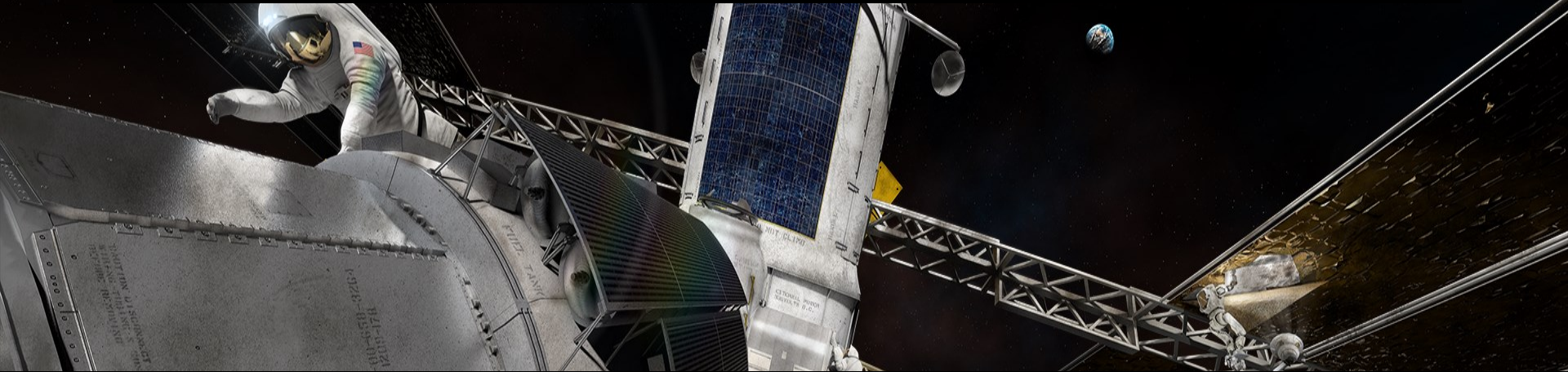


Autonomous Power Control



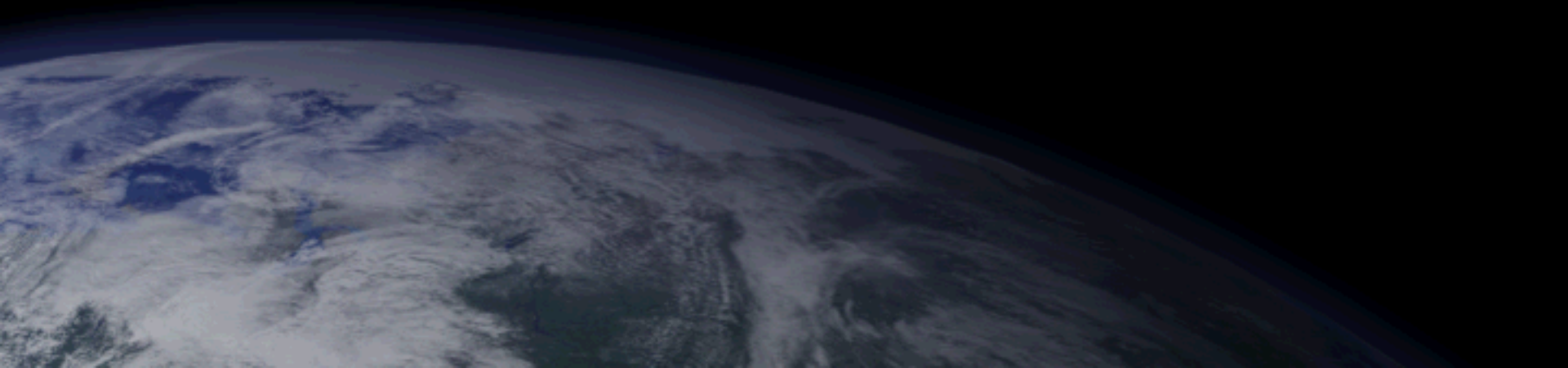
Jeffrey Csank
NASA Glenn Research Center
Cleveland, OH

2018 Energy Tech

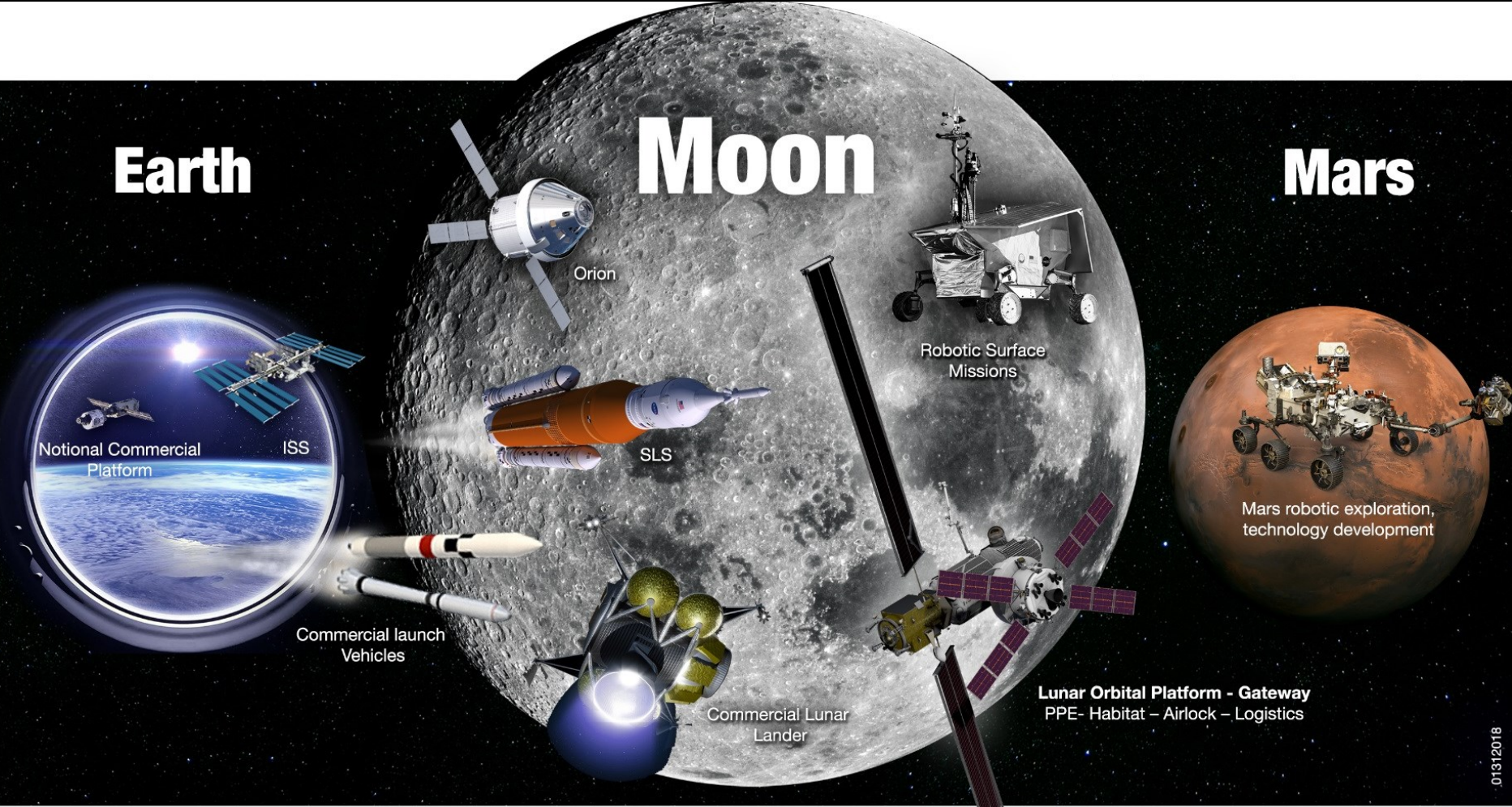


Agenda

- **Deep Space Exploration**
 - Current NASA mission goals and objectives
 - Deep space human exploration challenge
- **Autonomous Power Control**
 - What is autonomous power control
 - Proposed solution
- **Current Autonomous Power Control Capability**
 - What have we accomplished to date
- **Transition to Aeronautics**
 - Apply this technology to aeronautics



NASA's Vision of Future of Human Exploration



Earth

Moon

Mars

Notional Commercial Platform

ISS

Orion

SLS

Commercial launch Vehicles

Commercial Lunar Lander

Robotic Surface Missions

Lunar Orbital Platform - Gateway
PPE - Habitat - Airlock - Logistics

Mars robotic exploration, technology development

In LEO
Commercial & International partnerships

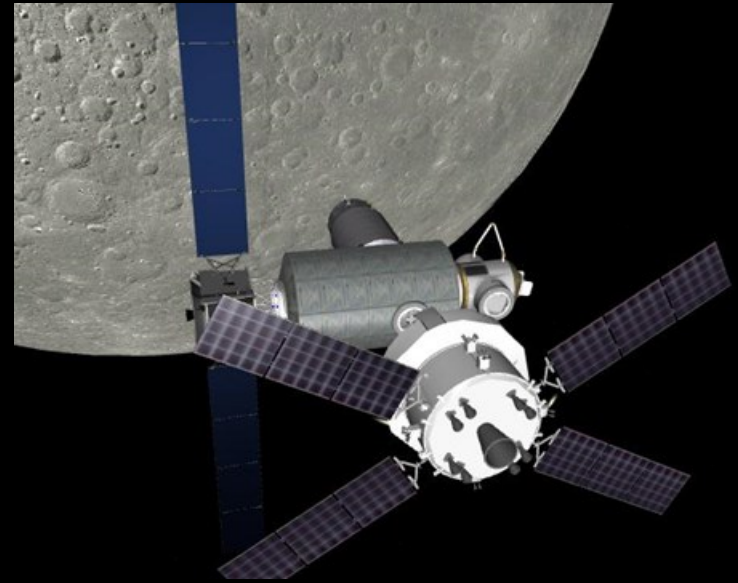
In Cislunar Space
A return to the moon for long-term exploration

On Mars
Research to inform future crewed missions

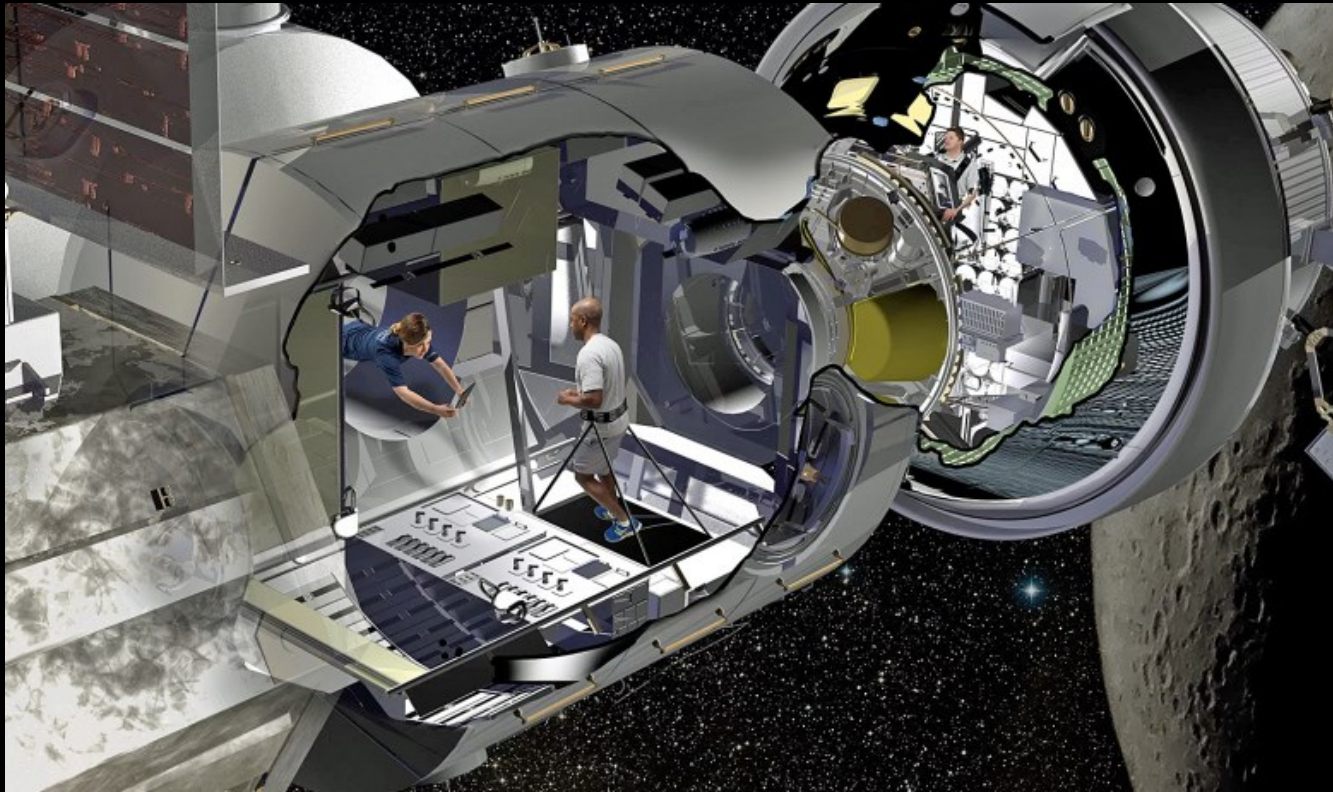


Gateway

- Crew of 4 to 6
- Provide living space for long duration missions
 - 30 to 60 Days
- Solar Array / Battery System
 - 24+ KW Habitation
 - 39 kW for propulsion
- Potential to be operated in Low Lunar Orbit, Near Rectilinear Orbit or Deep Space
- Provides docking accommodation for multiple vehicles – resupply as well as landers
- Platform for the checkout and validation of advanced technologies
 - Advanced automation systems
 - Etc.

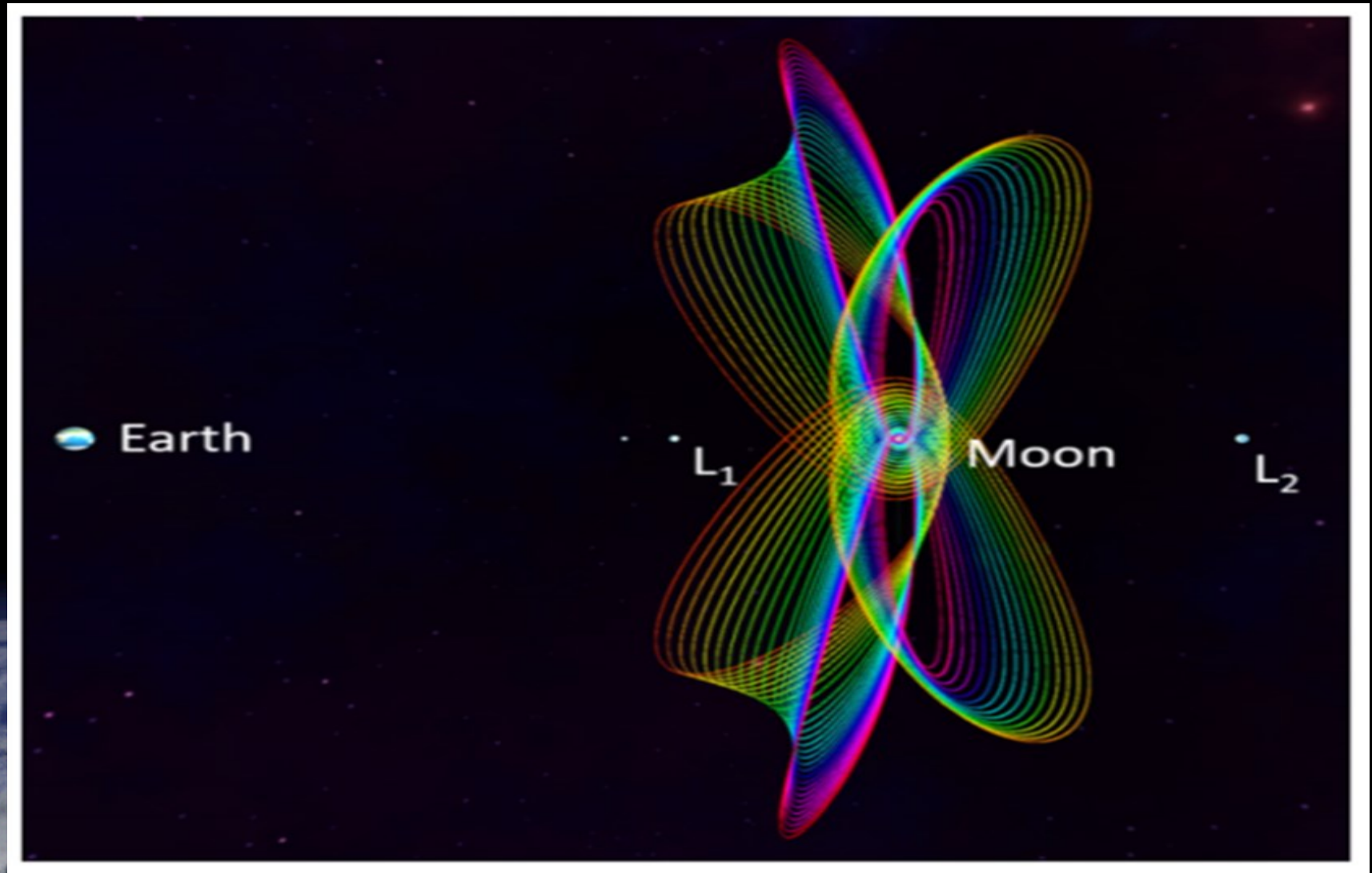


Deep Space Gateway



- **Concept for DSG Habitation Element**
 - **Crew Quarters**
 - **Exercise**
 - **Experiments**
 - **Galley**
 - **Modular Equipment**

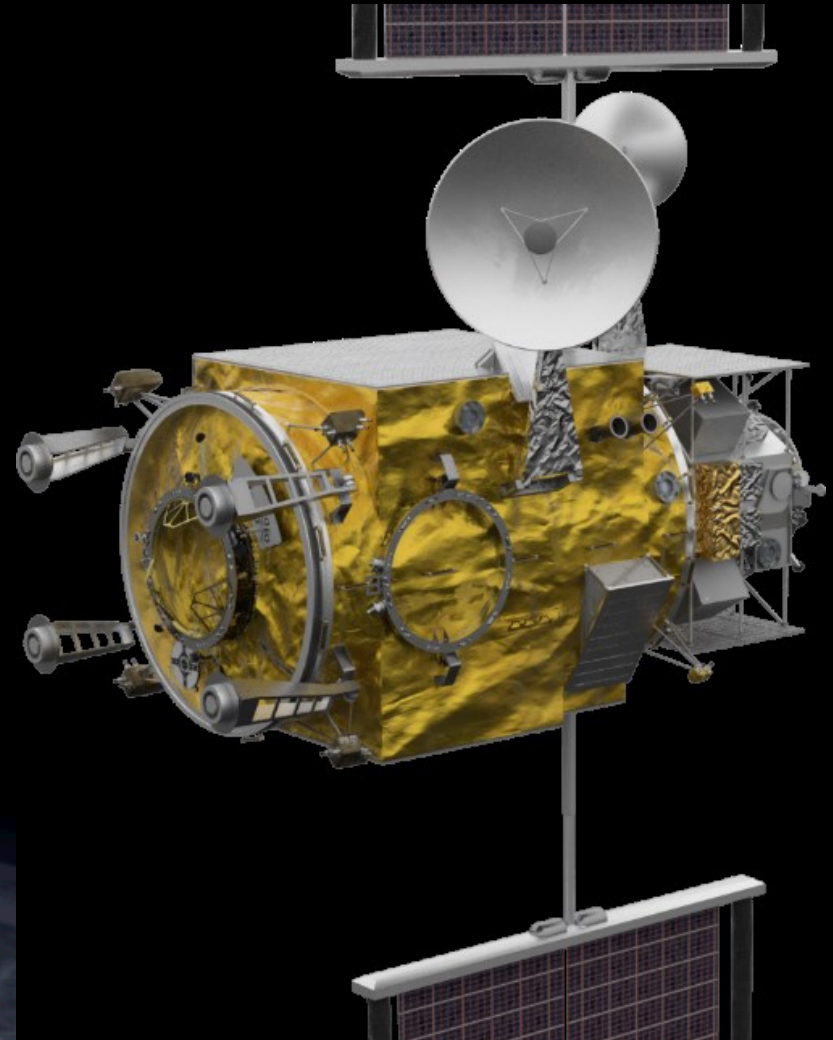
NRHO Orbit for Gateway





Power Propulsion Element

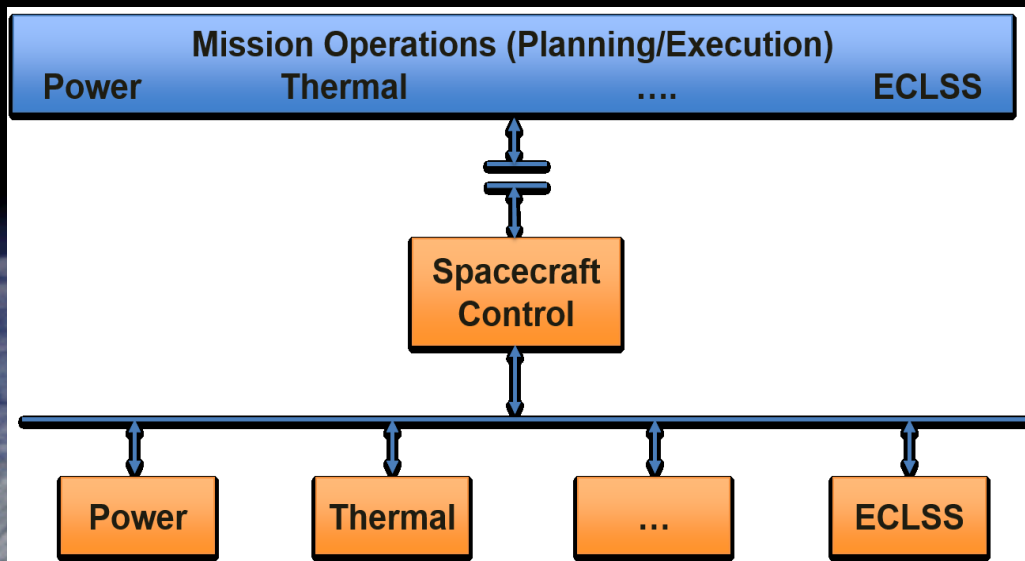
- **Development led by NASA Glenn**
- **Provides 60+ kW of electric power**
 - **60 + kW of Solar Array**
 - **16 kW hr of batteries**
 - **120 Vdc power**
 - **27 kW to Habitat etc.**
 - **39 kW to Thrusters**
- **4 Ion Thrusters**
 - **600 milli-Newtons of thrust**
 - **0.135 lbs. of thrust**
 - **Xenon propellant**
- **Lifetime 15 years**



Traditional Spacecraft Architecture - ISS



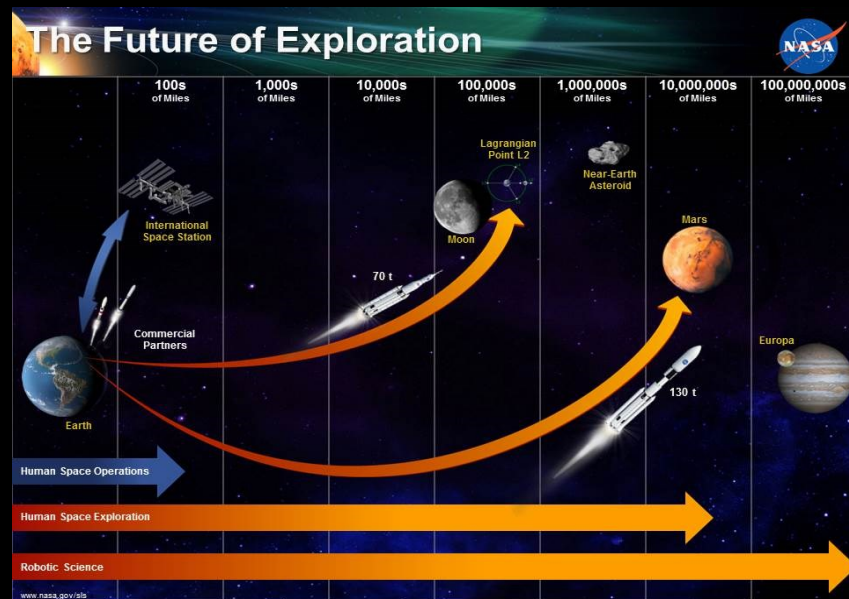
- All subsystems planning and execution are done by humans on the ground
- Spacecraft control is basically a communication system
- Subsystems (power) basically execute commands and set points – Reactive Layer Control
- 50+ years of mission operations.



Deep Space Exploration Challenge

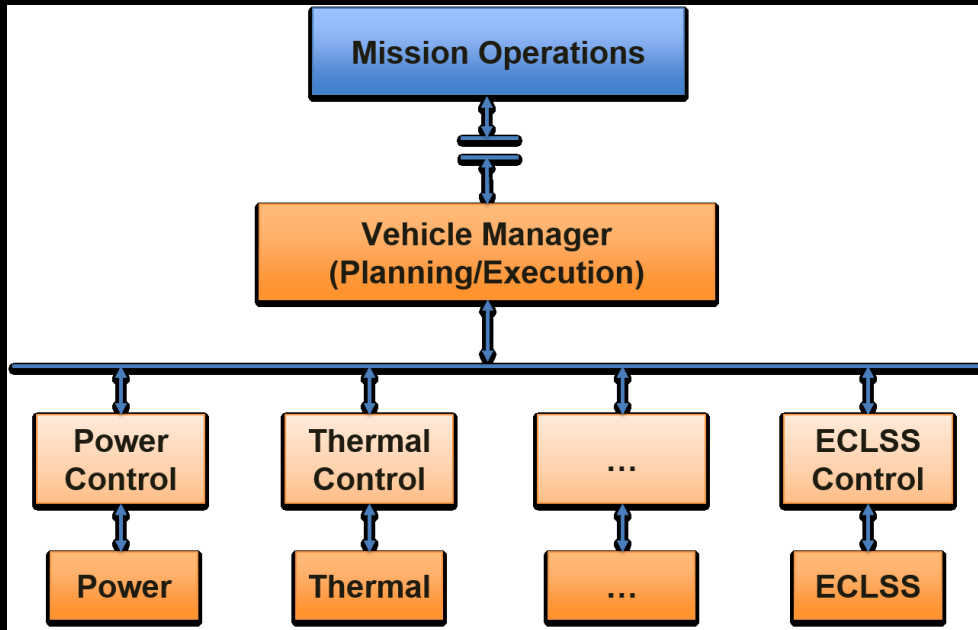


- **Communication becomes a problem**
 - Times are longer than any previous experience
- **Power is your most critical system**
 - Every system on the vehicle needs power
 - Electrical power needs a high level of availability and reliability
 - **MUST operate autonomously**

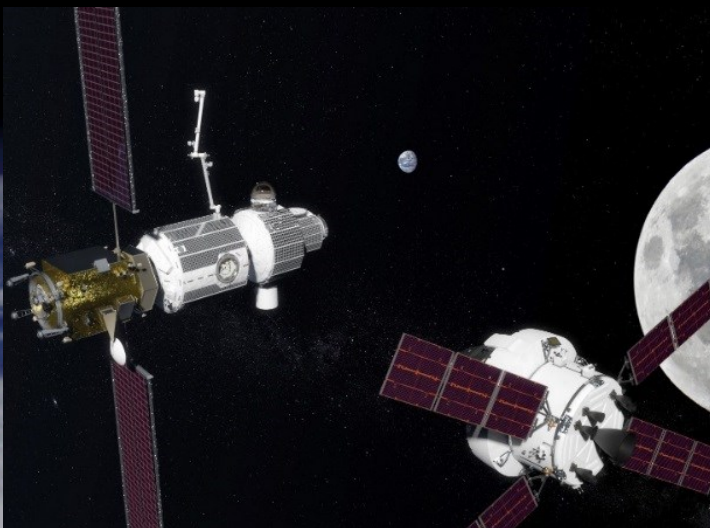


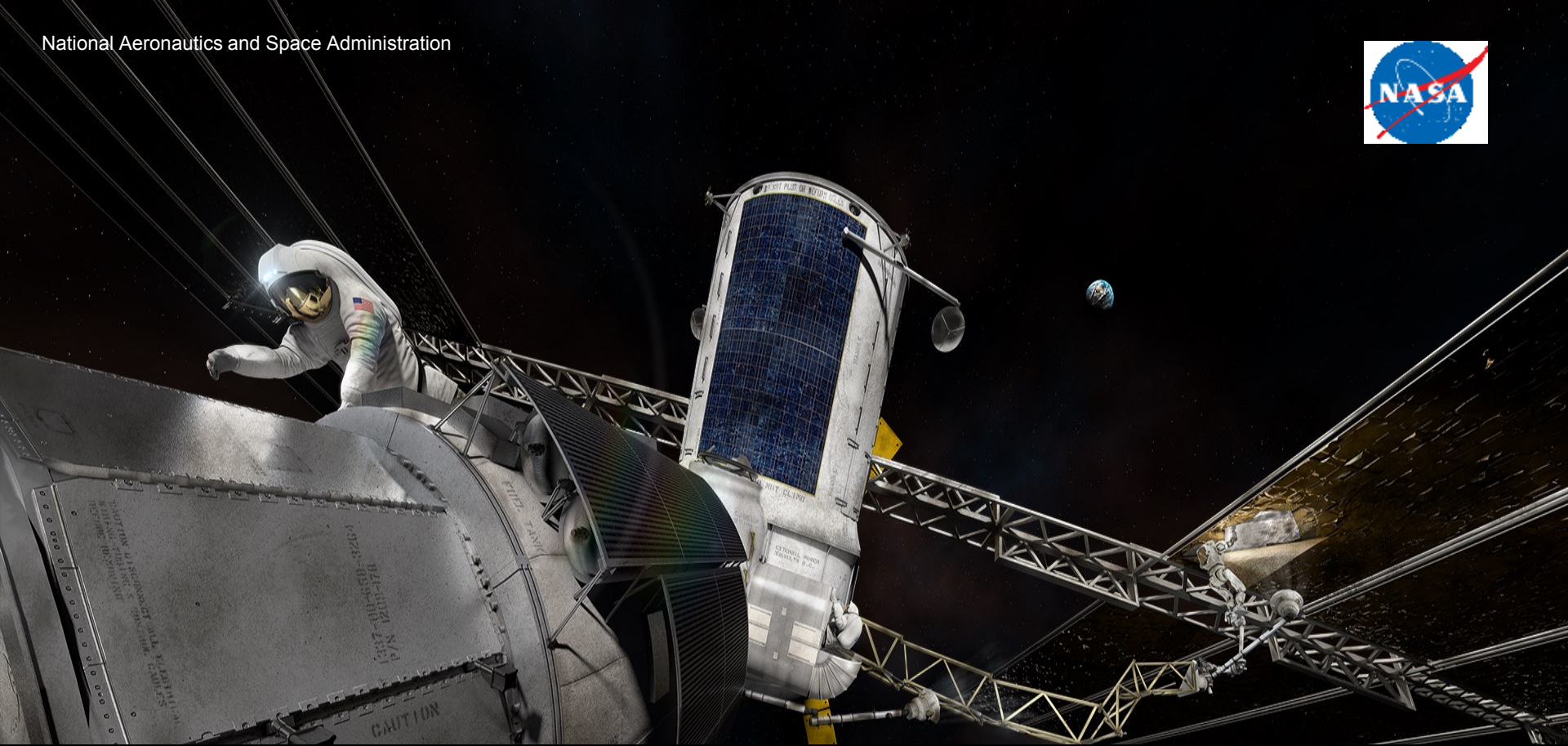
Mission	Communication Bandwidth	Communication Latency
ISS	300-800 Mbps (TDRS)	Real-time
Apollo / Orion	<2 Mbps (DSN)	1 to 2 seconds
Deep Space Vehicle	<2 Mbps (DSN)	15 to 45 minutes

Autonomous Spacecraft Architecture



- Goal is to remove the human element from real-time operation of the vehicle.
- Mission operations are included as oversight and to deal with mission level objectives
- Planning of vehicle operations are done at the vehicle manager level in coordination with the subsystem controllers.
- Autonomous subsystem controllers contains all the knowledge of the particular subsystem
- Distributed / Federated vehicle control architecture





Autonomous Power Control



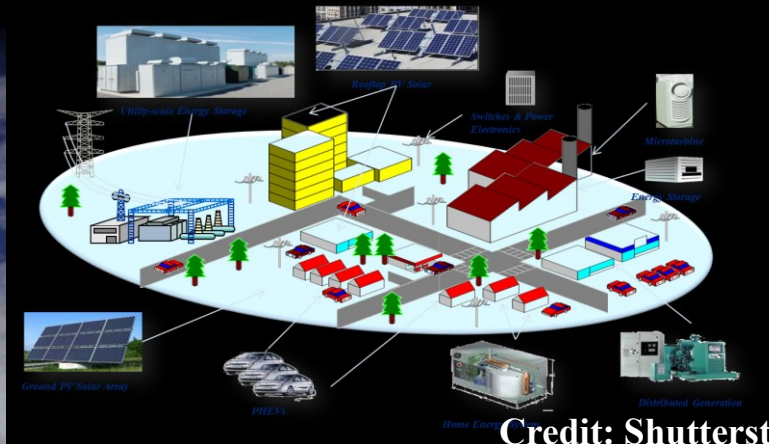
What is an Autonomous Power System?

- **Power System Needs**

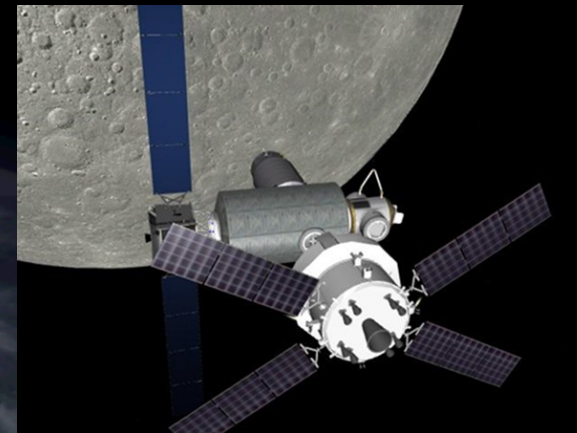
- Operate safely at all times
- Service the highest priority loads within the constraints of the generation and distribution systems

- **Power System Control Functions**

- Interact with the System (Vehicle) Manager to safely execute the mission
- Manage the power system to provide desired capability without human intervention
- **Permit humans to consent to any operations / actions during habitation**



Credit: Shutterstock



Vehicle Autonomous Control Architecture



- **Mission Operations**

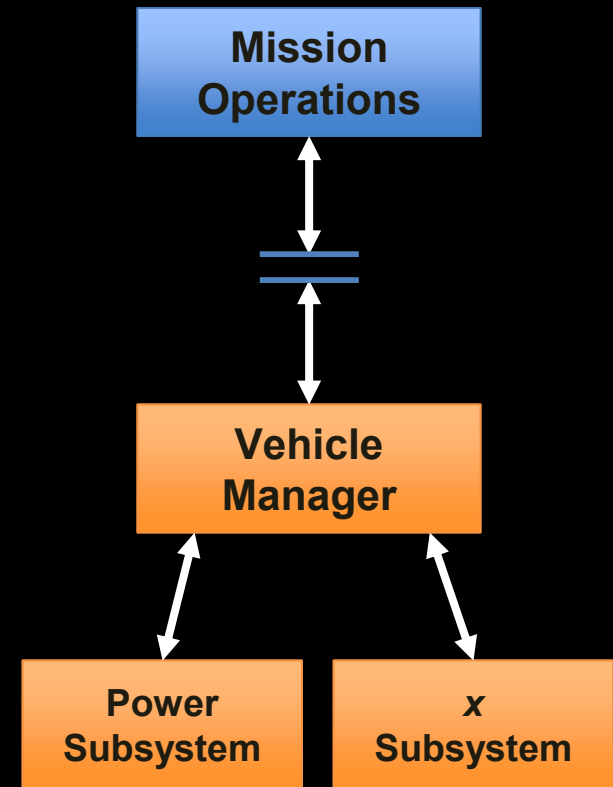
- Monitors vehicle operations
- Adjusts long term mission objectives

- **Vehicle Manager**

- Ensures mission objectives are met
- Contains knowledge of all subsystems requirements and current state
- Plan vehicle operation to achieve mission objectives and meet all subsystems constraints
- Deals with faults across subsystems

- **Subsystem (Autonomous)**

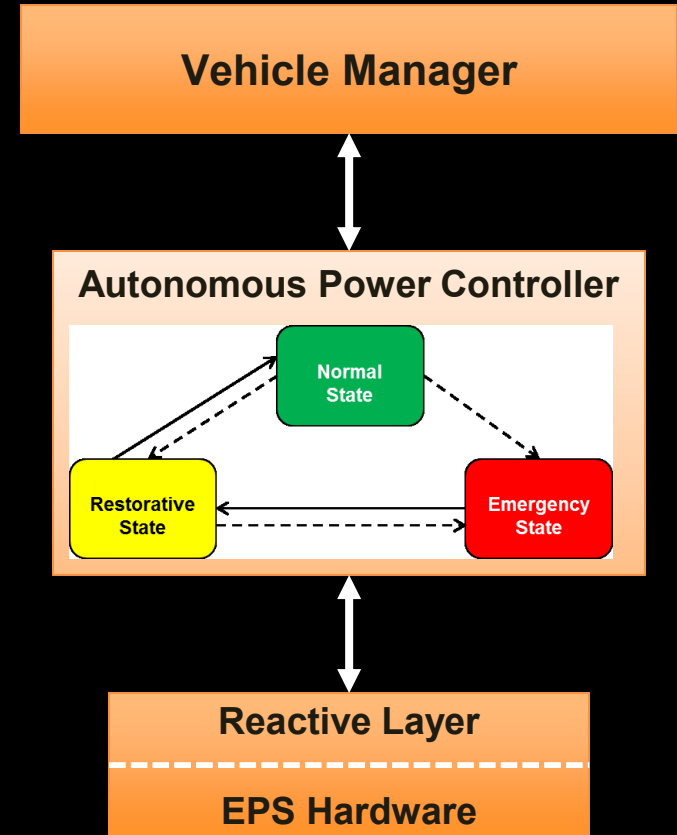
- Operates subsystems safely (within constraints) and for subsystem fault management
- Responsible for operating independently of human operator in the loop



Vehicle Autonomous Power Control Architecture



- **Vehicle Manager**
 - Meet mission objectives
 - Coordinate vehicle subsystems
- **Autonomous Power Controller**
 - Forecast energy availability (provides constraints for vehicle to operate within)
 - Safely operate the EPS hardware and EPS fault management
 - Provide power to the highest priority loads
- **Reactive Layer (Full Digital Control)**
 - Provides closed-loop control of the EPS hardware
 - Protect EPS from hard faults (safe the system)





Autonomous Power Controller

- **Energy Management**

- Manage the power generation and energy storage assets
- Determine power and energy availability into the future
- Evaluate proposed load schedules

- **Fault Management**

- Monitor system performance for soft faults
- Respond to detected faults within the EPS

- **Maintenance, Mitigation, and Recovery**

- Reconfigure the power system as required
- Determine alternative configurations for maintenance

- **Executioner**

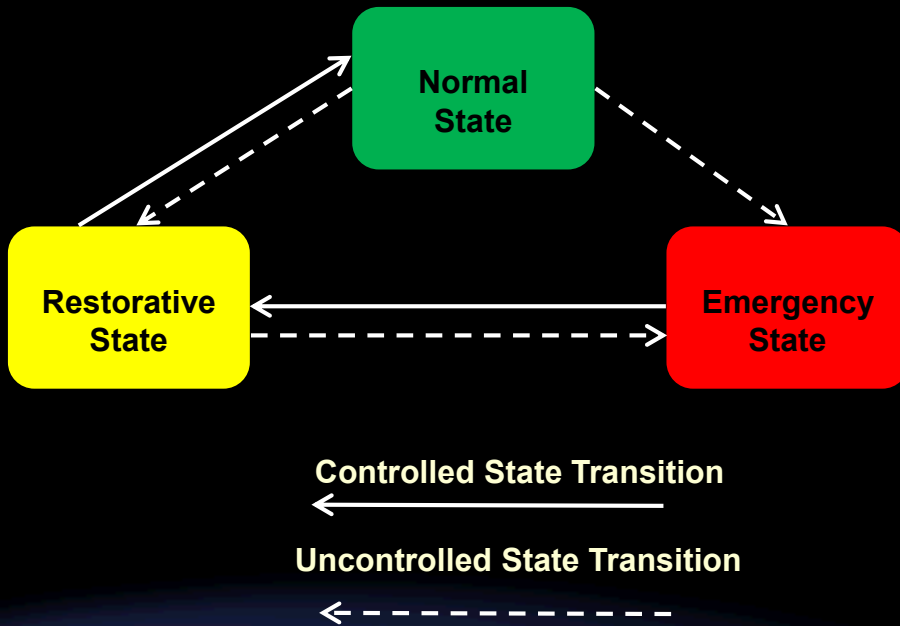
- Coordinate APC responses

- **External Interfaces**

- Vehicle manager – provide EP constraints and current state
- EPS – send commands and examine telemetry



Autonomous Control State Diagram



Normal State:

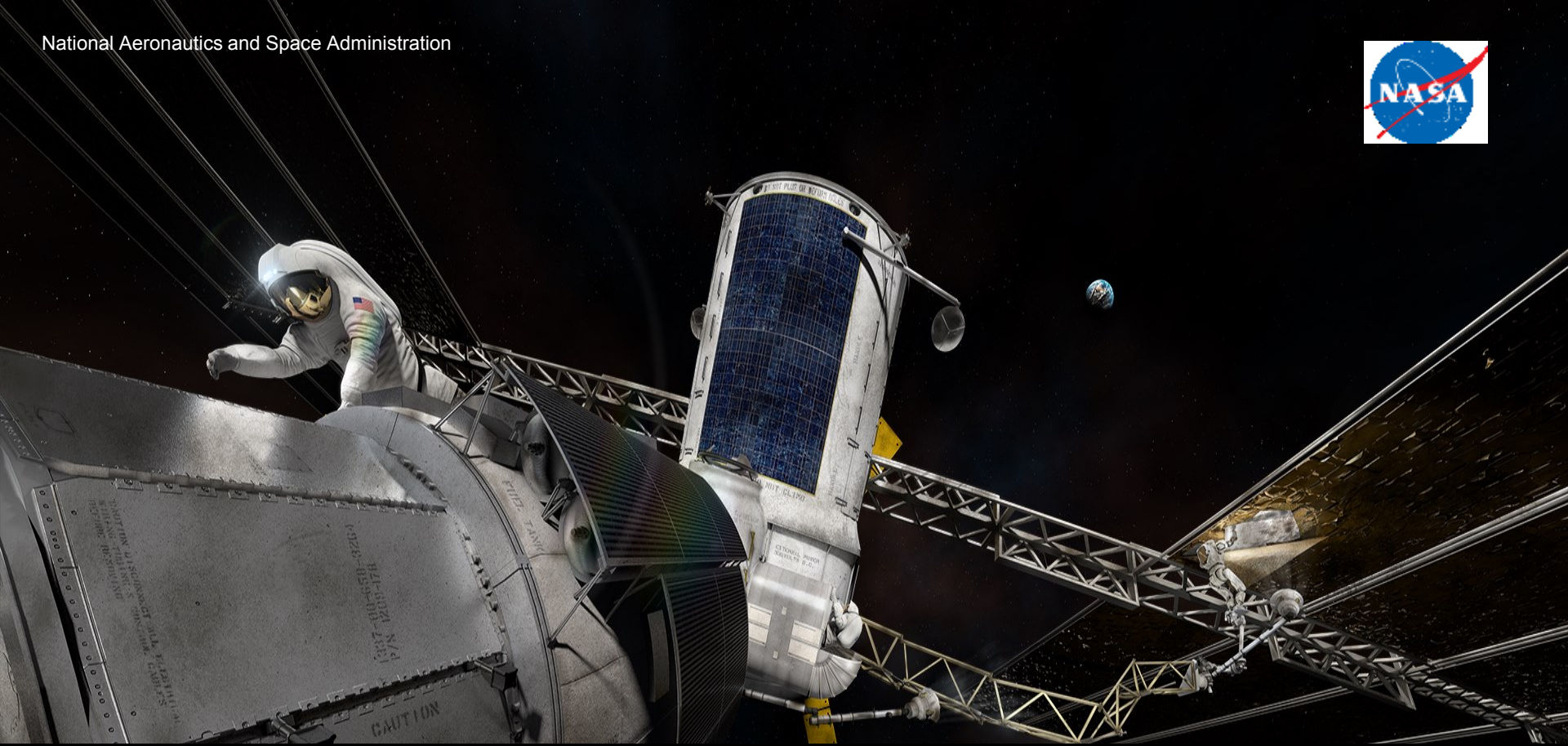
- System operating properly
- Calculates and provides an energy availability and power profile
- Analyzes proposed load schedules
- With no failures, continue indefinitely.

Emergency State:

- Failure has occurred in the EPS
- Reactive control will respond to any immediate faults and temporarily put the system in safe mode.
- APC reconfigures the system

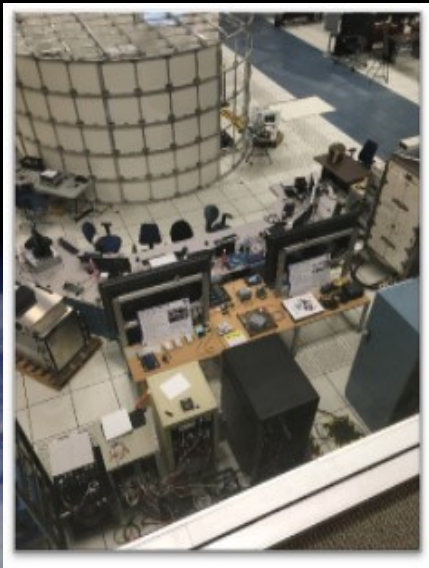
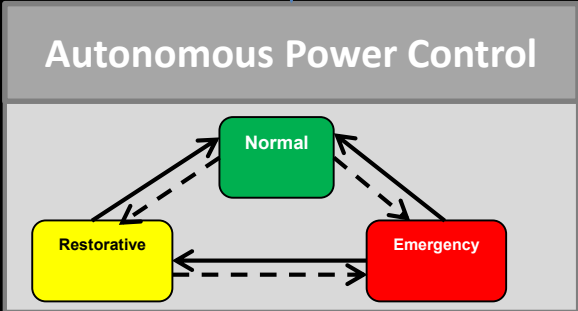
Restorative State:

- System is in a reduced power state and may not be servicing the complete normal load
- APC can perform all the operations of the normal state, with reduced power constraints.

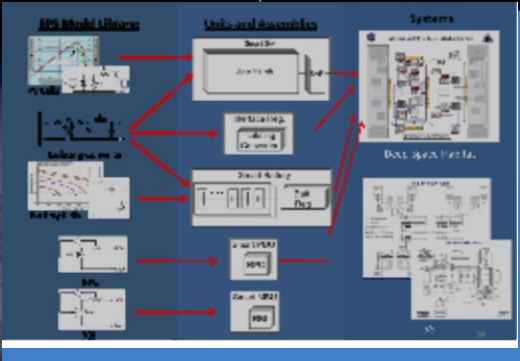


Current Autonomous Power Control Capability

System Integration Capability



JSC iPAS Test Bed

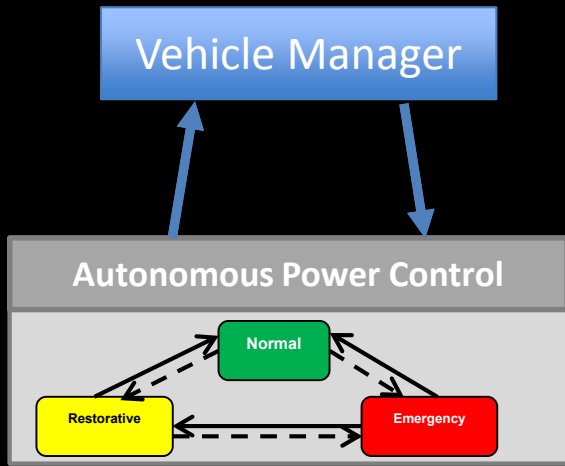


GRC Real Time Simulation



GRC Deep Space Vehicle Power System Test Bed

Demonstrations



Normal Mode

Energy Availability
(to VM)

time	Peak (kw)	Nominal (kw)
1	7.68	5.76
2	7.68	5.76
3	7.68	5.76
4	7.68	5.76
...		
24	7.68	5.76
Total energy (kW tu)		138.24

Load Schedule
(from VM)



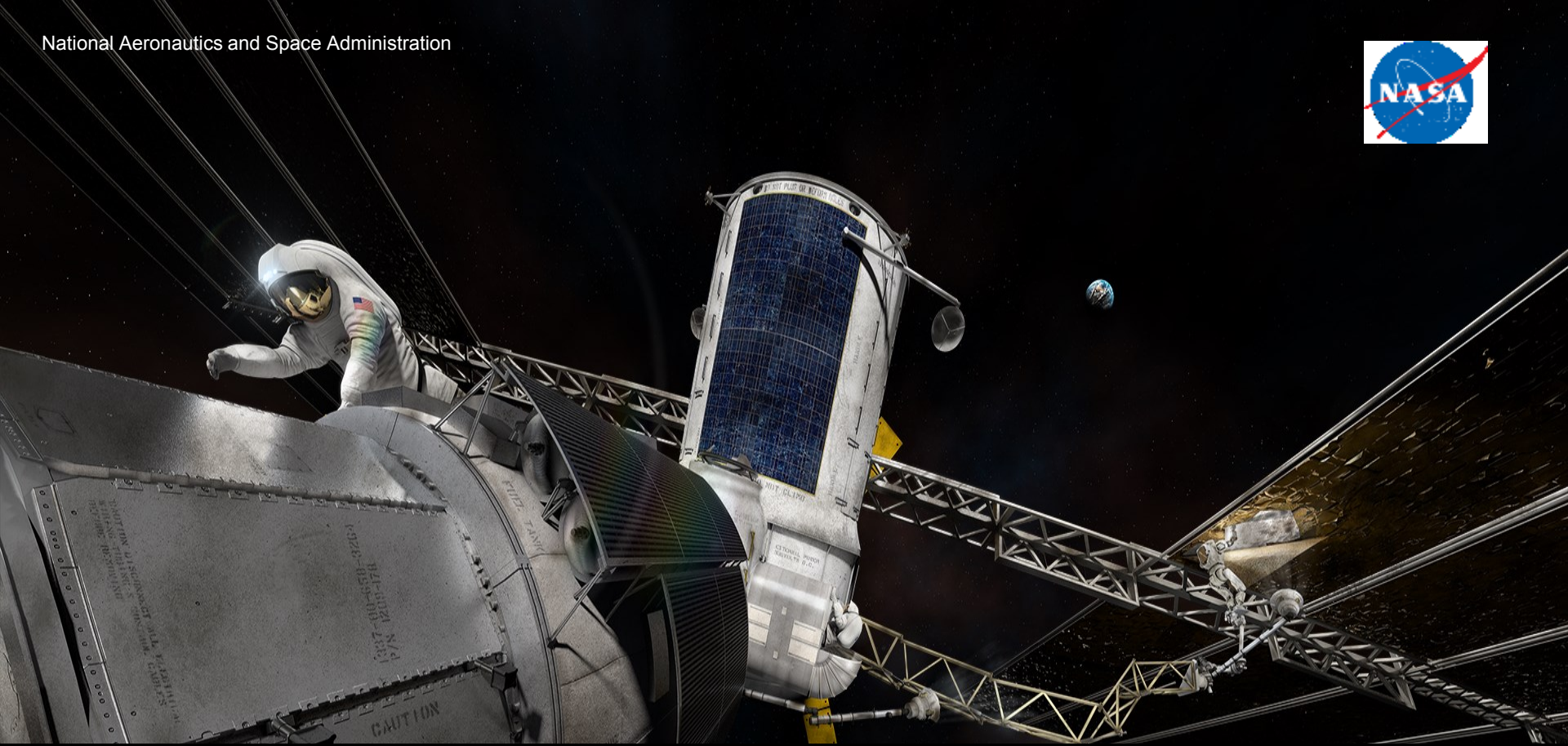
Load	Tu1	Tu2	Tu3	Tu4	Tu5
1	7	0	7	0	7
2	1	1	1	1	1
3	0	7	0	7	0
4	2	2	2	2	2
5	9	9	9	9	9
6	11	11	11	11	11
7	6	6	6	6	6
8	0	0	0	0	0
9	8	0	8	0	8
10	5	5	5	5	5
11	0	8	0	8	0
12	4	4	4	4	4
13	12	12	12	12	12
14	10	10	10	10	10
15	3	3	3	3	3
16	0	0	0	0	0

Fault Mode

Load	Tu1	Tu2	Tu3	Tu4	Tu5
1	7	0	7	0	7
2	1	1	1	1	1
3	0	7	0	7	0
4	2	2	2	2	2
5	9	9	9	9	9
6	11	11	11	11	11
7	6	6	6	6	6
8	0	0	0	0	0
9	8	0	8	0	8
10	5	5	5	5	5
11	0	8	0	8	0
12	4	4	4	4	4
13	12	12	12	12	12
14	10	10	10	10	10
15	3	3	3	3	3
16	0	0	0	0	0

time	Peak (kw)	Nominal (kw)
1	7.68	2.88
2	7.68	2.88
3	7.68	2.88
4	7.68	2.88
...		
24	7.68	2.88
Total energy (kW tu)		69.12

Load	Tu1	Tu2	Tu3	Tu4	Tu5
1	7	0	7	0	7
2	1	1	1	1	1
3	0	7	0	7	0
4	2	2	2	2	2
5	0	0	0	0	0
6	0	0	0	0	0
7	6	6	6	6	6
8	0	0	0	0	0
9	8	0	8	0	8
10	5	5	5	5	5
11	0	8	0	8	0
12	4	4	4	4	4
13	0	0	0	0	0
14	0	0	0	0	0
15	3	3	3	3	3
16	0	0	0	0	0



Other Potential Applications for Autonomous Power Control



Power Autonomy in Aeronautics

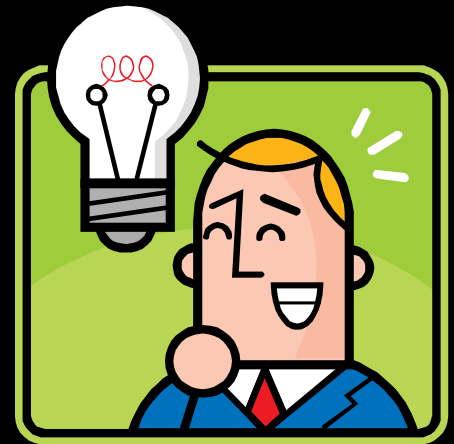
- Synergy between Space and Aeronautics regarding autonomous power systems
- Transfer Space technologies to Aeronautics
 - Automation architecture
 - Algorithms for
 - Electrical power system fault management
 - Energy management
 - System reconfiguration
 - Platform for algorithm execution and coordination

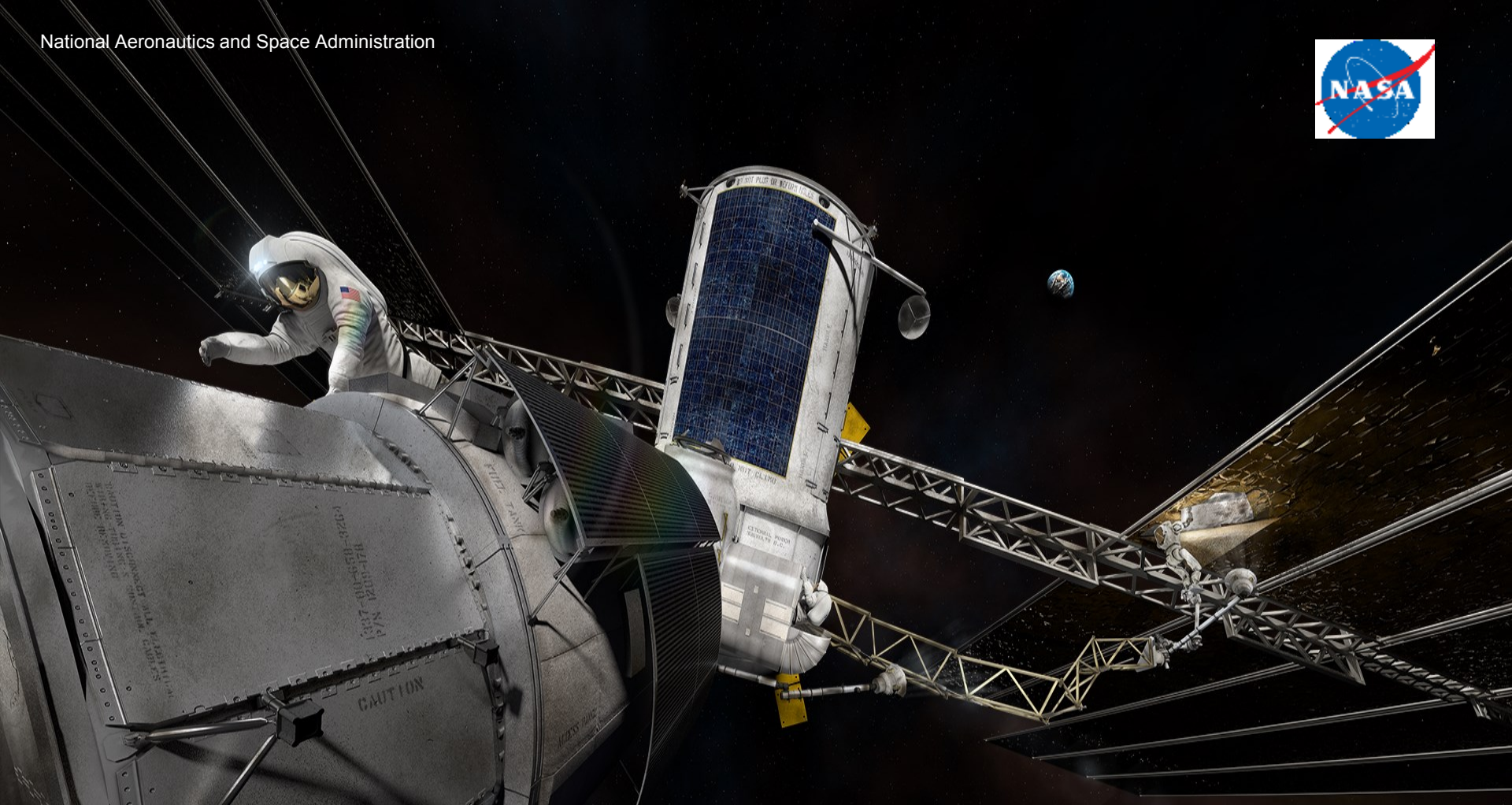


Conclusion



- **Autonomous Power System capability is required for long term operation far from earth.**
- **Developed and demonstrated the ability to safely operate an electrical power system without a human operator in the loop.**
- **Technology developed for deep space exploration vehicles can be transition to other areas**
 - **Aeronautics for use with hybrid electric airplanes**
 - **Terrestrial micro-grids**
 - **Moon base**





**Thank you!
Questions?**

