NASA Science Mission Directorate

Autonomy Workshop

Small Body Design Reference Mission

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Uniqueness of Small Bodies

- Abundant
- Disparate
- Diverse in their composition and origin
- Relatively unknown

Focus and applicability

- Working group focused on near-Earth objects (NEOs), comets, and asteroids
- Capabilities applicable to small ocean world moons and KBO

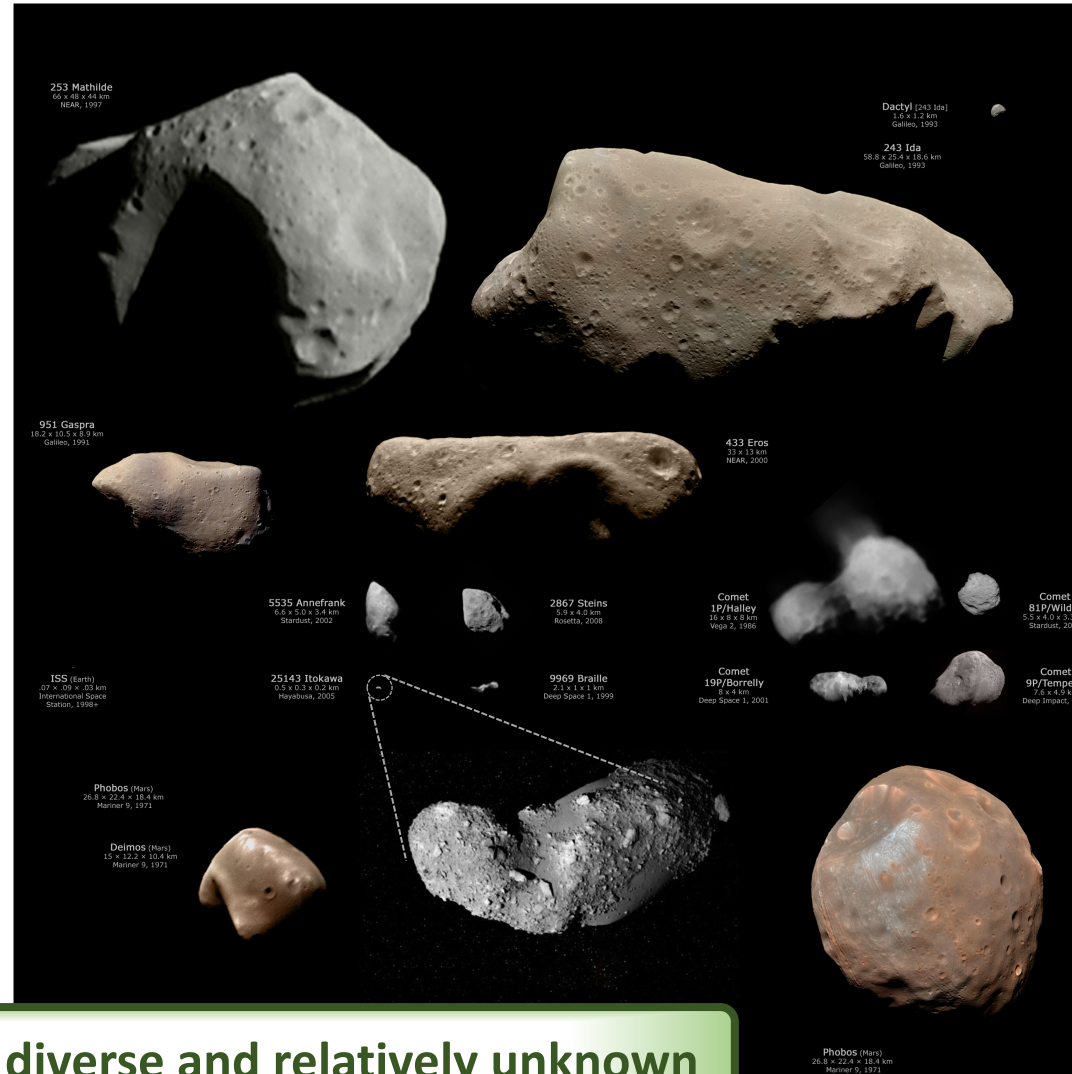
Small Bodies

As of October 18, 2019

- >850,000 found
- 99.6% asteroids; 0.4% comets
- 2.6% NEO (incl. 2,005 PHA)

What do we know about them?

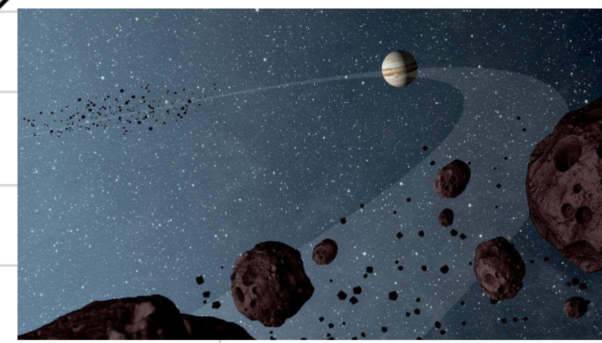
Method	Property	Population	
Ground	Orbit	828,913	~100%
	Abs. Magnitude	826,217	~100%
	Albedo	137,939	17%
	Approx. Diameter	139,360	17%
	Period	18,818	2.3%
	Spectral Type	2,174	0.3%
Flyby	Macro Details	25	0.003%
Rendezvous	Micro Details	5	0.0006%

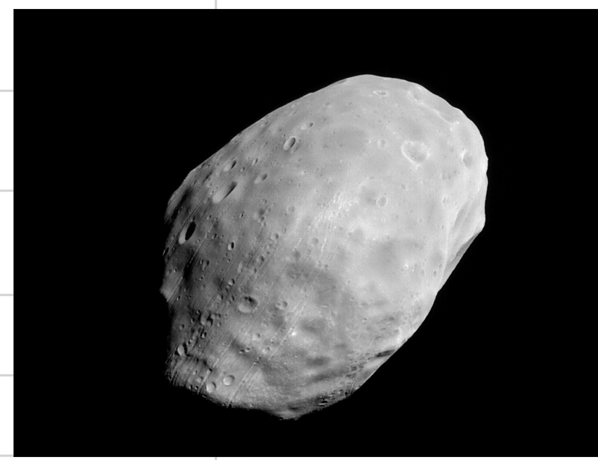


Small Bodies are diverse and relatively unknown

Benefits

Benefits		What is where?	What is what (composition)?	Current Processes	Mass	Geotechnical Properties
Science Exploration	Origins					
	Precusors for Life		Water detection			
	Evolution					
Planetary Defense	Assessing threats					
	Mitigation					
Human Exploration	Access					
	Operations					
ISRU	Assessment					
	Extraction					





Benefits Multiple Thrusts

Synergies

Why Small Bodies?

- They embody representative challenges
  - Surface is not known *a priori*
  - Surface has rugged topography
  - Surface/spacecraft interaction is dynamic, yet forgiving

Why Autonomy?

- Enables greater access to more diverse bodies
- Enables effective operations on and below their surfaces

Why SmallSats?

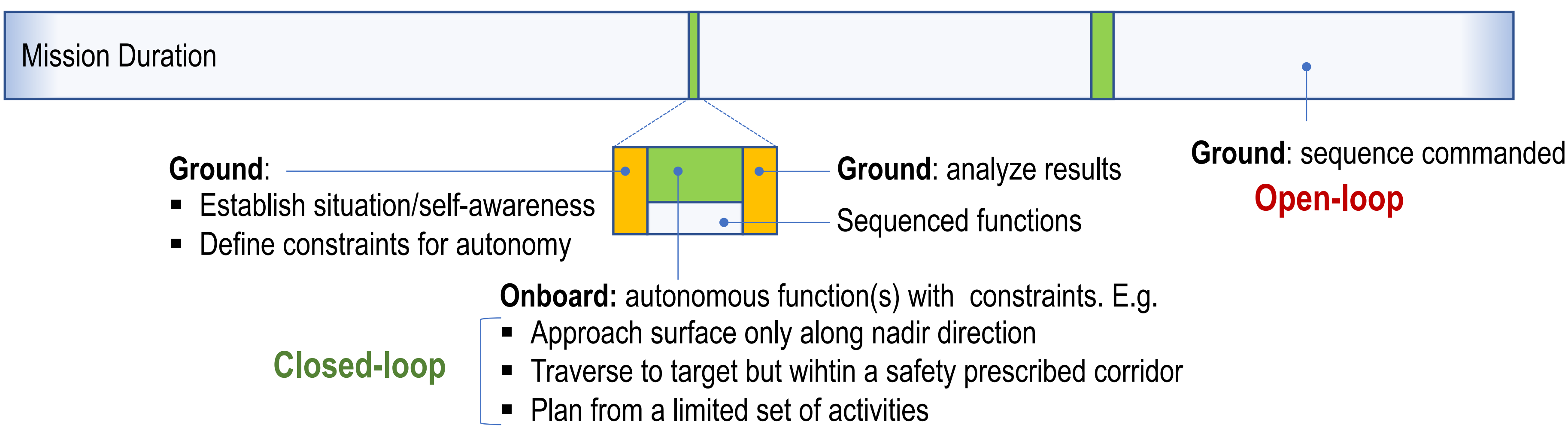
- More affordable to advance *autonomy* for *greater access*
- Rapid growth and lower launch opportunities

Autonomy + Small Bodies + SmallSats are highly synergistic

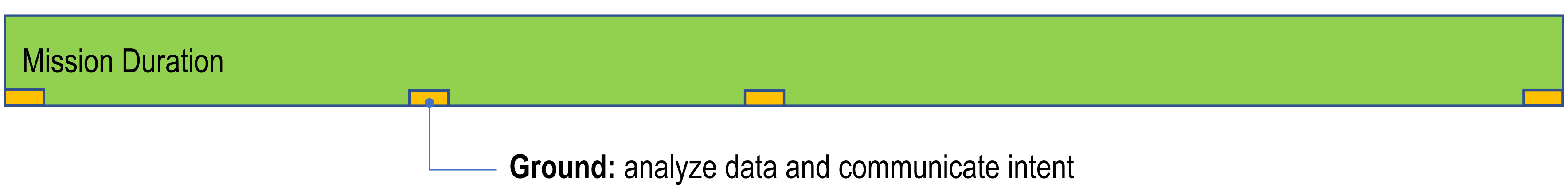
State of the Art in Autonomy

Several missions used some form of autonomy, but all operated within narrow windows and constraints.

Current Spacecraft Autonomy



Future Spacecraft Autonomy



Design Reference Mission #1

Near-term DRM (launch in 2030s)

Autonomous Mission

From Earth's Orbit to the Surface of a Small Body

Places an affordable SmallSat in Earth's orbit with a high-level goal of reaching a selected asteroid, which includes:

- Approaching and landing on an unknown body
- Precisely accessing at least one target on the surface
- Sampling and analyzing the measurements
- Retargeting follow-on measurements based on local analyses, and sending the results to Earth

Required Autonomous Capabilities

- End-to-end, long-duration autonomy
- Approaching and landing on an *a priori unknown* body
- Handling the environment
- Proximity maneuvering around body
- Adapting and learning from its operations
- Establishing situational awareness (perceiving, assessing hazards, and selecting safe landing spot)
- Reaching specific targets on the rugged surface targets
- Manipulating the surface or subsurface
- Analyzing and identifying samples for analysis

Design Reference Mission #2

Long-term DRM (launch in 2040s)

Autonomous Mission

Understanding the Populations of Small-Bodies

Places a centralized mother platform with multiple daughter satellites in Earth's orbit to scan, identify, characterize, and eventually enable access to a range of Small Bodies.

- The mother craft will dispatch daughter craft to explore diverse bodies (including opportunistic visits to interstellar or hazardous objects).
- These daughter craft will visit the targets to collect samples and return material to the mother craft for further analysis or for resource extraction.

Required New Autonomy

In addition to the autonomy required by previous DRM:

- **Detecting Small Bodies and coordinating multi-craft:**
  - Identify bodies based on intent
  - Track and estimate trajectories; plan cruise trajectories
  - Coordinate mother/daughters; dispatch daughters to specific bodies
  - Return to mother, dock and refuel
- **Extracting resources:**
  - Anchor or hold on to the surface and reach deep into the body;
  - Extract and handle large volumes of material for processing
- **Planetary defense:**
  - Understand composition and geotechnical properties
  - Deal with a largely unknown interior and surface
  - Adjust body trajectory in real-time (e.g. kinetic impactor or gravity tractoring) to deflect body

Feedforward Potential

- Near-term DRM would substantially advance autonomy in a *representative environment*
- Matures technologies in a forgiving environment and at an affordable cost
- Capabilities would feed forward to:
  - Missions of opportunity
  - Bodies with rugged surfaces
  - Interactions between assets and unknown environments
  - Situations w/ dynamically hazardous environments
  - Situations w/ obstructions to line-of-sight communications

Recommendations

1. **Establish a project** (NASA/industry/academia) *to flesh out design details and plans* and estimate cost of a SmallSat tech demo mission to a NEO
2. **Define engineering challenges** to **seed solicitations** for:
   - Developing a high-fidelity end-to-end simulation for DRM
   - Developing key autonomy technologies using simulation
3. **Establish an integration project** for hardware and software, test in simulation, and mature for flight demonstration
4. **Demonstrate** substantial advance in autonomy **through** several **SmallSat missions** and/or extended missions of opportunity

BACKUP SLIDES

Other Supporting Technologies

- Low-mass replenishable propulsion w/ initial $\Delta V > 5{,}000$ m/s
- Docking/undocking with ability to transfer volatiles
- Onboard computing/storage for long-term operations
- Advanced sensing and optics for remote detection
- Large-scale surface mobility, subsurface excavation, and material handling
- Communication among multiple space, surface, and below-surface assets

Table 1: Highlights of autonomy advances across Small-Body missions (past and current)

	Demonstrated Autonomy Advance	Capability/ Technology	Key Gaps and Needed Capabilities
1998 – 2001 Deep Space I	Cruised autonomously for 3 of 36 months (<10%); 30-minute autonomous flyby	Planning/scheduling Autonomous navigation (asteroid detection, orbit update, spacecraft low-thrust TCMs) System health management	<u>**Key Gaps**</u> ▪ **Limited scope of autonomy use:** capabilities have only been used for relatively short durations of the mission with pre- and sometimes post-monitoring from ground. ▪ **Use of *a priori* maps:** missions with proximity operations required extensive ground processing to generate maps that were used in subsequent autonomous maneuvers. ▪ **Reliance on ground-based resource planning** <u>**Needed Capabilities**</u> ▪ End-to-end, long-duration autonomy ▪ Autonomy in light of faults and failures ▪ Autonomy in environments with large uncertainties and limited *a priori* knowledge of the environment ▪ Autonomy that can handle a wide range of conditions, adapt and learn from its operations
2002–2011 Stardust	30-minute autonomous flyby of one asteroid and two comets	Target-body detection (one body) Attitude updates for tracking nucleus through flyby	
2005 – 2010 Deep Impact	Two-hour autonomous terminal guidance of comet impactor Flyby tracking of two comets	Target-body detection (one body), orbit update, and spacecraft low-thrust TCMs	
2005 Hayabusa	Autonomous terminal descent of last 50 m toward a near-surface goal for sample collection	Laser ranging (at < 100m) to adjust altitude and attitude	
2019 Hayabusa II	Same as Hayabusa	Same as Hayabusa; bright surface object detection and centroiding; hybrid ground/onboard terminal descent control: ground controls boresight approach, while onboard controls lateral motion in final 50 m; on surface, open-loop control of surface hopping mobility	
2020 OSIRIS-REx	<u>Potential plan:</u> terrain-relative navigation (TRN) for touch-and-go maneuver	Uses ground-generated shape-model, match natural features to model using TRN with ground oversight; onboard final maneuvers to initiate touch-and-go for sample collection	
022 ART	Several hours of autonomous terminal guidance (similar to Deep Impact)	Identification of each body for target selection; thruster control to guidance impact; targeting the 170-m moon of a	

- **Critical Autonomy Technologies for DRM 1**
- **Situation-awareness Self-awareness Reasoning and Acting**
- Spacecraft **guidance** and **navigation** with trajectory correction maneuvers
- Unknown body rotation, shape and gravity **estimation** during approach
- **Hazard assessment** (debris or orbiting moons) near and on the body (gas vents, rough topography, boulders) for safe and precise landing
- Surface, and *possibly interior*, **composition**

- **Success Metrics:**
- A program to achieve the near-term DRM initially in simulation and later through flight missions could have the following metrics:
- A SmallSat mission with ΔV of 0.8 – 1 km/s that launches, cruises and reaches (fly by and images) a small body destination without ground-in-the-loop
- Above + an ability to autonomously approach, rendezvous (ΔV of 5 – 10 km/s) and map a Small Body
- Above + an ability to select a landing site and land

- **Value to NASA:**
- Space exploration is an endeavor with numerous challenges and constraints. Autonomy could prove to be a pivotal technology that establishes a new paradigm of exploration. To usher this new era, a systematic and focused approach is needed for a sustained development program to overcome the multitude of challenges. As such, it is critical for the program to be affordable and with easy-to-evaluate success-milestones. Not only would these technologies advance the Small-Body thrusts, they would have strong feedforward benefit to more

NASA Small Spacecrafts
- 68 missions
    - 22 in operation
    - 46 in development
        - 10 outside EO