National Aeronautics and Space Administration

Autonomous Power Controller For the NASA Gateway

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Next Generation Intelligent (Electrical) Power Systems

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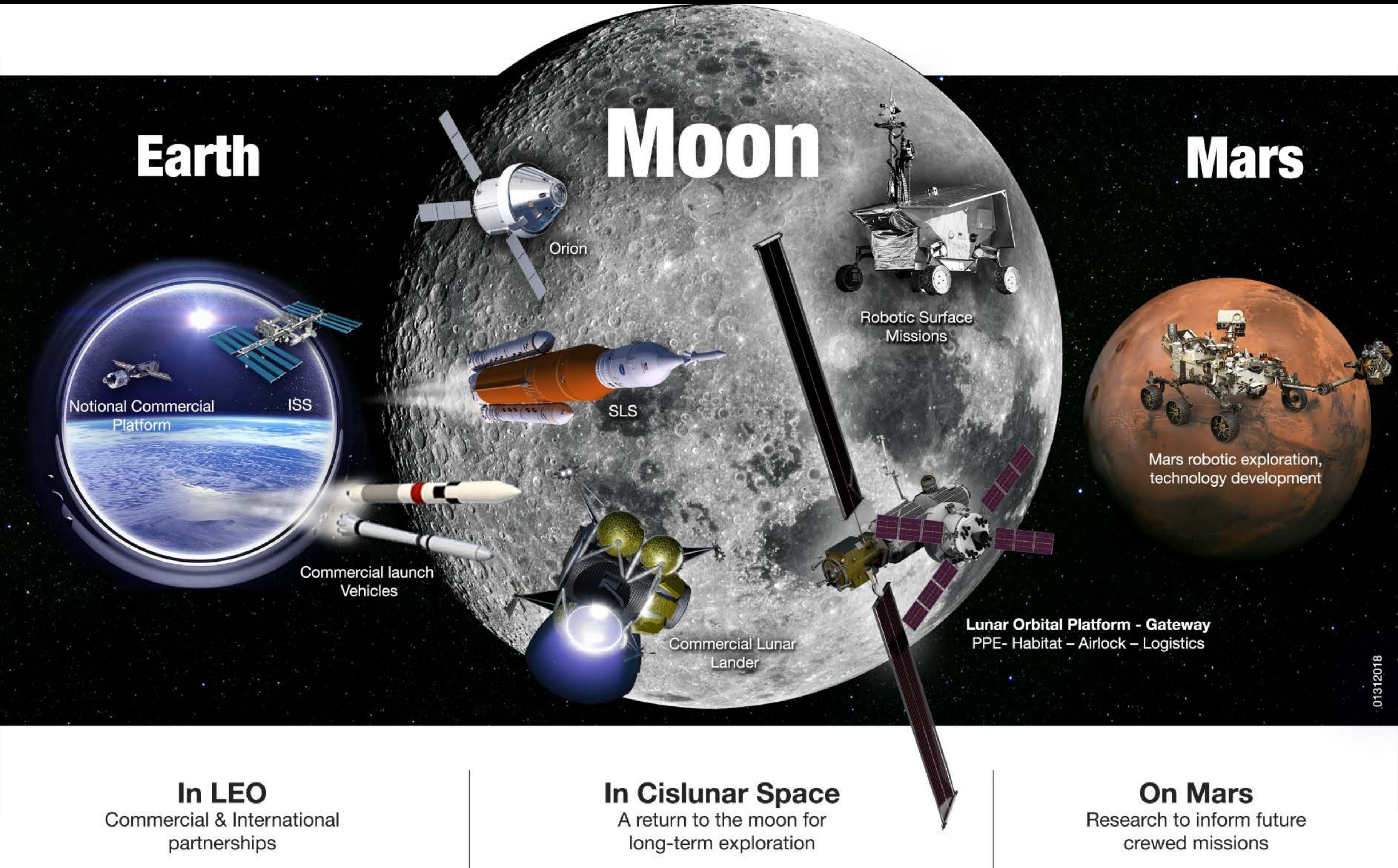
Agenda

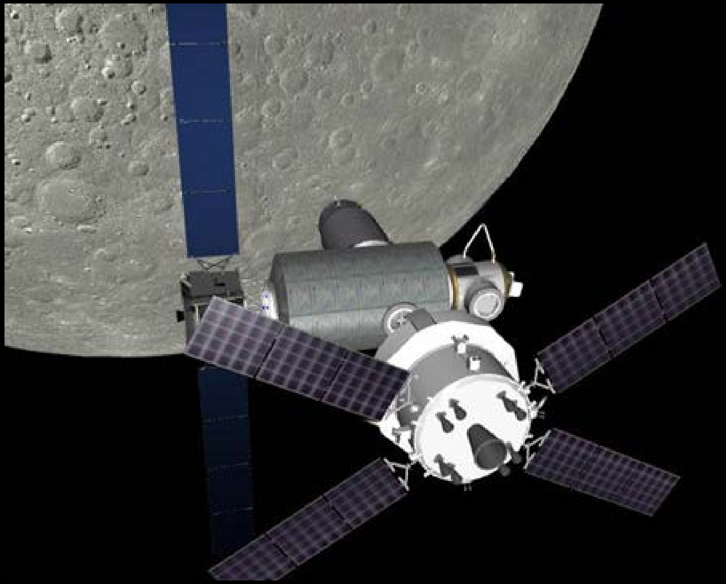
- **Deep Space Exploration**
  - Current NASA mission goals and objectives
  - Deep space human exploration challenge
- **Autonomous Power Control**
  - What is autonomous power control
  - Proposed solution
- **Current Autonomous Power Control Capability**
  - What have we accomplished to date
- **Transition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

NASA's Vision of Future of Human Exploration

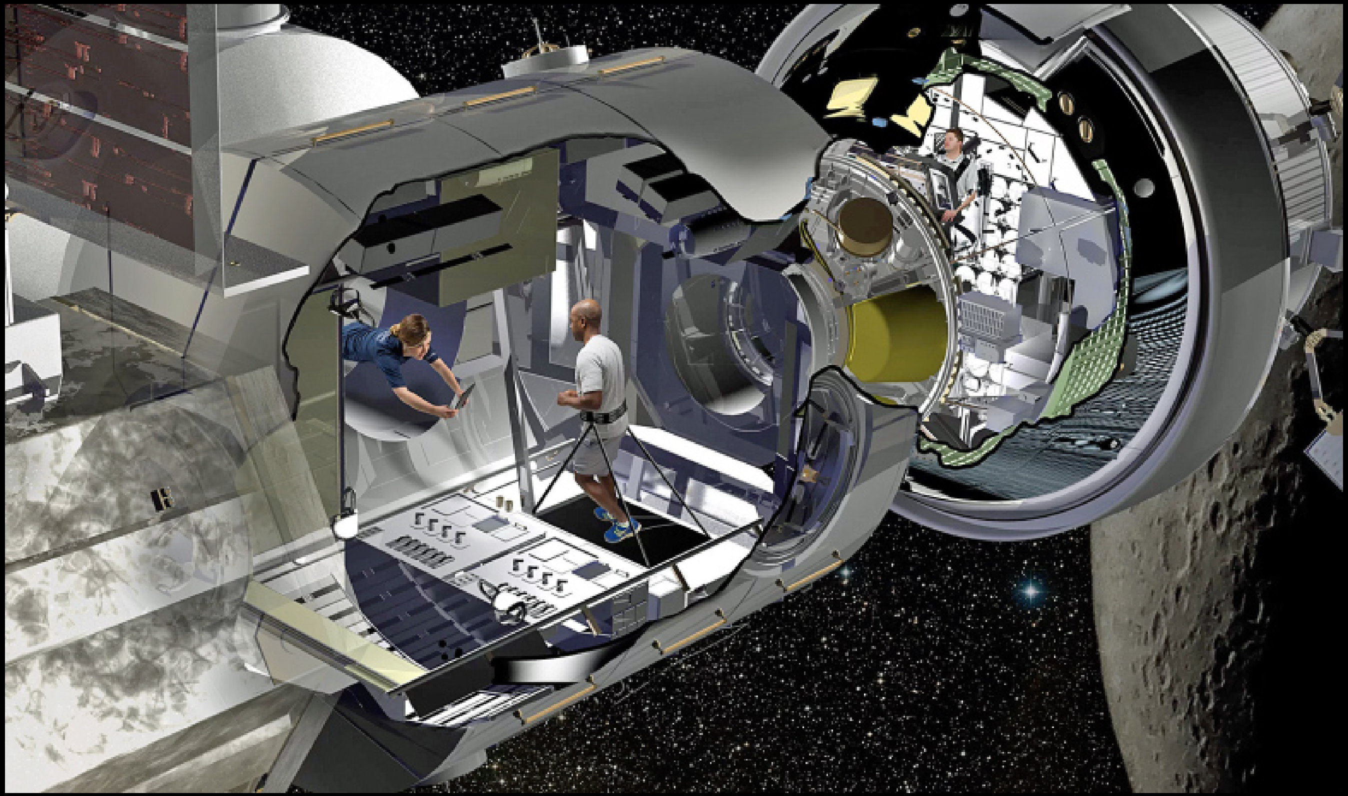


Gateway

- 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.

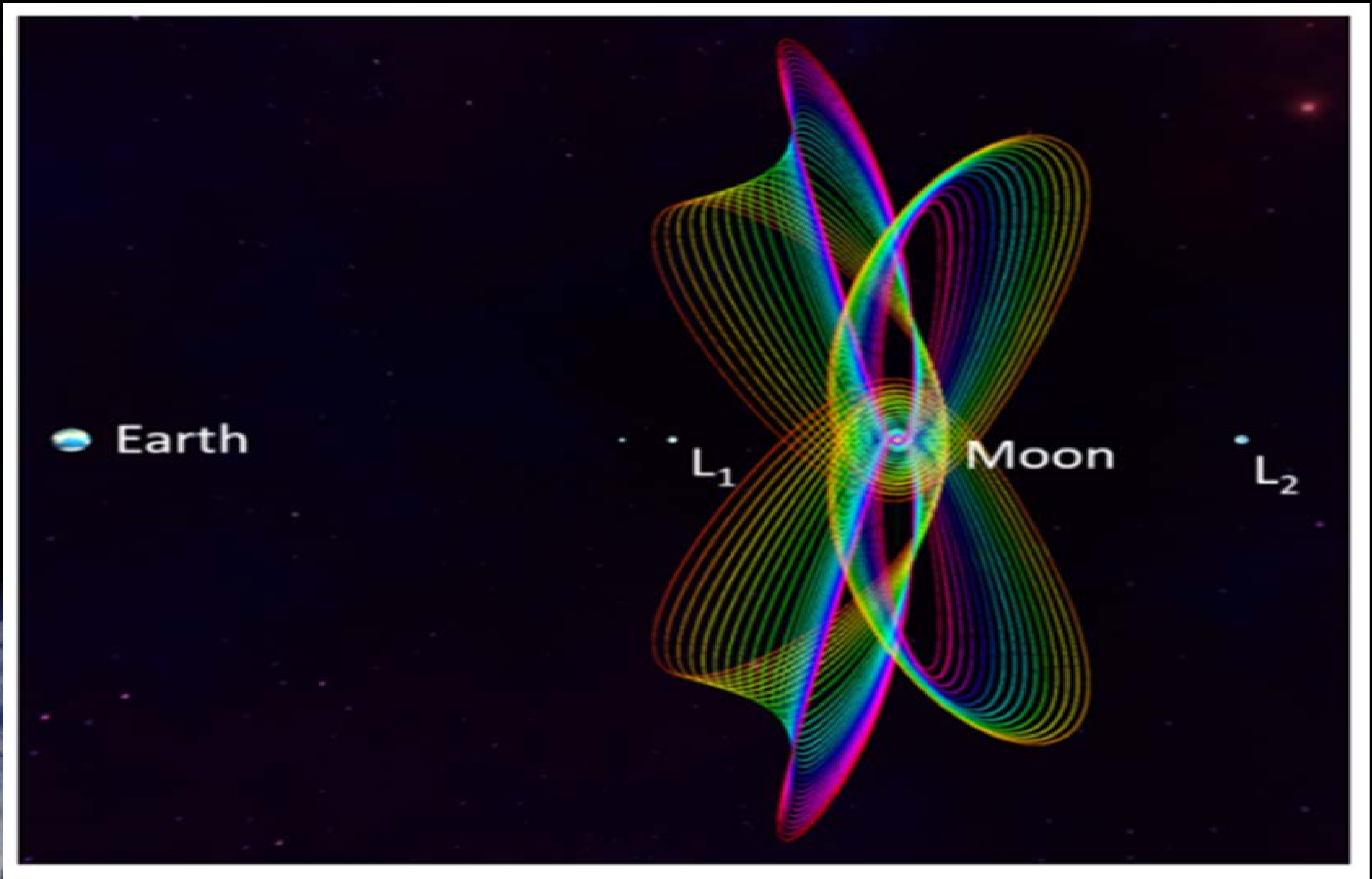


Deep Space Gateway



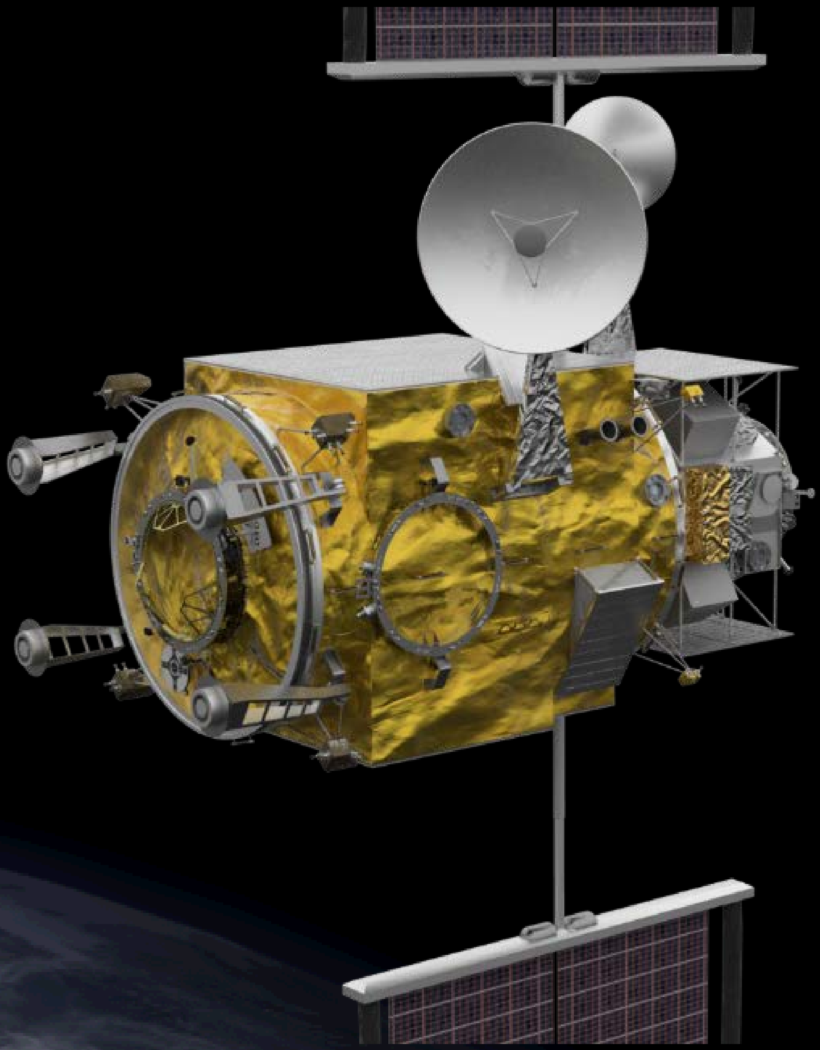
- Concept for DSG Habitation Element
  - Crew Quarters
  - Exercise
  - Experiments
  - Galley
  - Modular Equipment

NRHO Orbit for Gateway



Power Propulsion Element

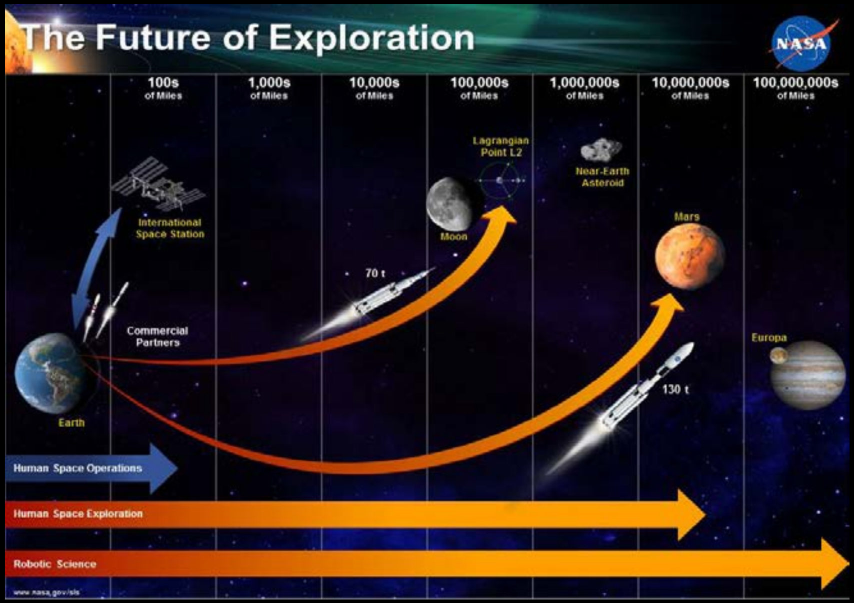
- Development led by NASA Glenn
- Provides 60+ kW of electric power
  - 60 + kW of Solar Array
  - 16 kW hr of batteries
  - 120 Vdc power
  - 27 kW to Habitat etc.
  - 39 kW to Thursters
- 4 Ion Thrusters
  - 600 milli-Newtons of thrust
  - 0.135 lbs. of thrust
  - Xenon propellant
- Lifetime 15 years



Deep Space Exploration Challenge

- **Communication becomes a problem**
  - **Times are longer than any previous experience**

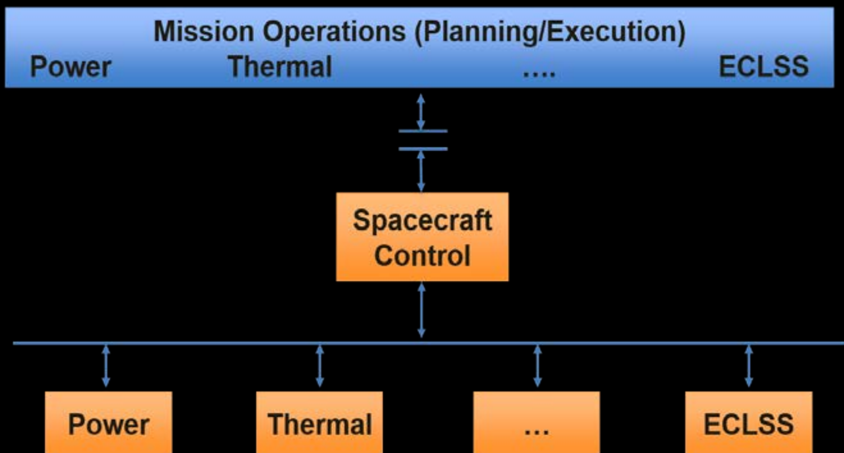
- **Power is your most critical system**
  - **Every system on the vehicle needs power**
  - **Electrical power needs a high level of availability and reliability**
  - **MUST operate autonomously**



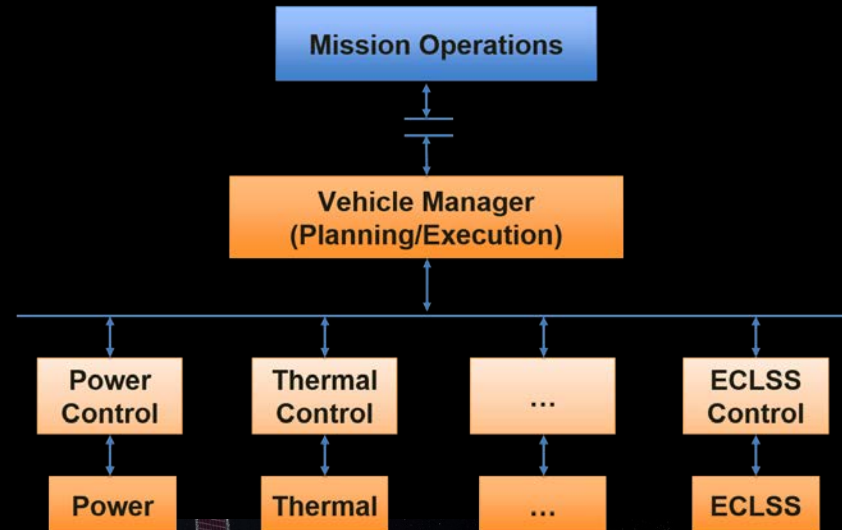
Mission	Communication Bandwidth	Communication Latency
ISS	300-800 Mbps (TDRS)	Real-time
Apollo / Orion	<2 Mbps (DSN)	1 to 2 seconds
Deep Space Vehicle	<2 Mbps (DSN)	15 to 45 minutes

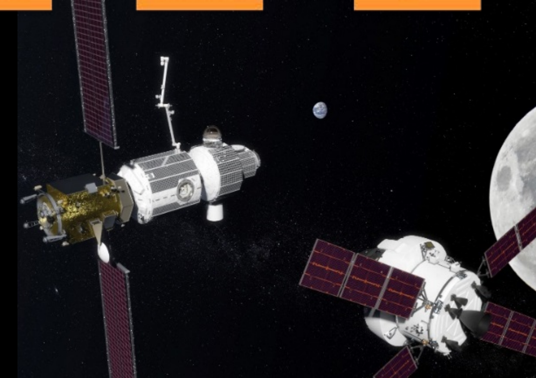
Traditional vs Autonomous Spacecraft Architecture

Traditional Spacecraft Architecture



Autonomous Spacecraft Architecture





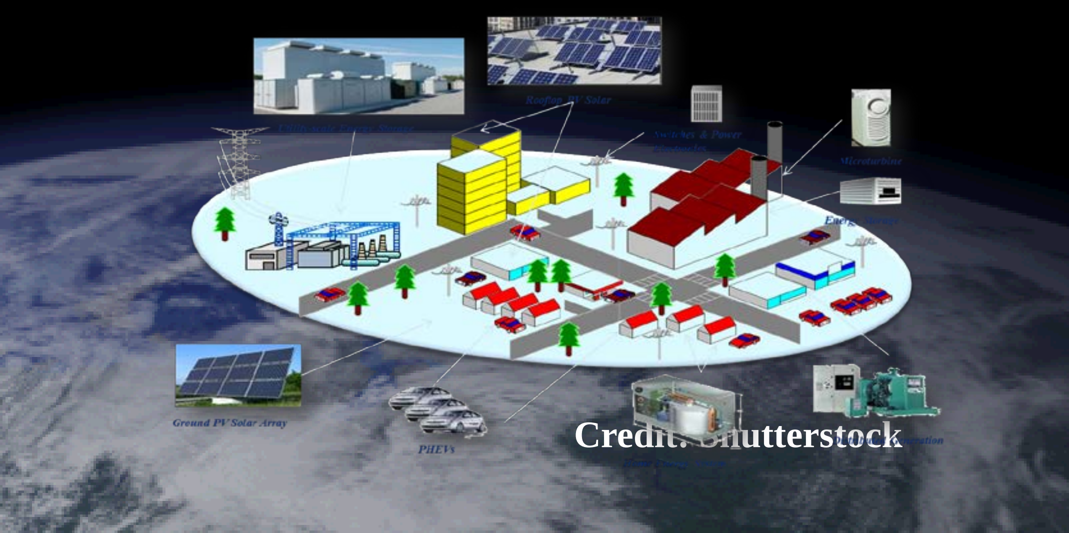
Rely on automation and autonomous systems technology to safely operate spacecraft

Autonomous Power Control

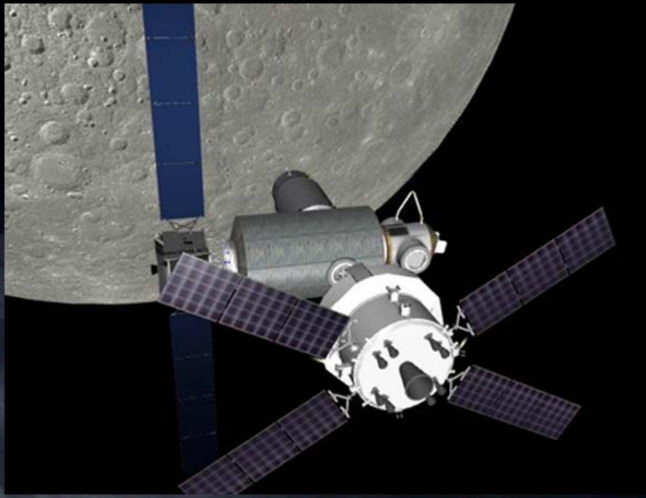
What is an Autonomous Power System?

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

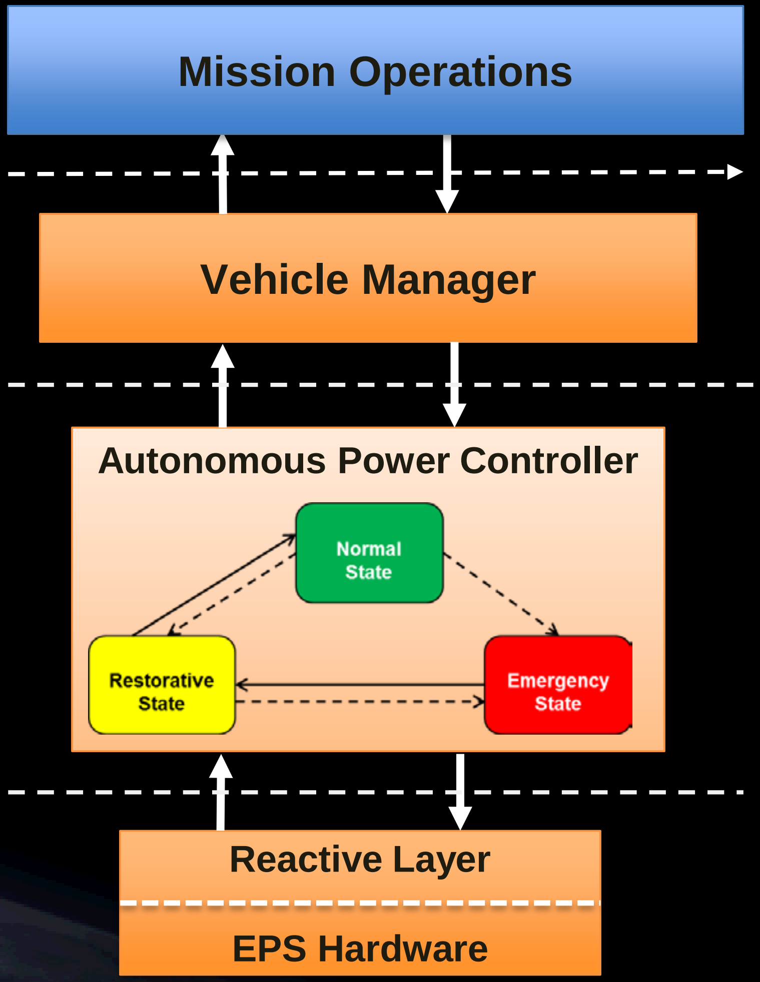


Credit: Shutterstock

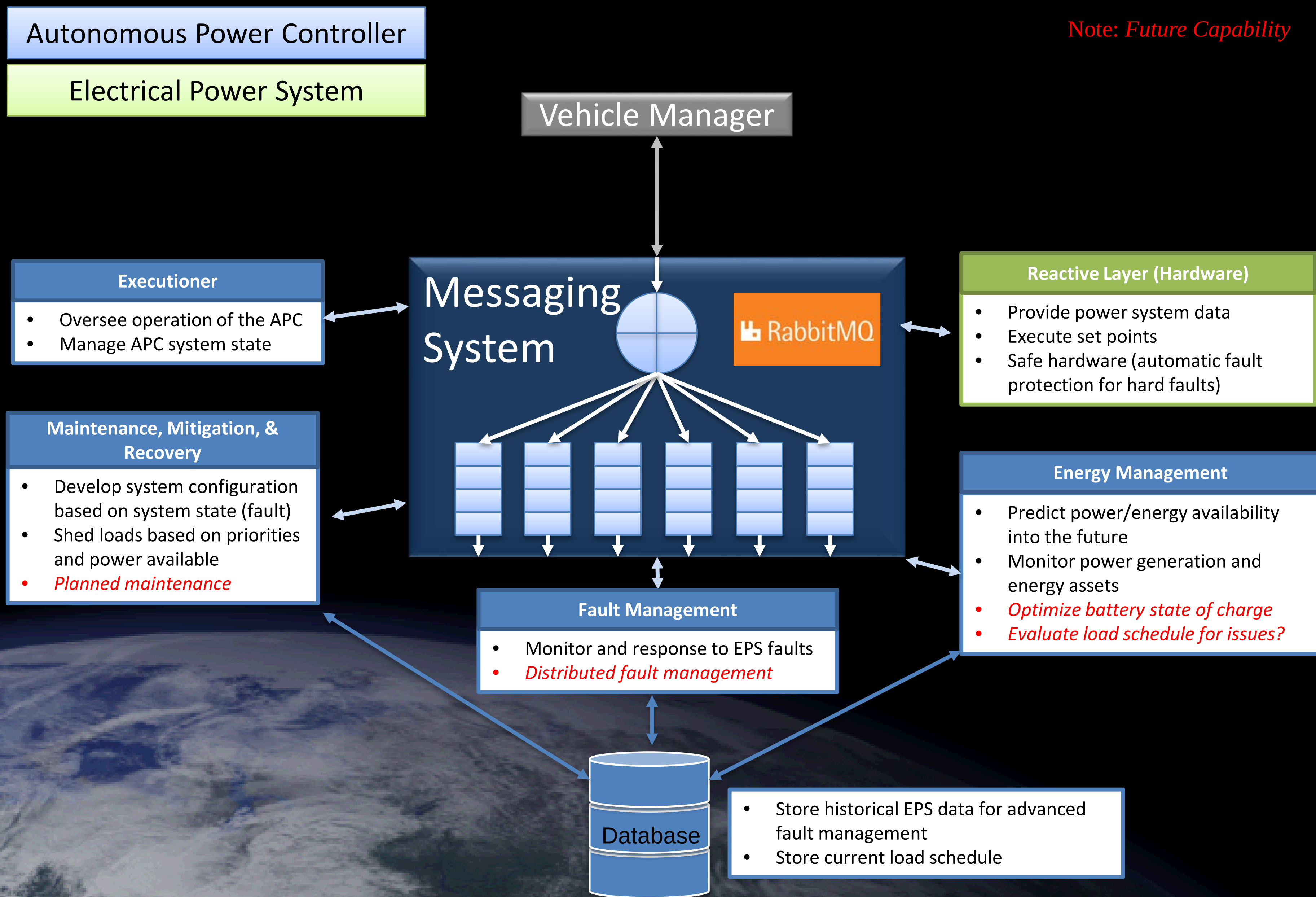


Vehicle Autonomous Power Control Architecture

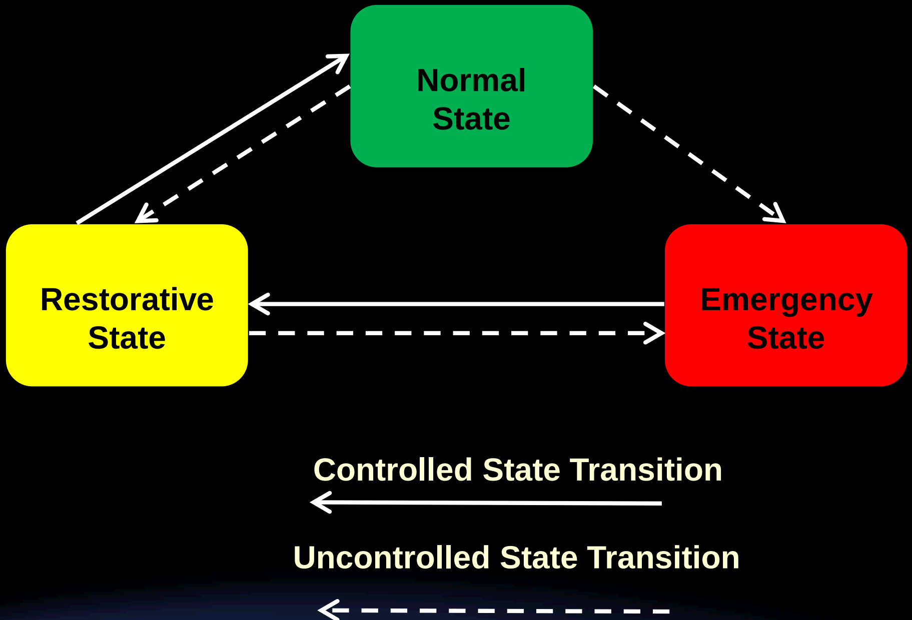
- **Mission Operations**
  - Monitors vehicle operations
  - Adjusts long term mission objectives
- **Vehicle Manager**
  - Plan vehicle operation (Load Schedules, etc) to achieve mission objectives
  - Coordinate vehicle subsystems
- **Autonomous Power Controller**
  - Forecast energy availability and provide power to the highest priority loads
  - Safely operate the EPS hardware.
- **Reactive Layer (Full Digital Control)**
  - Provides closed-loop control of the EPS hardware
  - Protect EPS from hard faults (safe the system)



Autonomous Power Control System (Conceptual)



Autonomous Control State Diagram



Normal State:

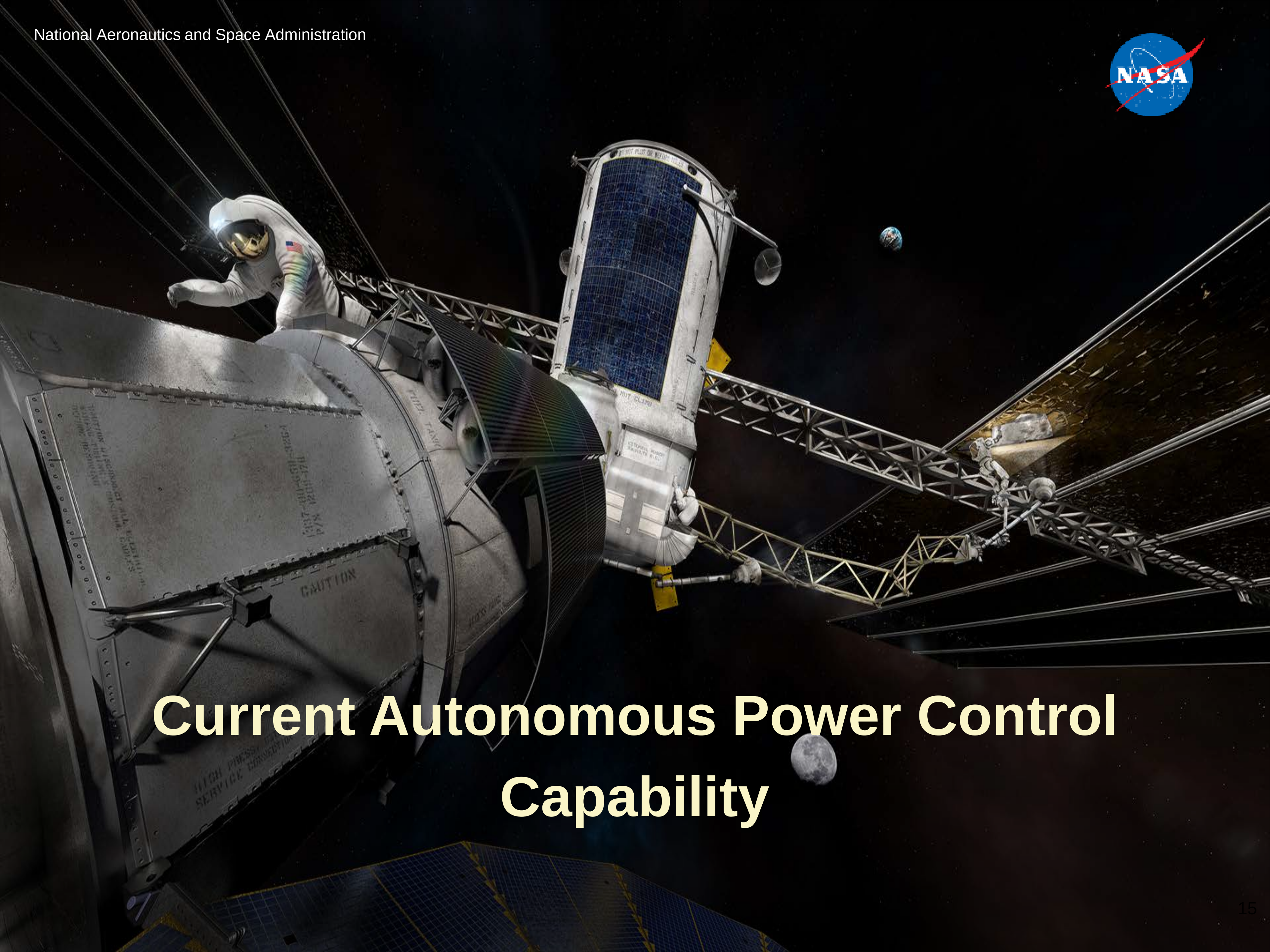
- System operating properly
- Calculates and provides an energy availability and power profile
- Analyzes proposed load schedules
- With no failures, continue indefinitely.

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

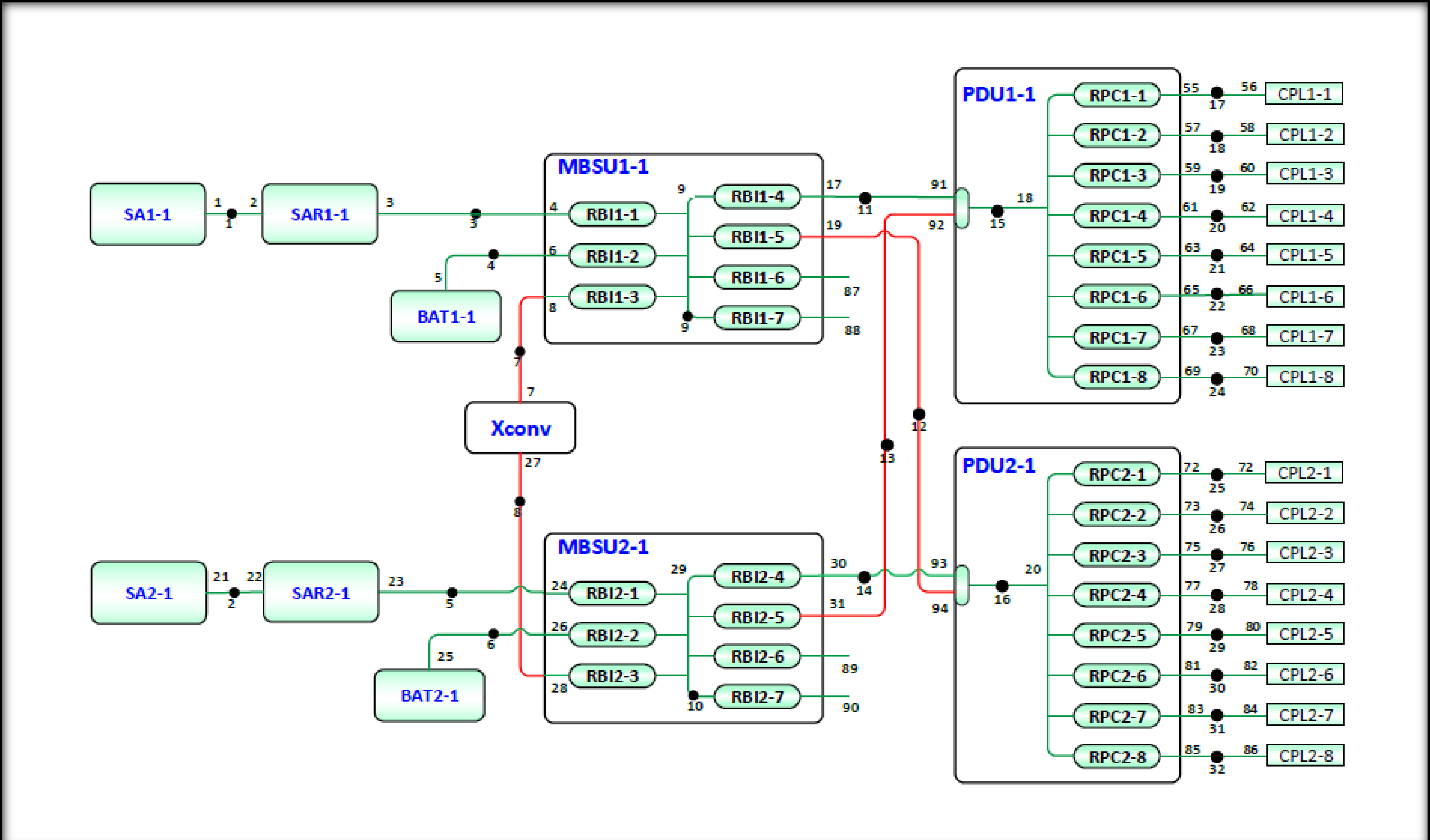
Restorative State:

- 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.



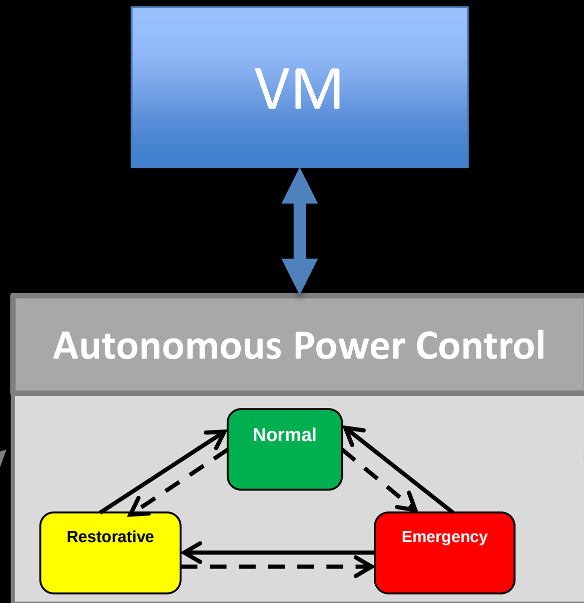
Current Autonomous Power Control Capability

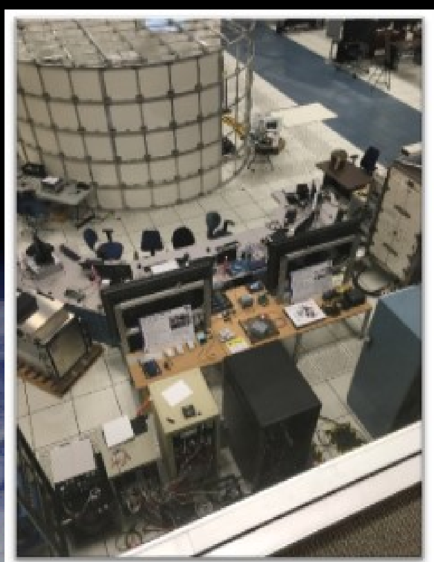
EPS 2-String System Architecture



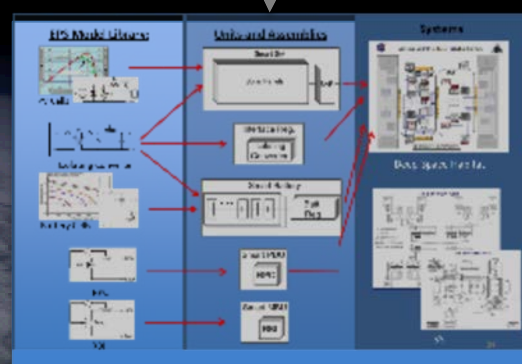
Power System Ratings	Peak	Nominal
RPC Current Rating (Amps)	4	3.2
RPC Power Rating @ 120V (kW)	0.48	0.384
PDU Current Rating (Amps)	32	24
PDU Power Rating @ 120V (kW)	3.84	2.88
Total Power to Loads (kW)	7.68	5.76

System Integration Capability





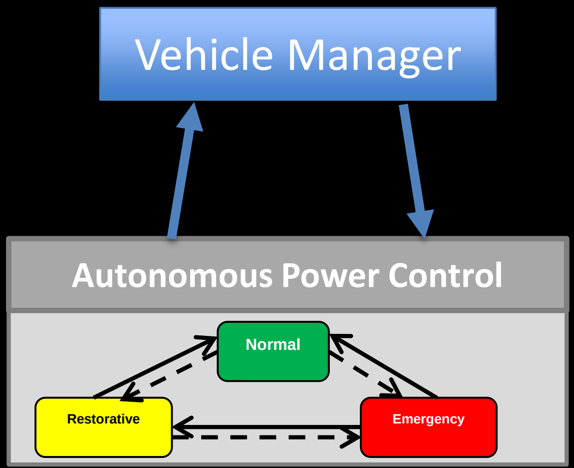
JSC iPAS Test Bed



GRC Real Time Simulation

GRC Deep Space Vehicle Power System Test Bed

Demonstrations



Energy Availability (to VM)

Load Schedule (from VM)

Normal Mode

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	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

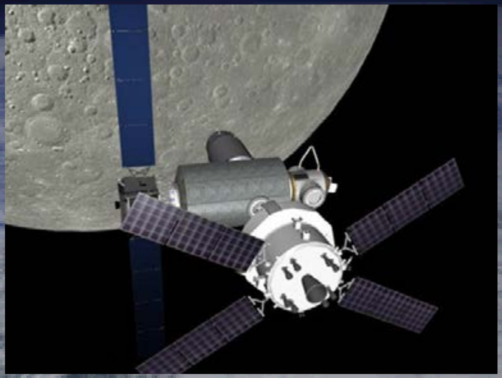
time	Peak (kw)	Nominal (kw)
1	7.68	2.88
2	7.68	2.88
3	7.68	2.88
4	7.68	2.88
…		
24	7.68	2.88
Total energy (kW tu)	69.12	

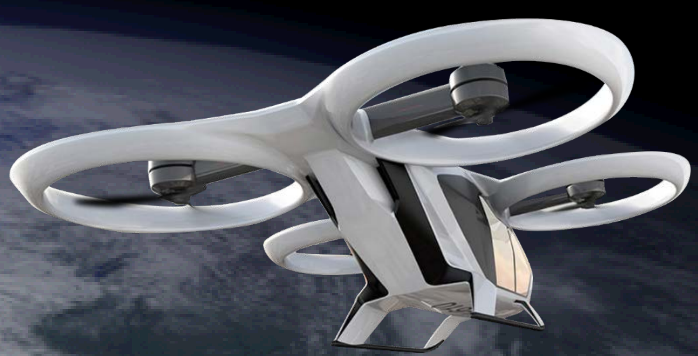
Load	Tu1	Tu2	Tu3	Tu4	Tu5
1	7	0	7	0	7
2	1	1	1	1	1
3	0	7	0	7	0
4	2	2	2	2	2
5	0	0	0	0	0
6	0	0	0	0	0
7	6	6	6	6	6
8	0	0	0	0	0
9	8	0	8	0	8
10	5	5	5	5	5
11	0	8	0	8	0
12	4	4	4	4	4
13	0	0	0	0	0
14	0	0	0	0	0
15	3	3	3	3	3
16	0	0	0	0	0

Transition to Aeronautics

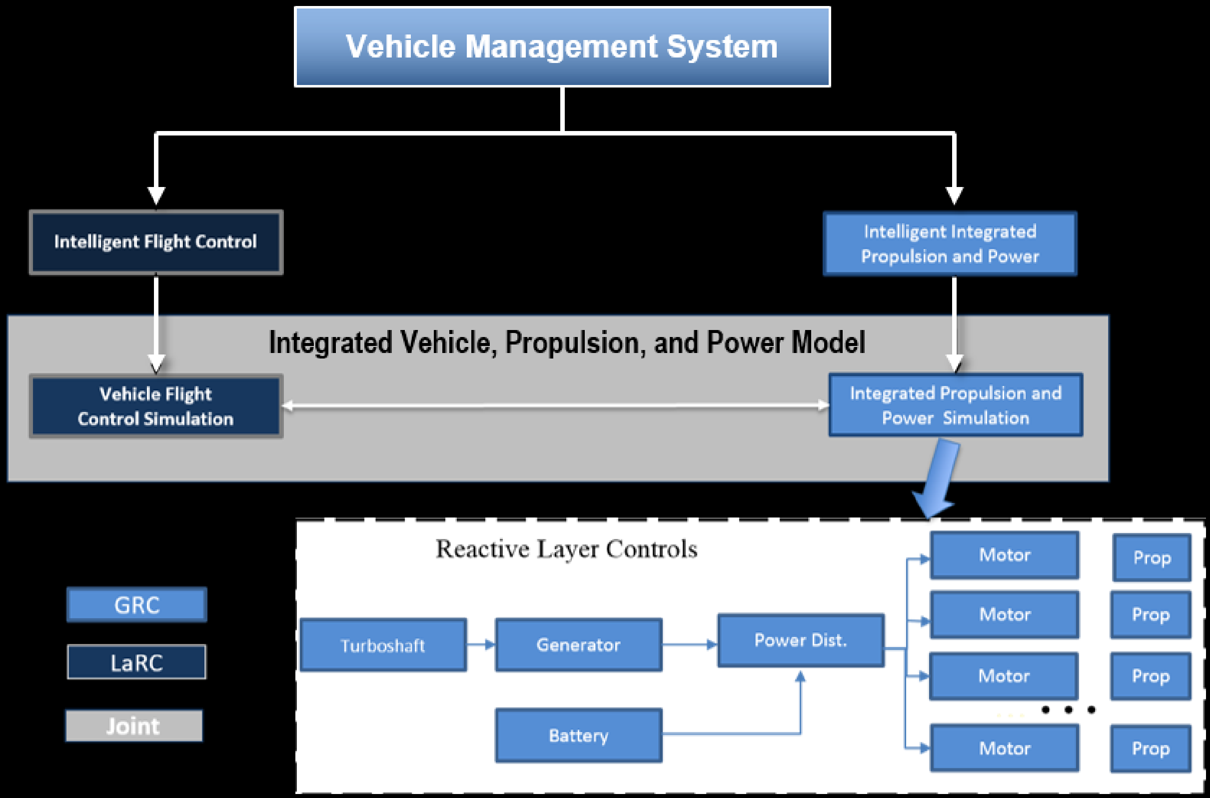
Power Autonomy in Aeronautics

- **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





Federated Control Architecture



Distributed or federated control architecture

- **Individual "intelligent" subsystem controllers**
- **Coordinated control/response**
- **Decentralized decision making**
- **Rapid response of local subsystem**
- **More efficient computation and communication**

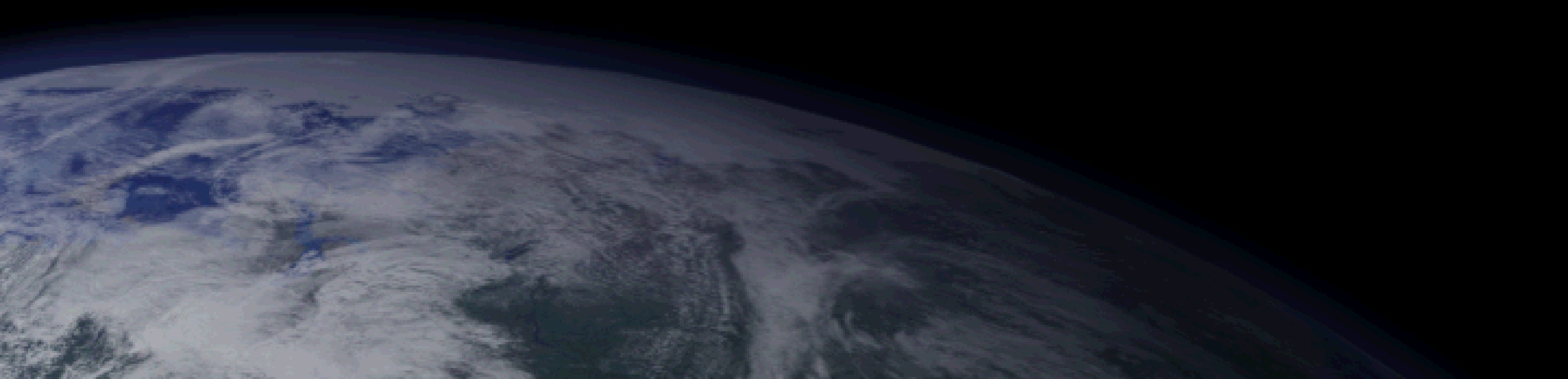
Conclusion

- Autonomous Power Systems capability is required for long term operation far from earth

- Developed an initial autonomous power controller and demonstrated required capability to safely operate an electrical power system without human operator in the loop.

- Technology developed for deep space exploration vehicles can be transition to aeronautics for use with Hybrid Electric Airplanes and other applications such as operating micro-grids.

Thank you!
Questions?



Typical Spacecraft Control Architecture