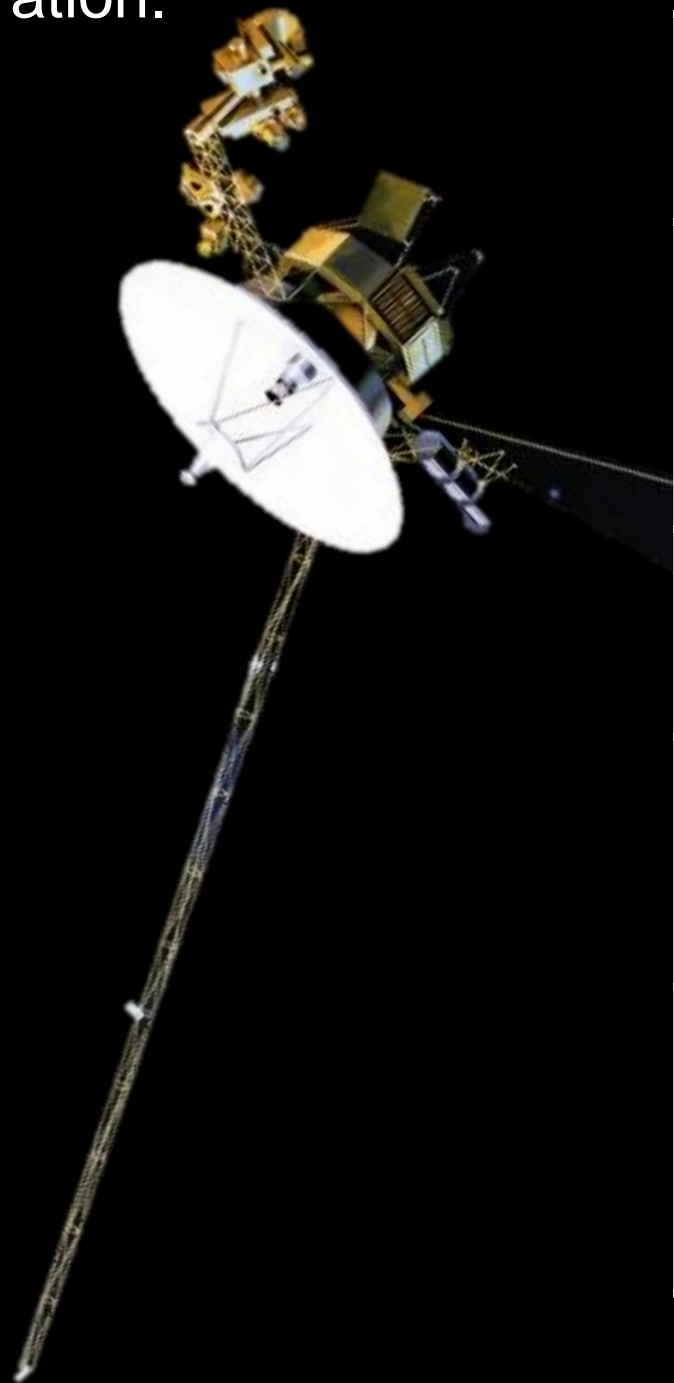


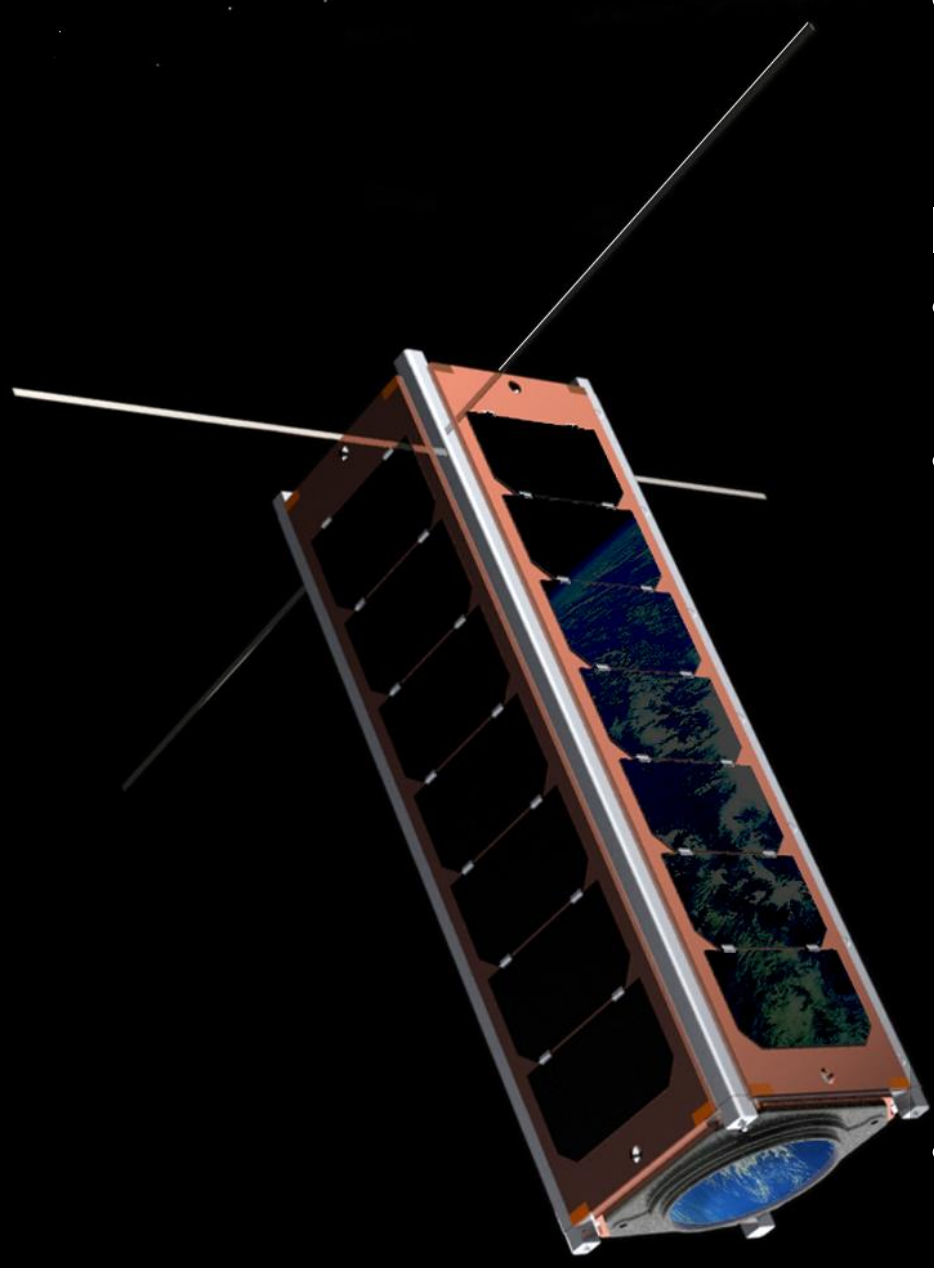
SmallSat Exploration of the Outer Planets

Leveraging the SmallSat Approach

Early NASA planetary exploration missions used series of similar spacecraft, launched at short intervals, to build up target science. The SmallSat paradigm reflects many elements of this successful mission strategy that can be leveraged to augment outer planet exploration.



Features of Early Explorer Missions <small>(Pioneer, Ranger, Lunar Orbiter, Surveyor, Mariner)</small>	Features of the SmallSat Approach
Spacecraft with identical or similar designs launched in series of 5 to 10 missions over the course several years	SmallSats can leverage standardization and commercially available hardware to enable cost-effective exploration campaigns over many individual missions
Short intervals between individual missions: 3 months to 1 year were typical	Short development times enable rapid turnaround for follow-on missions (as launch opportunities allow)
Higher tolerance to risk early in series as lessons learned from one mission improved subsequent spacecraft in series	More frequent, lower-cost missions enable higher-risk science objectives
Repeated missions built up database of target science over time and many target locations.	Lower cost and mass of individual spacecraft enables missions with multiple units that enhances target diversity and enables opportunistic science or repeated visits to one site






Attitude Control System Components & SmallSat Explorers

Currently Available Hardware Capabilities


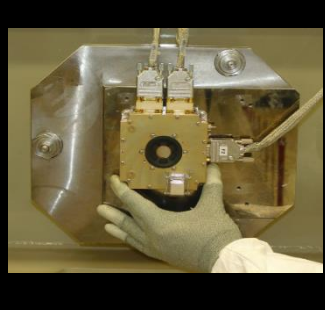
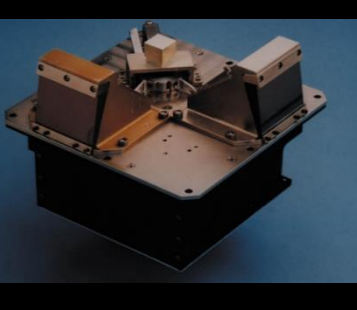


- SmallSat ACS systems are becoming increasingly sophisticated, with integrated systems offering sensor and actuator suites similar to those seen on traditional outer planet missions (including star trackers, sun sensors, gyros, thrusters, and reaction wheels)
- Typical system components tolerate <20 krad, have an operating thermal range of -20 deg C to +60 deg C
- Pointing control accuracy of better than 1 deg is becoming more commonplace, but highly stable systems and tight pointing control not yet demonstrated on flight

Considerations at the Outer Planets

- Actuators

Reaction Wheels/CMGs	Torque Rods	Thrusters
		
May need larger momentum storage and torque capabilities to scale with s/c inertia (likely larger than most SmallSats) and larger environmental disturbances	Requires a consistent and well-understood magnetic field, especially to model it	May require larger delta Vs, larger fuel tanks

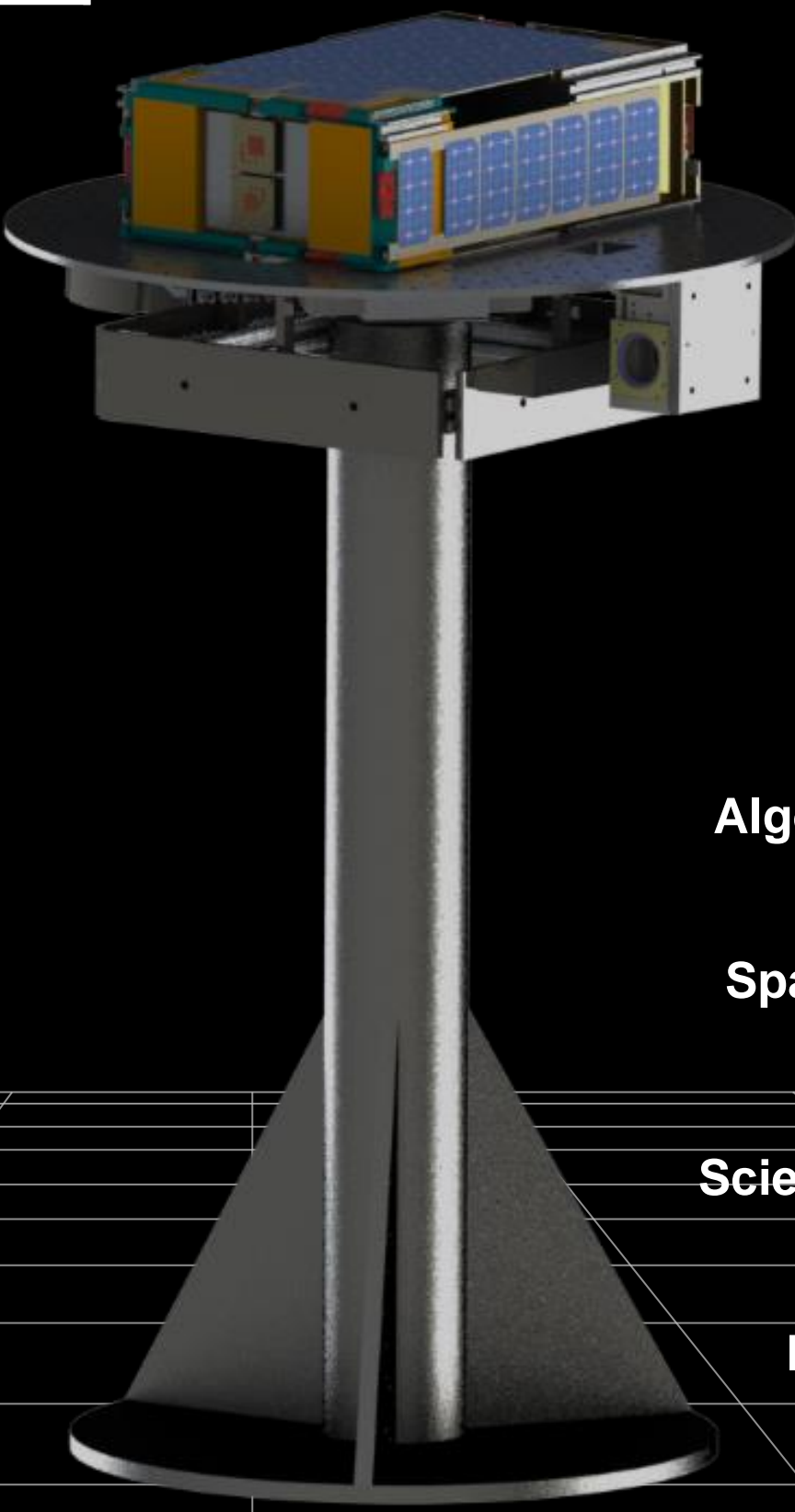
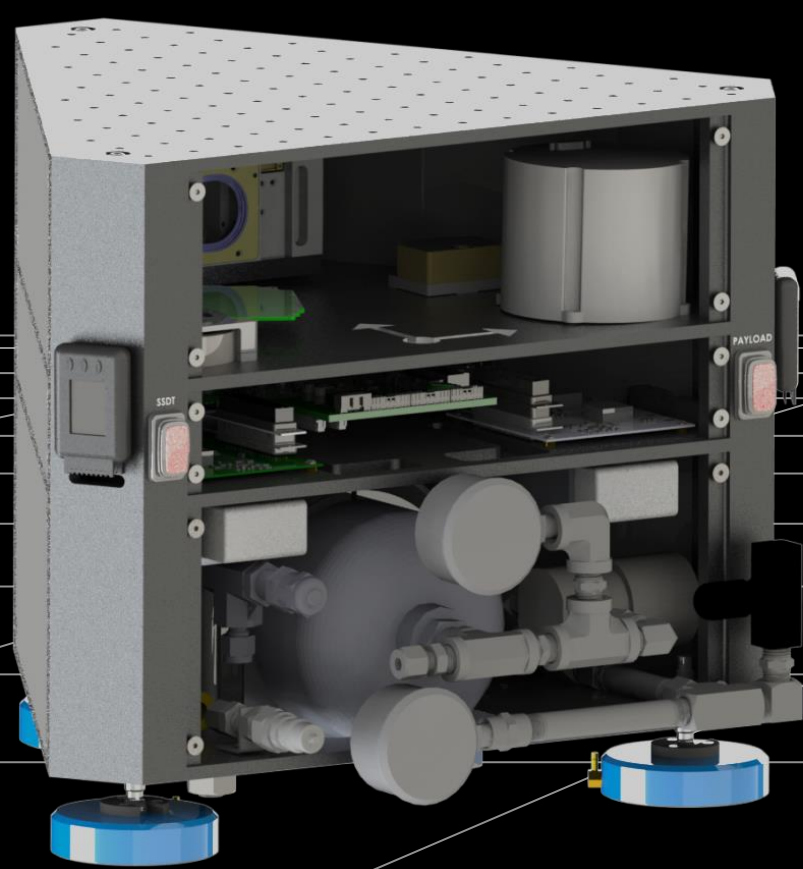
- Sensors

Star Tracker	Sun Sensor	Horizon Sensor	IMU	Magnetometer
				
Possible radiation concerns	Might need to change sensor electronics	Requires good thermal model of body, may not be feasible for some bodies due to low thermal emissions	No changes needed for outer planets	Requires magnetic field, may require different ranges and sensitivities than traditional Earth sensors

- Sensors generally operate the same way, actuators don't scale
- Traditional smallsat are capability-driven, but for outer planet explorers, science requirements are much more likely to drive the need for higher-performing, customized systems

ACS Technologies

- Reaction wheel isolators for low-jitter observing
- Systems with low-cost sensors and large actuators
- Software to support improved autonomy/FP
- Low-power sensors and actuators



Key Challenges for SmallSats at the Outer Planets

Survivability and Environmental Tolerance




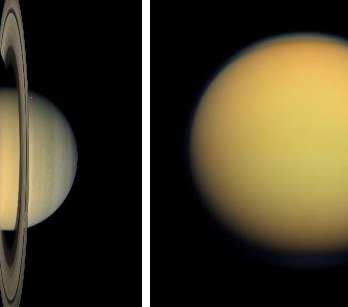
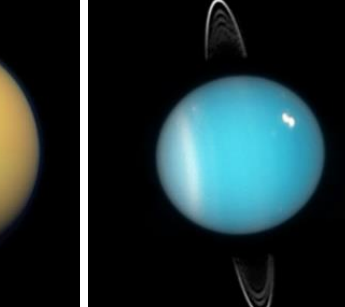
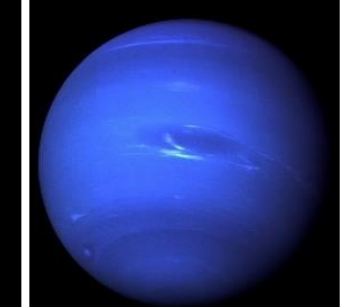

- Parts reliability in the more stringent thermal and radiation environments – most CubeSats are designed to survive in LEO
- Surviving the longer mission lifetimes due to longer cruise – many CubeSat missions are <1 year, and relatively few are >3 years

Increased System Capability

- Designing cost-effective systems for the unique magnetic, aerodynamic, gravity, and solar environments of the outer planets
- Developing systems with larger fuel tanks, communication hardware, power or energy storage systems, and attitude control actuators while maintaining a COTS-driven standardized platform (most SmallSats are <100 kg, while most early NASA explorers were 200 – 1000 kg)
 - ACS actuator sizing scales with spacecraft size, meaning most SmallSat hardware is not applicable
 - Less available solar power and other energy resources
- Increasing system autonomy – and perhaps fault protection – due to limited contact with ground
- Developing effective mother-daughter interface systems to enable primary exploration assets to support smaller missions

Risk Management

- Establishing an appropriate technical risk posture that takes into account the higher cost-to-transport and relatively low frequency of outer planet missions
- Meeting stringent planetary protection requirements near sensitive targets such as Europa or Enceladus

	Earth	Jupiter	Galilean Moons	Saturn	Titan	Uranus	Neptune
							
Distance, AU	1.0	5.20	5.20	9.52	9.52	19.21	30.09
Gravity μ , m ³ s ⁻²	3.99E14	1.27E17	Various	3.79E16	8.98E12	5.79E15	6.84E15
Magnetic Moment, T·m ³	7.91E15	1.56E20	Various	4.60E18		3.80E17	2.10E17
Solar Flux, W·m ⁻²	1370	50.5	50.5	14.90	14.90	3.71	1.51
Atmosphere	1 atm (surface)	Thick, gaseous, windy	<1 atm (surface)	Thick, gaseous, windy	1.45 atm (surface)	Thick, gaseous, windy	Thick, gaseous, windy
Radiation (Electron/Proton) flux, cm ⁻² s ⁻¹	10 ⁵ /10 ⁴	10 ⁹ /10 ⁷	High due to Jupiter	10 ⁵ /10 ⁴		10 ⁴ /10	

JPL's Approach for SmallSats

Reducing ACS Risk for SmallSats

- Developing SmallSat ACS technology to support science-class observations
- Fully characterizing COTS sensors and actuators to understand range of performance
- Improve access/reduce cost of ACS testing

SmallSat Dynamics Testbed Infrastructure

- Hardware library of common SmallSat components
- In-house test environments:
 - Spherical Air Bearing (3 DOF rot)
 - Planar Air Bearing (2 DOF trans + 1 DOF rot)
 - Dynamics Simulator (6 DOF), with Empirically validated models of hardware in simulation environment
- Access to JPL hardware characterization facilities: FCT, rate table, Kistler table, observatory, Helmholtz coil, etc.

