adjustments; 38,000 nmi from the surface of the Moon
14. **DRO DEPARTURE**
    Leave DRO and start return to Earth
15. **RETURN POWER FLY-BY (RPF)**
    RPF burn prep and return coast to Earth initiated
16. **RETURN TRANSIT**
    Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 3-11 days
17. **FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN**
    Precision targeting for Earth entry
18. **ENTRY INTERFACE (EI)**
    Enter Earth's atmosphere
19. **SPLASHDOWN**
    Pacific Ocean landing within view of the U.S. Navy recovery ships



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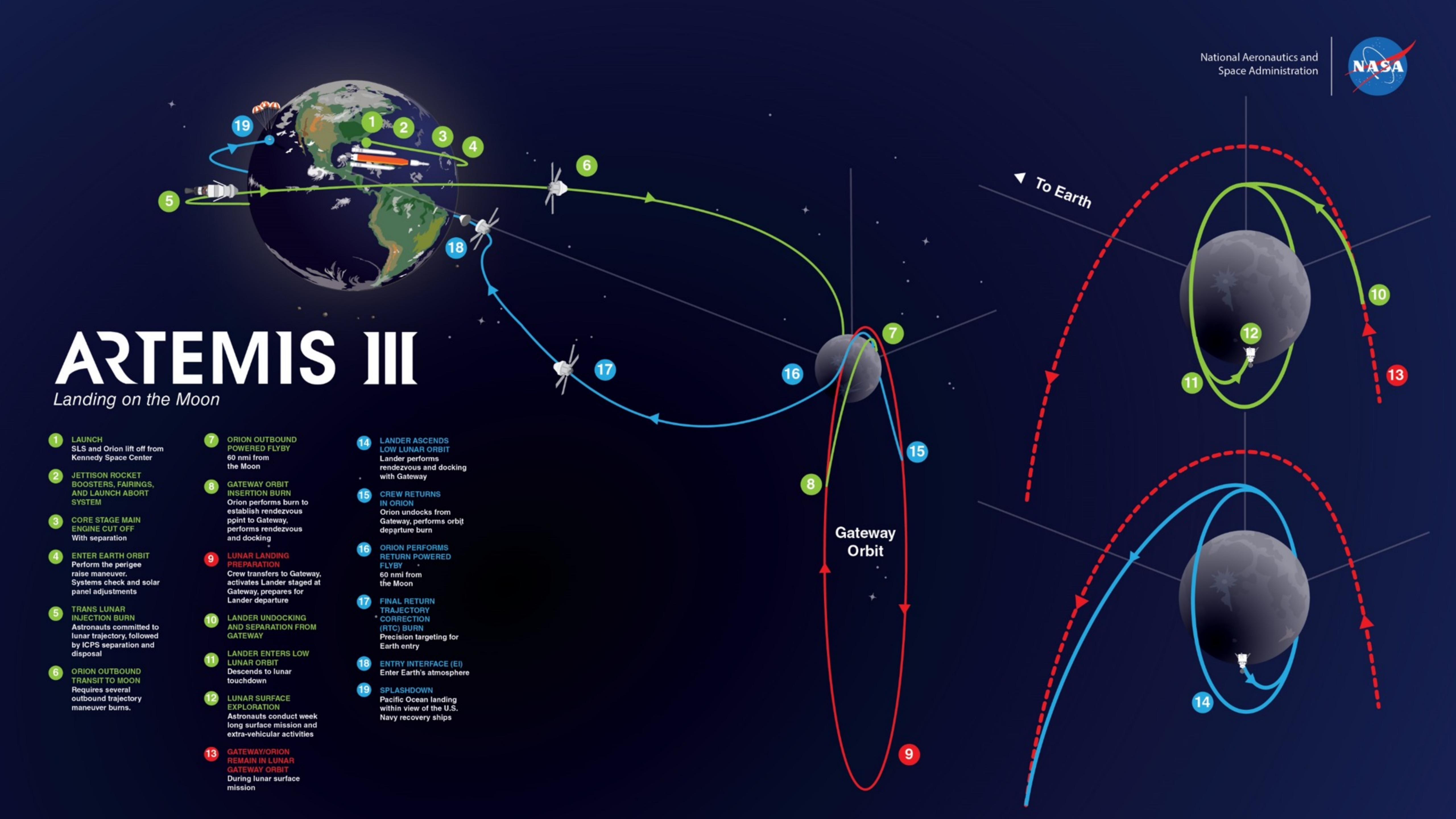
ARTEMIS II

Crewed Hybrid Free Return Trajectory, demonstrating astronaut flight and spacecraft systems performance beyond Low Earth Orbit.

1. **LAUNCH**
2. **ENTER EARTH ORBIT**
   Perigee Raise Maneuver (PRM) by Interim Cryogenic Propulsion Stage (ICPS) into 100x1545 nmi orbit
3. **HIGH EARTH ORBIT**
   Life support, exercise, and habitation equipment evaluations. 42 hour checkout of spacecraft
4. **APOGEE RAISE BURN TO HIGH EARTH ORBIT**
   Followed by ICPS separation and disposal burn
5. **ORION TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**
6. **TRANS-LUNAR OUTBOUND**
   4 days outbound transit along free return trajectory
7. **LUNAR FLYBY**
   4,000 nmi (mean)
8. **TRANS-EARTH RETURN**
   4 days return transit along free return trajectory
9. **CREW MODULE/SERVICE MODULE SEPARATION**
10. **ENTRY, DESCENT, AND LANDING**
11. **CREW AND ORION CAPSULE RECOVERY**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ARTEMIS III
Landing on the Moon
1 LAUNCH
SLS and Orion lift off from Kennedy Space Center
2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3 CORE STAGE MAIN ENGINE CUT OFF
With separation
4 ENTER EARTH ORBIT
Perform the perigee raise maneuver. Systems check and solar panel adjustments
5 TRANS LUNAR INJECTION BURN
Astronauts committed to lunar trajectory, followed by ICPS separation and disposal
6 ORION OUTBOUND TRANSIT TO MOON
Requires several outbound trajectory maneuver burns.
7 ORION OUTBOUND POWERED FLYBY
60 nmi from the Moon
8 GATEWAY ORBIT INSERTION BURN
Orion performs burn to establish rendezvous point to Gateway, performs rendezvous and docking
9 LUNAR LANDING PREPARATION
Crew transfers to Gateway, activates Lander staged at Gateway, prepares for Lander departure
10 LANDER UNDOCKING AND SEPARATION FROM GATEWAY
11 LANDER ENTERS LOW LUNAR ORBIT
Descends to lunar touchdown
12 LUNAR SURFACE EXPLORATION
Astronauts conduct week long surface mission and extra-vehicular activities
13 GATEWAY/ORION REMAIN IN LUNAR GATEWAY ORBIT
During lunar surface mission
14 LANDER ASCENDS LOW LUNAR ORBIT
Lander performs rendezvous and docking with Gateway
15 CREW RETURNS IN ORION
Orion undocks from Gateway, performs orbit departure burn
16 ORION PERFORMS RETURN POWERED FLYBY
60 nmi from the Moon
17 FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN
Precision targeting for Earth entry
18 ENTRY INTERFACE (EI)
Enter Earth's atmosphere
19 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ships
Gateway Orbit
To Earth

Flight Test Objectives Coverage Options

Sum total coverage of objectives accomplished on each manifest *prior to* Artemis III (excluding ground test

SPACE LAUNCH SYSTEM

Mission/Test	Core Int. MPS	Core Stage Perf.	Booster Perf	Sep Motor	Booster Sep/Pyro	Engine Perf.	Engine Ctl.	Crew Cap (EDS/SW)	ICPS Perf	ICPS Sep Events	Int. Crew Capable FSW	Integrated B1 Stack	B1 Liftoff/sep/timing	B1 Flight Env	EUS Sep Events	EUS Performance	Integrated MPS	Int. Flight Operations
Option A - Enhanced Manifest	●	●	●	●	●	●	●	●	●	●	●	●	●	◐		◐	◐	●
Option B - Maximize Cap. Demos	●	●	●	●	●	●	●	●	●	●	●	●	●	◐				●
Option C - Lunar Encounter Demo	●	●	●	●	●	●	●	●	●	●	●	●	●	◐				●
Option D - HLS 2 Element HEO FT	●	●	●	●	●	●	●	●	●	●	●	●	●	◐				●
Option E - HLS 3 Element NRHO FT	●	●	●	●	●	●	●	●	●	●	●	●	●	◐				●
HLS Launch & Cis-lunar Transit (B1B)															🔴	🔴	🔴	
Integrated Lunar Landing	●	●	●	●	●	●	●	●	●	●	●	●	●	◐				●

ORION

Mission/Test	CM Structural	EDL Systems	GN&C	CM Thermal Mgmt	CM Power Mgmt	Communications	CM Propulsion	ECLS	Crew Systems	RPOD	Separation Events	SM Structural Integrity	TPS (Ascent)	SM Thermal Mgmt	SM Power Mgmt	SM Propulsion	Mission Sequencing	FDIR	Primary FSW	Backup FSW	Ascent Abort	SLS B1 Interfaces	EGS Interfaces	Int. Flight Operations
Option A - Enhanced Manifest	●	●	●	●	●	●	●	●	●	◐	●	●	●	●	●	●	●	●	●	●	●	●	●	◐
Option B - Maximize Cap. Demos	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Option C - Lunar Encounter Demo	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Option D - HLS 2 Element HEO FT	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Option E - HLS 3 Element NRHO FT	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
HLS Launch & Cis-lunar Transit (B1B)																								
Integrated Lunar Landing	●	●	●	●	●	●	●	●	●	🔴	●	●	●	●	●	●	●	●	●	●	●	●	●	🔴

GATEWAY

Mission/Test	Int. Loads	ECLS	Docking & Plumes	GNC	Int. Thermal	Comm Systems	Cmd & Control	Environments	Power Systems	Crew Systems	Flight Software	Int. Flight Operations
Option A - Enhanced Manifest	◐	◐		●	●	◐	●	●	●		●	◐
Option B - Maximize Cap. Demos	◐	◐	◐	●	●	◐	●	●	●	◐	●	◐
Option C - Lunar Encounter Demo	◐	◐		●	●	◐	●	●	●		●	◐
Option D - HLS 2 Element HEO FT	◐	◐		●	●	◐	●	●	●		●	◐
Option E - HLS 3 Element NRHO FT	◐	◐		●	●	◐	●	●	●		●	◐
HLS Launch & Cis-lunar Transit (B1B)												
Integrated Lunar Landing (w/ Gateway)	🔴	🔴	🔴	●	●	🔴	●	●	●	🔴	●	🔴

HLS - VEHICLE FUNCTIONS

Mission/Test	Avionics/GNC checkout and use	RF comm commanding and ranging	Propulsion checkout and use	All guidance control modes	Thermal management	Long duration in situ operation	Inter-element RPOD (3-elmt only)	Uncrewed partial active/passive RPOD	Crewed Partial active/passive RPOD	Integrated Stack Control	ECLSS checkout and use	Manual control	Automation	Element staging/separation	Separation from Launch Vehicle*	Precision orbital insertion	Precision landing	Hazard avoidance	Lander leveling (if applicable)	Propulsive disposal	Aborts/off-
Option A - Enhanced Manifest	◐	◐	◐	◐	●	◐	◐			◐			◐			◐	◐	◐			◐
Option B - Maximize Cap. Demos	◐	◐	◐	◐	●	◐	◐	◐		◐			◐			◐	◐	◐			◐
Option C - Lunar Encounter Demo	◐	●	◐	◐	●	◐	◐	●	●	◐			◐			◐	◐	◐			◐
Option D - HLS 2 Element HEO FT	◐	●	●	●	●	◐	n/a	●	●	●		●	◐	●	●	●	◐	◐		●	●
Option E - HLS 3 Element NRHO FT	◐	●	●	●	●	◐	●	●	●	●		●	◐	●	●	●	●	●		●	●
HLS Launch & Cis-lunar Transit (B1B)	◐	●	◐	◐	●	◐	◐			◐					●	●					
Integrated Lunar Landing (w/ Gateway)	🔴	●	🔴	🔴	●	🔴	🔴	🔴	🔴	🔴	●	🔴	🔴	🔴	●	●	🔴	🔴	🔴	🔴	🔴

Assumes AE & CLPS, addition of optional free flyer DE test would close additional gaps

Majority of additional objectives achieved through addition of DE FT

◐: Partial Demonstration of Capability ●: Full Demonstration of Capability 🔴: Landing Mission Is First Demonstration of Full Capability

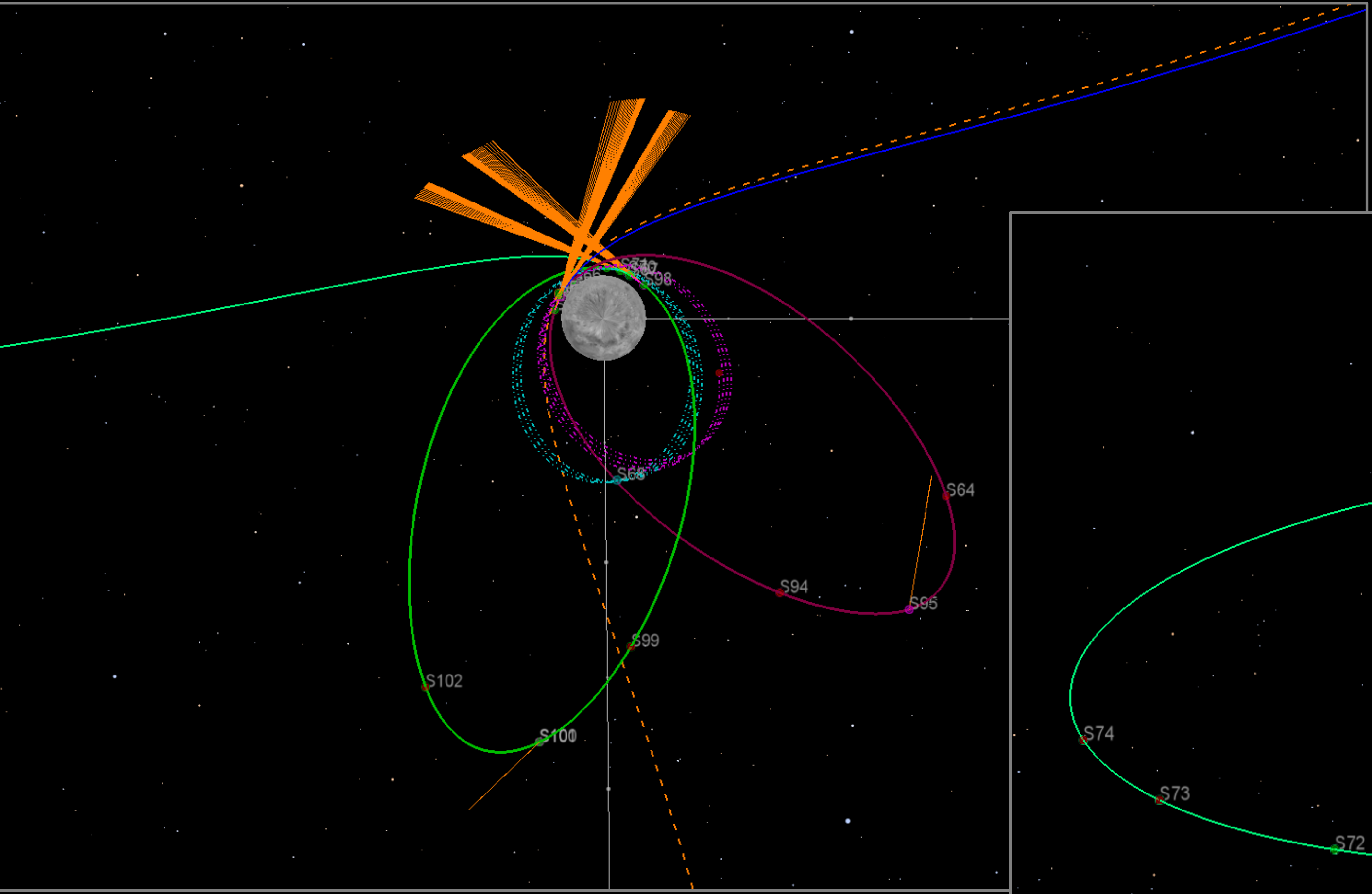
Gaps are closed via Orion RPO(D), AE and DE test flights

Capability Gap Findings

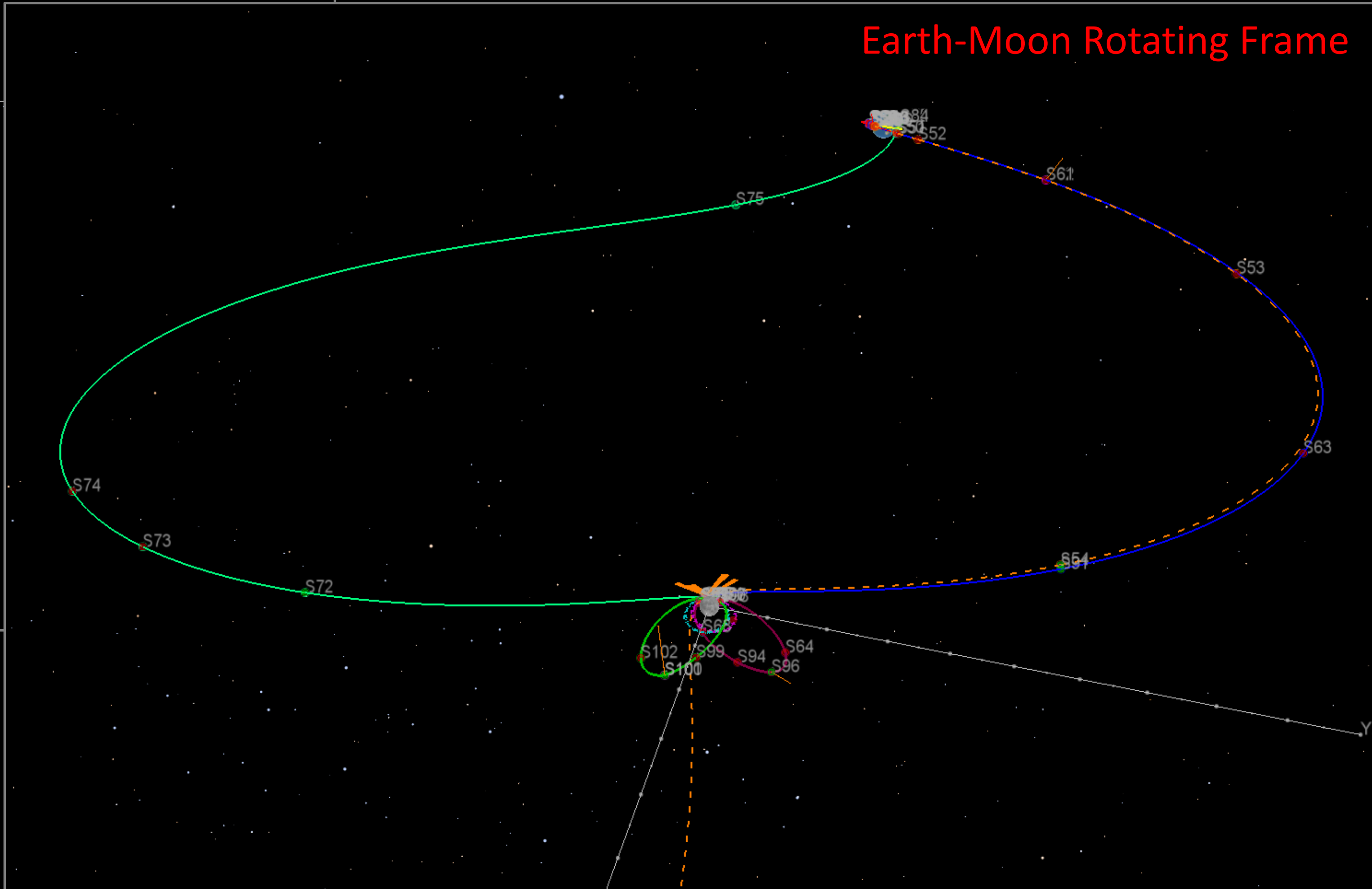
Program	Assessment			Benefit	Tech Risk	Sched Risk	Findings
Orion	Modify Artemis I to NRHO			Low	Low	Low/Med	Modification is feasible; however, requires rework of mission products/competing resources
	Artemis II RPOD Capability	Prox Ops/Hnd. Qual		High	Low	Med	Exercises majority of higher risk RPOD objectives, smaller schedule risks to Artemis-II
		Docking		Med	Med	High	Min additional benefit above Prox Ops/HQ demo, Hardware demonstrated via CCP-ISS flts
	Mission implementation	HEO	Prox Ops/HQ	High	Low	Low	Primary risks for RPOD are sensor demo which could be accomplished with ICPS operation
			RPOD	Med	High	High	No highly elliptical RNDZ exp., high mission opp. constraints, does not feed to AIII
		NRHO RPOD		Med	Low	Low	Near-linear dynamics, most flight like, w/o HEO dissimilar ECLS backup possible w/ 3 crew
Gateway	Support as a docking target	HEO		High	Med	High	Technically feasible, dual launch with limited schedule margin before Artemis III
		NRHO		High	Low	Infeas.	Availability on station in NRHO is too late to support flight tests
	GLS docking target	For Orion		Med	Low	Low	Not Test Like You Fly implementation, least schedule risk option for Orion docking
		For HLS AE		Low	Low	Med	AE rendezvous demonstration only, AE is the target vehicle for Orion in prox ops
HLS	Ascent Element flight test	Independent		Med	Med	Med/High	Most significant portion of HLS risk mitigated with any AE FT
		Orion Integrated		High	High	High	Most beneficial; boilerplate flight test int. avionics/crew ops possible, limited AIII schedule
	Descent/Transfer flight test	2- Element Arch		High	High	High	2-element or B1B sized could only be launch w/ New Glen to HEO, New Glen constrains dia.
		3- Element Arch		High	Med	High	Viable launch architecture for CLV heavy class operations per baseline design
		No DE FT mitigation		Med	Med	Med/High	CLPS or AE end of life demo to perform simulated lunar surface approach

Targeted modifications to the campaign could close integrated capability gaps

Elliptical Coplanar Posigrade



Graphics for a 4500x100 km coplanar
- Similar profile for 5500x100



- 4500 x 100 km orbit achievable near the limit of Orion performance
- Mission durations 15-17 days available
- 3-7 days available in parking orbit

Mission Risk Comparison to NRHO

Orbit Selection				Crew Risk				
	Orbit Period	Time in Orbit	MET	Abort Time (Surface to Orion, Does not include RPOD)	Abort Time (Orion to Earth)	Delay for missed Earth return window	Critical Maneuvers (Number of HLS maneuvers consistent)	Communication Outage to Orbit
Baseline NRHO	~6.5 days	~13-18 days	~25-34 days	0.5 to 2.5 days	~5-8 days ~1-2 day window per NRHO rev (some NRHO arrival conditions allow for aborts with METs <21 days total)	~4.5 days	OPF, NRI, RPODUs*, NRD, RPF	N/A
Elliptical Polar Orbit (EPO) with CoLA (6500 x 100 km)	~9 hours	~4.5-10.5 days	~20.5-23.5 days	11-13 hours	3.5-10 days Continuous abort window during orbit phase	~17 days	3 burn LOI Sequence 3 burn TEI Sequence (these occur in front of the Moon) RPODUs*	Comm losses due to occultation behind the Moon
Elliptical Lunar Orbit (ELO) Coplanar Posigrade ***[Equatorial- No Polar Access]*** (5500 x 100 km)	~8 hours	~7 days	~17.5 days	11 - 13 hours	3-8 days 5 day window	~20-21 days	3 burn LOI Sequence 3 burn TEI Sequence (these occur in front of the Moon) RPODUs*	Comm losses due to occultation behind the Moon

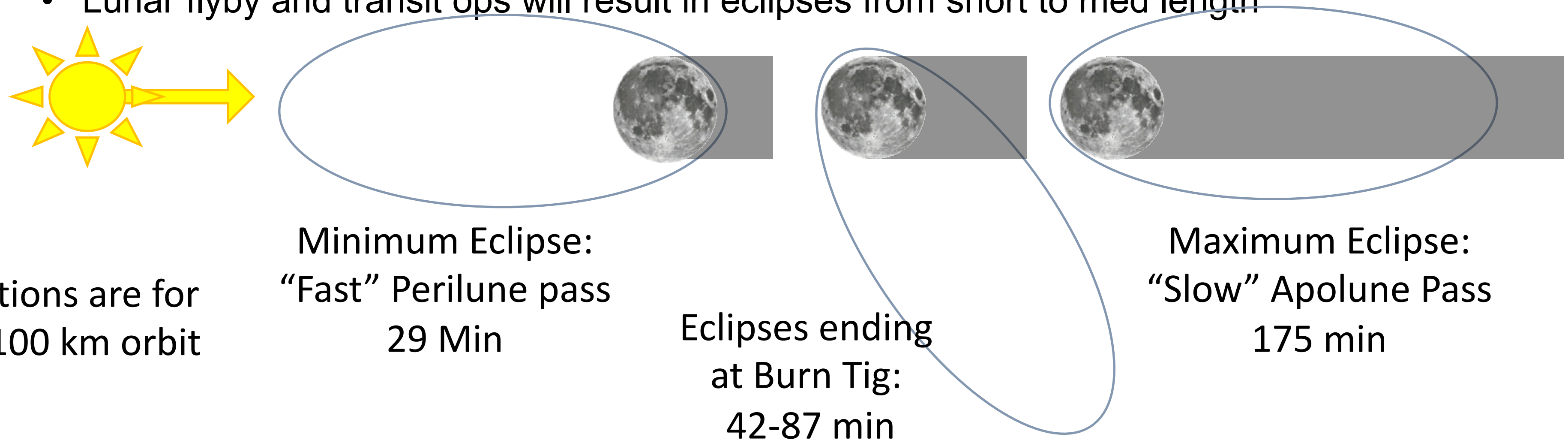
<u>Color compares to NRHO</u>
Blue – better than NRHO
Orange – worse than NRHO
Red – not viable

* All missions have Orion RPOD, HLS undock, HLS RPOD, and Orion undock

Forward Work - Eclipses

Example from previous analysis of 10000 x 100 km orbit:

- Utilizing perilune, apolune, and beta angle eclipse and insolation variations are derived
  - Thermal conditions of HLO are similar to transit (negligible lunar albedo)
- Use of resulting eclipse range used as a sizing bound for all operations
  - Mission design applies 3 hr long eclipse as sizing capability
  - Transit eclipses could be up to 7-8 hrs in length, eclipses >3hrs would be ‘cutouts’ in launch opportunity
- Lunar flyby and transit ops will result in eclipses from short to med length

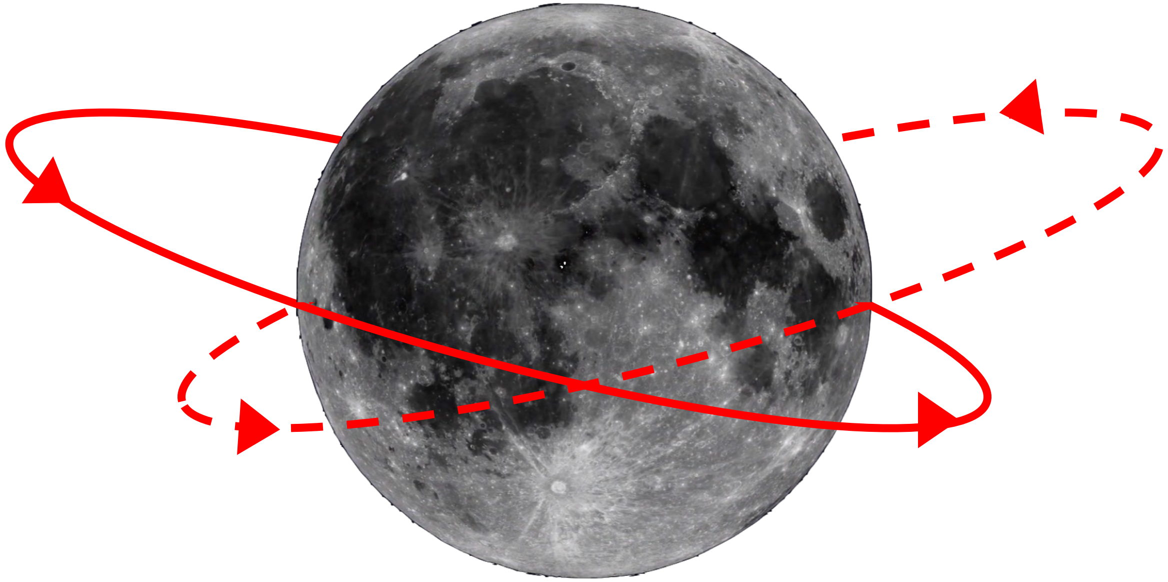


Note: durations are for a 10000 x 100 km orbit

Estimates for maximum eclipse durations for a 5500x100 coplanar posigrade orbit are ~2 hours

- Further work needed to assess seasonal variations and relations to major burns

Forward Work – Landing Site Impacts



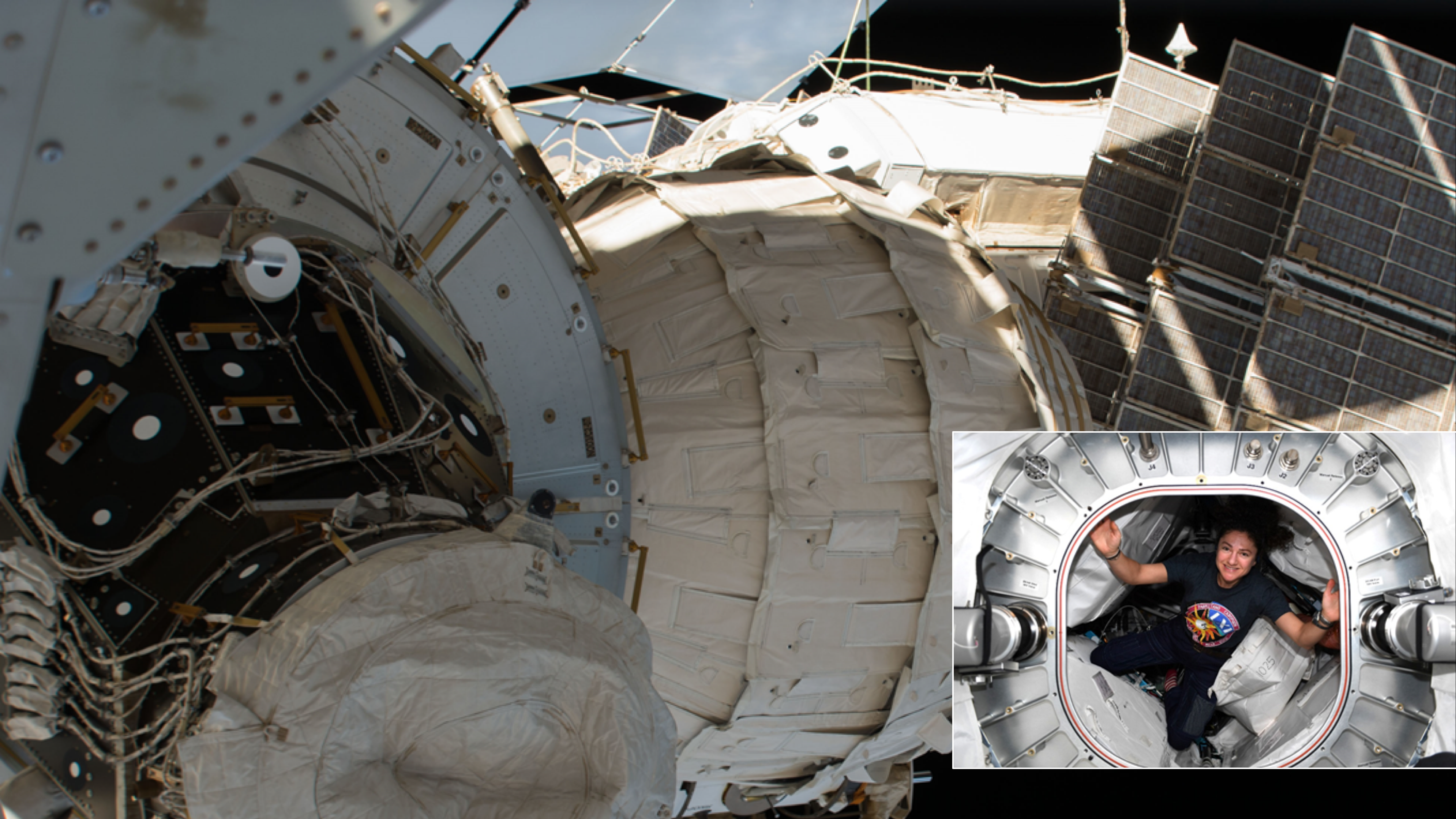
- Example shows the precession of an Earth-Moon “coplanar” orbit in the Moon centered Moon ME frame
  - Solid line indicates original orbit
  - Dashed line indicates orbit after ~14 days
- Orion drifts away from landing site during surface mission
  - Need to account for plane change

AES TECHNOLOGY DEVELOPMENT

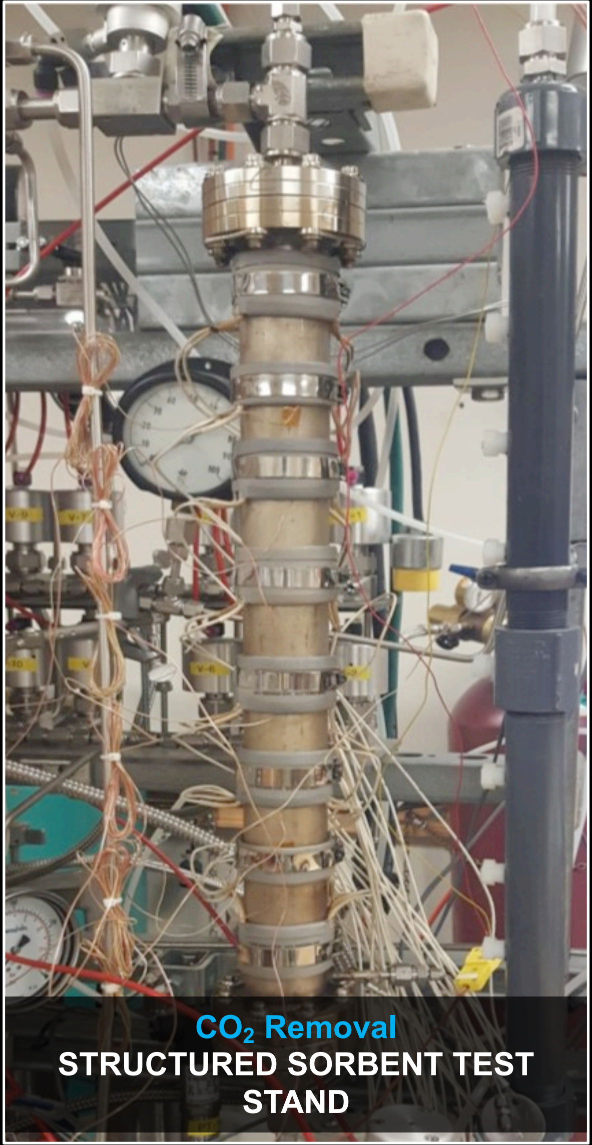
NextSTEP A: Habitation Systems

Phase 1 – 2015-2016: Concept Designs and Operations
Phase 2 – 2016-2019: Prototype Development and Testing
Phase 3 – 2019-2020: Continued testing focused on Gateway and Foundation Surface Habitat

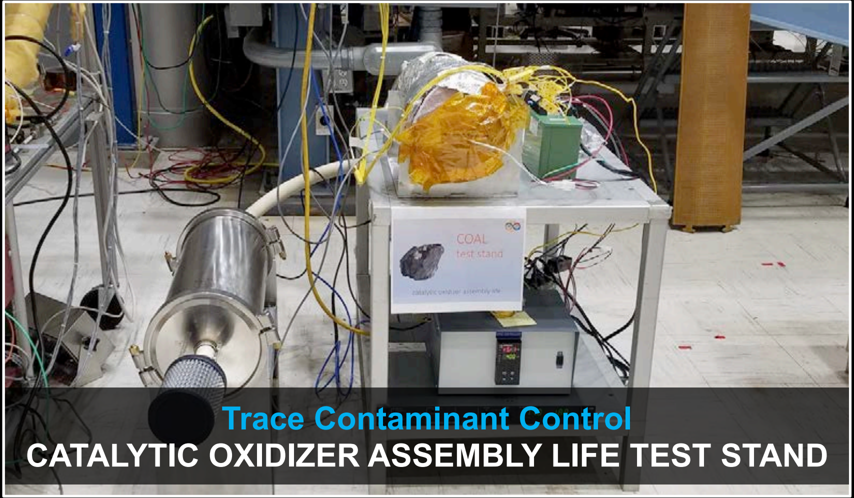
edit: Sierra Nevada Corporation


J4
J3
J2

Life Support Systems

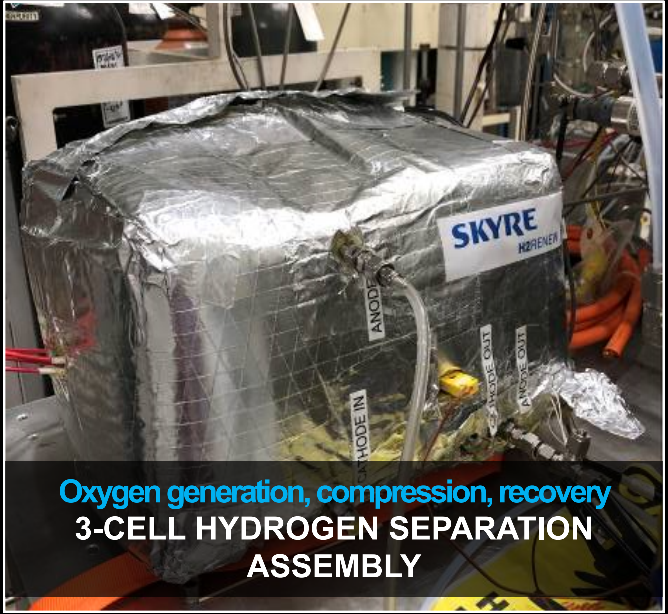


CO_2 Removal
STRUCTURED SORBENT TEST STAND

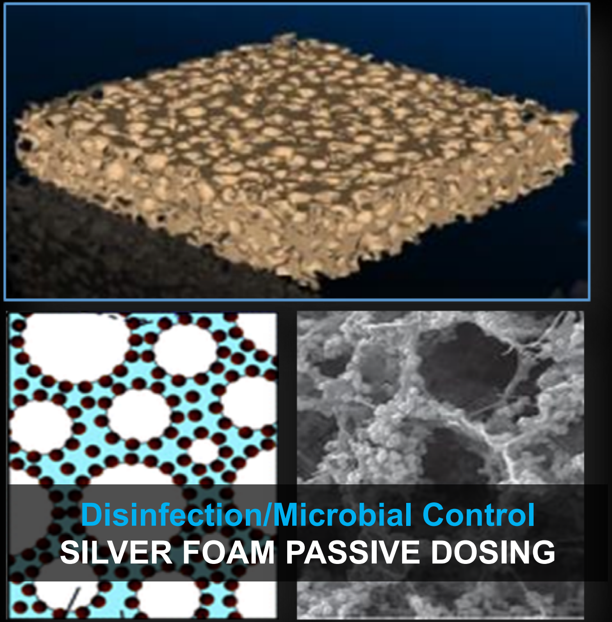


Trace Contaminant Control
CATALYTIC OXIDIZER ASSEMBLY LIFE TEST STAND

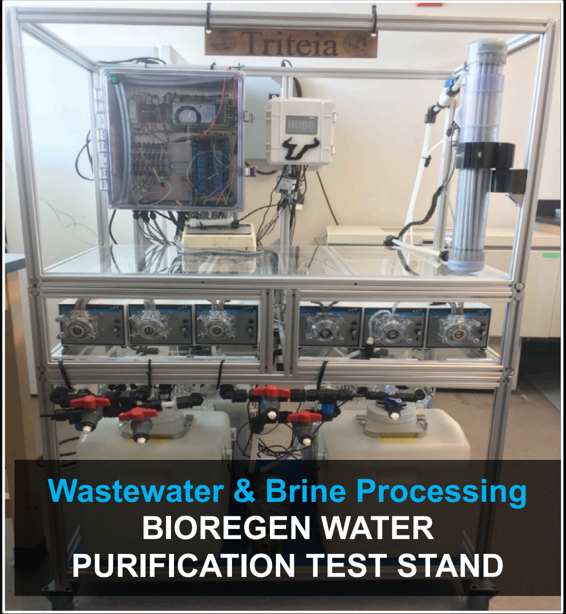
Environmental Monitoring
SPACECRAFT ATMOSPHERE MONITOR



Oxygen generation, compression, recovery
3-CELL HYDROGEN SEPARATION ASSEMBLY



Disinfection/Microbial Control
SILVER FOAM PASSIVE DOSING



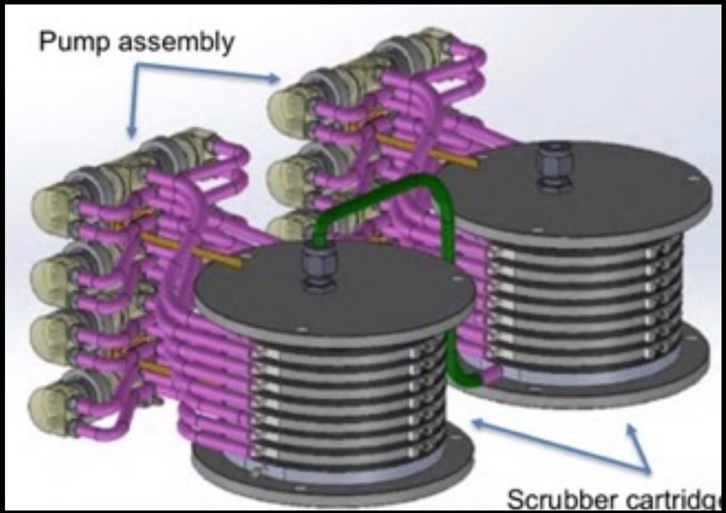
Wastewater & Brine Processing
BIOREGEN WATER PURIFICATION TEST STAND

Atmosphere Management Approach

INTERNATIONAL SPACE STATION DEMONSTRATIONS

4-Bed CO_2 Scrubber
(NASA in-house)
2021 flight

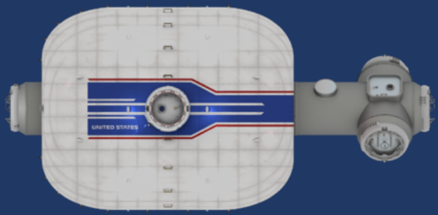
Thermal Amine CO_2 Scrubber
(Collins)
On board



Mini CO_2 Scrubber
(Dynetics)
2021 flight

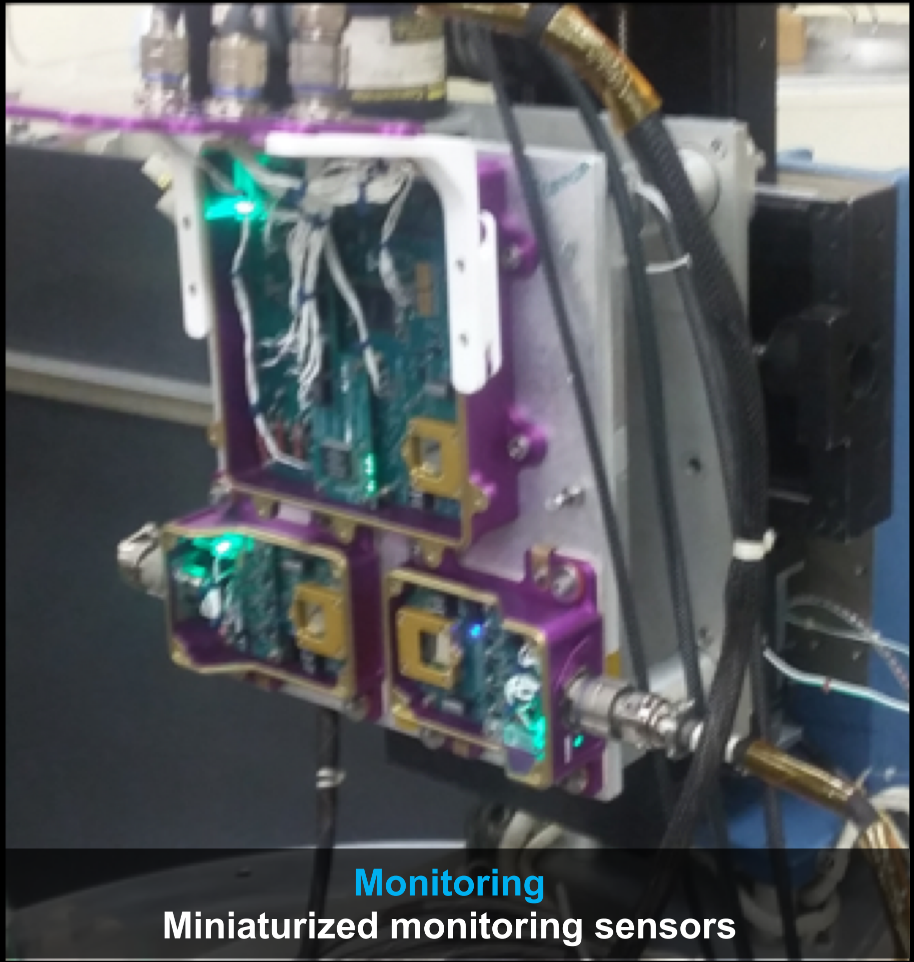
Ionic Liquid CO_2 Scrubber
Test Stand
(Honeywell investment)
2021 flight via CASIS

Down-select to best and integrate with redesigned Oxygen Generation Assembly & Sabatier CO_2 Reduction Assembly for long-duration ISS demonstration

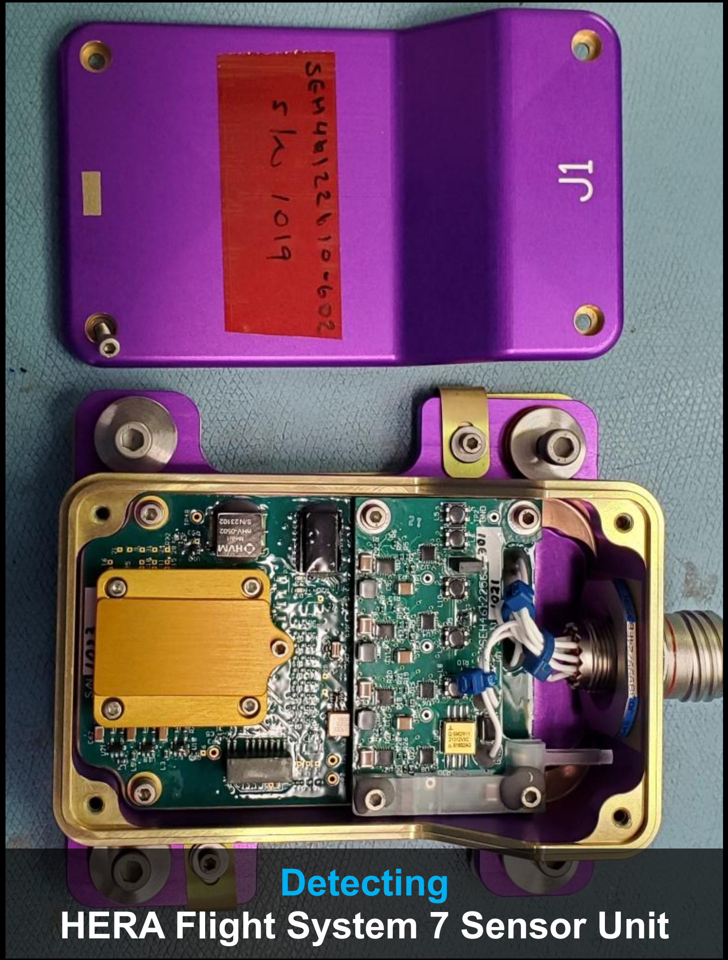


ECLSS for 800-day Mars missions

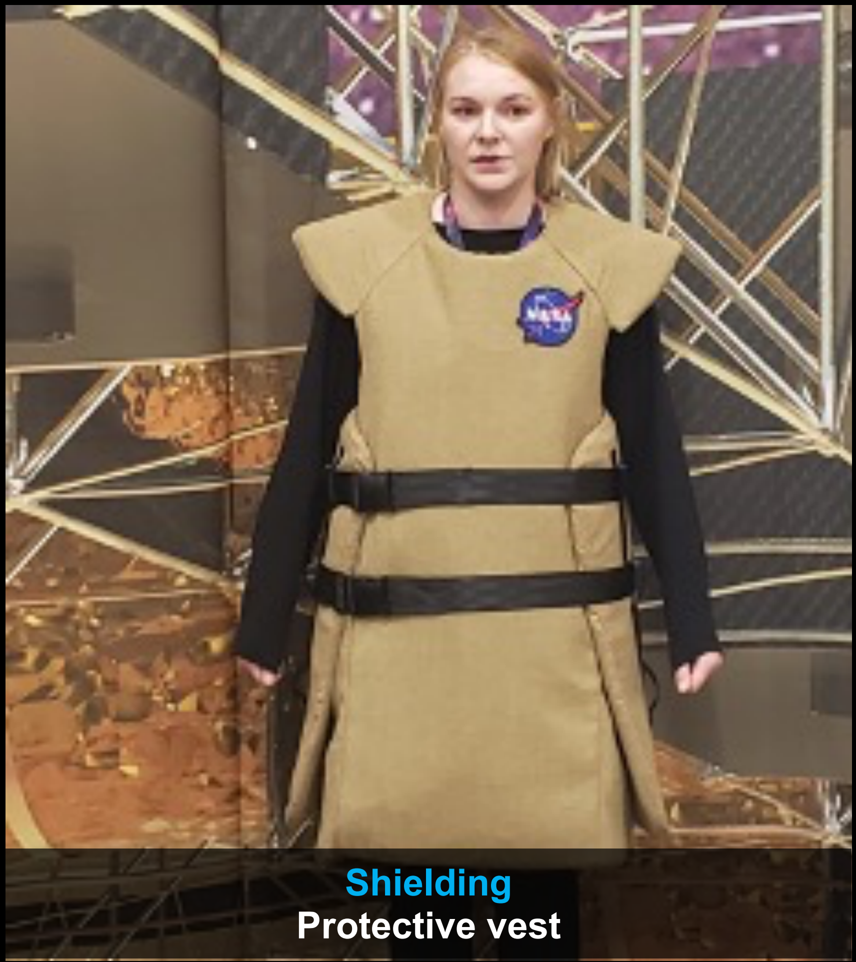
RadWorks – Radiation Detection, Shielding, Monitoring



Monitoring
Miniaturized monitoring sensors



Detecting
HERA Flight System 7 Sensor Unit



Shielding
Protective vest

Spacecraft Fire Safety Experiment (Saffire)

Large-scale fire experiment series conducted inside Cygnus cargo vehicle after it departs the International Space Station, before its destructive re-entry through Earth's atmosphere

Saffire IV loaded into Cygnus NG-13, December 2019

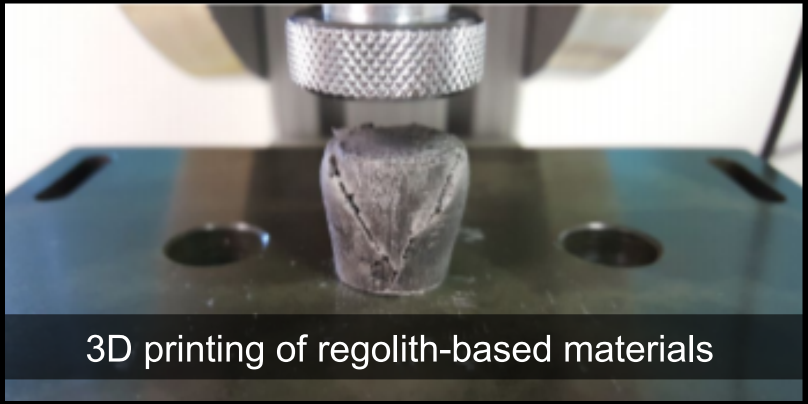
- Saffire IV was remotely activated by Northrop Grumman operators on May 11. NASA/GRC Saffire staff are monitoring the experiment as it burns and returns data back to Earth.
- Saffire IV will burn multiple samples (45 cm wide and of varying length) to determine how the flame spreads across different materials.
- Saffire IV will burn some of the same materials as in Saffire II but at different pressures and oxygen concentrations for comparison.

Saffire II

Logistics Reduction

Developing technologies that reduce logistical mass, volume, and crew time dedicated to logistics management

Intravehicular robotics to unload resupply vehicles and retrieve items



3D printing of regolith-based materials

Universal Waste Management System (UWMS)

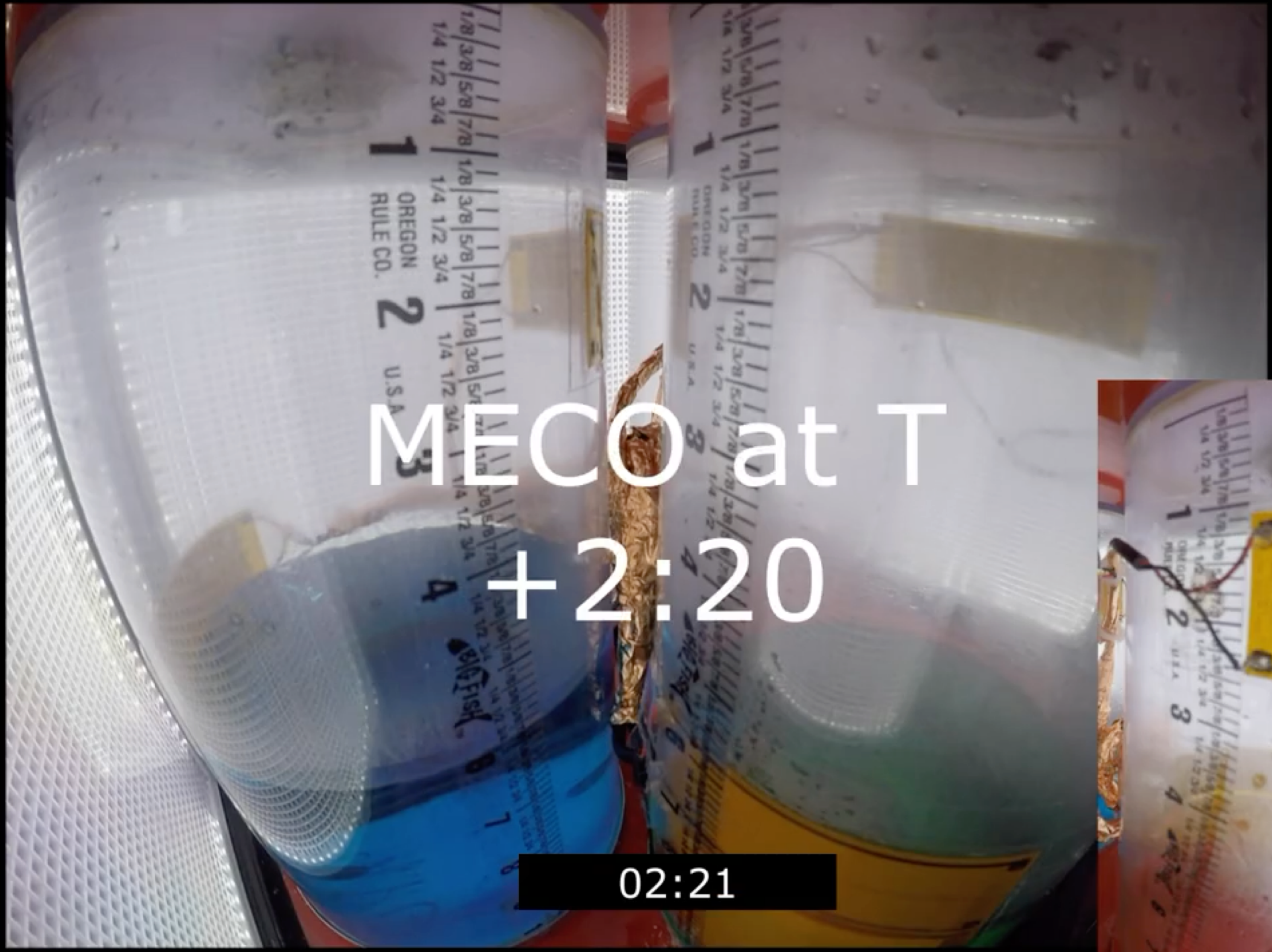
Trash Compaction and Processing Systems

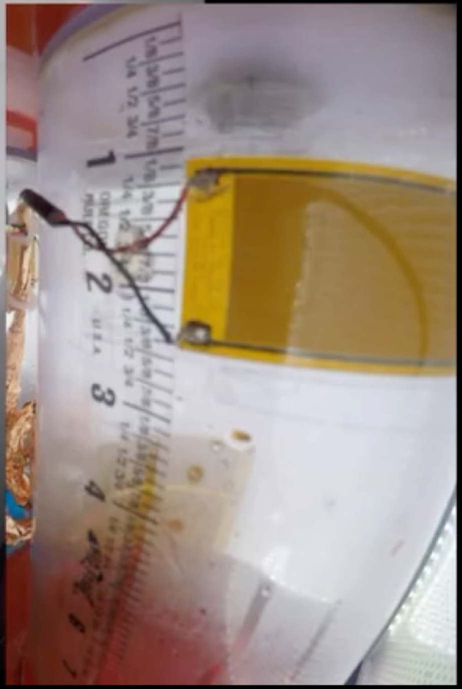
Autonomous Logistics Management using RFID tag readers to track inventory and locate missing items.

Trash-to-Gas: recover effluent water and gases from trash.

Tank Health Monitoring

Modal Propellant Gauge



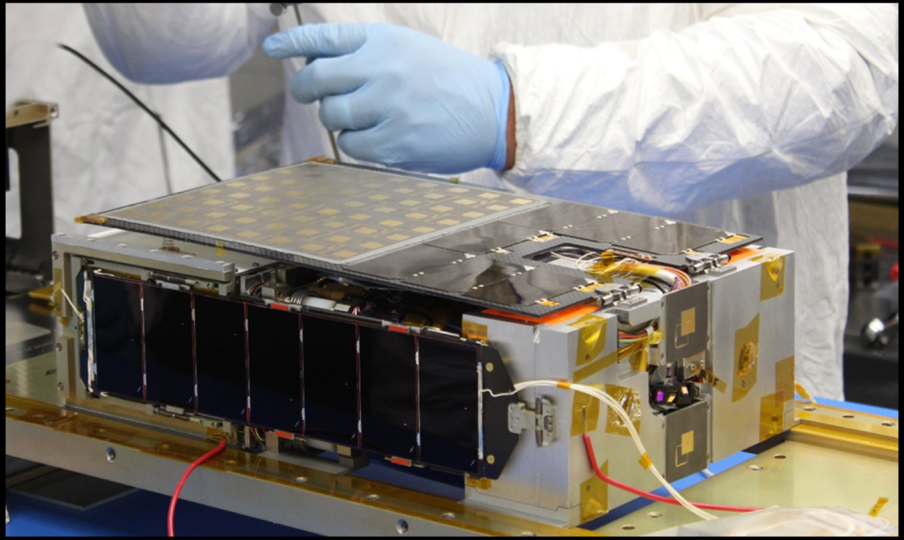


Artemis I Secondary Payload CubeSats

BioSentinel

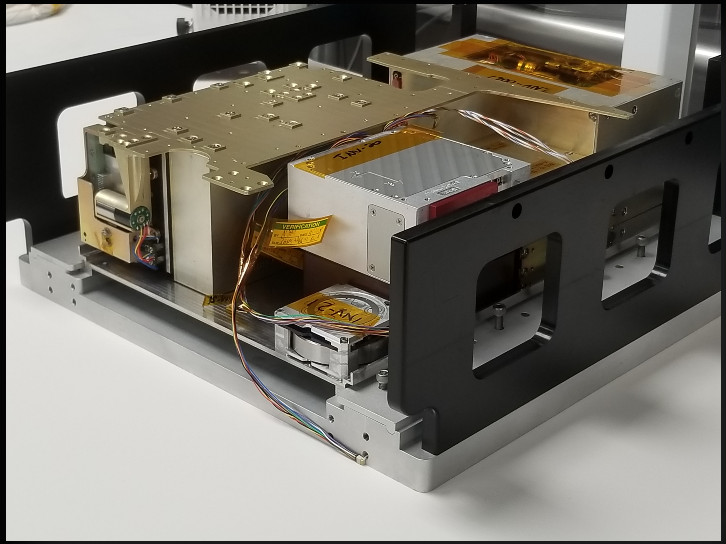
- Detect, measure and correlate the impact of space radiation on living organisms over long durations.
- Ready for Delivery to Dispenser Integrator, Tyvak by June/July 2020*

NEA Scout



- Image/characterize a near-Earth asteroid during a slow flyby using solar sail deployment and navigation
- Spacecraft integration 95% complete

Lunar IceCUBE



- Majority student-led team with a mission to prospect for ice, liquid, vapor forms of water on the Moon using IR spectrometer
- Hardware delivery to GSFC 6-8 weeks after re-open

*Does not take COVID-19 into account

Launch and Payload Schedule

Launch Date	Mission	Payload
Jul. 2020	Mars 2020	MEDLI-2, MOXIE, MEDA
Sep. 2020	NG-14	Saffire-V
Sep. 2020	NG-14	UWMS
TBD	ISS	Brine Processor Assembly
Apr. 2021	NG-15	Saffire-VI
Nov 2021	Artemis I	Secondary Payloads – BioSentinel, NEA Scout
Nov 2021	Artemis I	Hybrid Electronic Radiation Assessor (HERA)
Dec. 2022	KPLO	ShadowCam