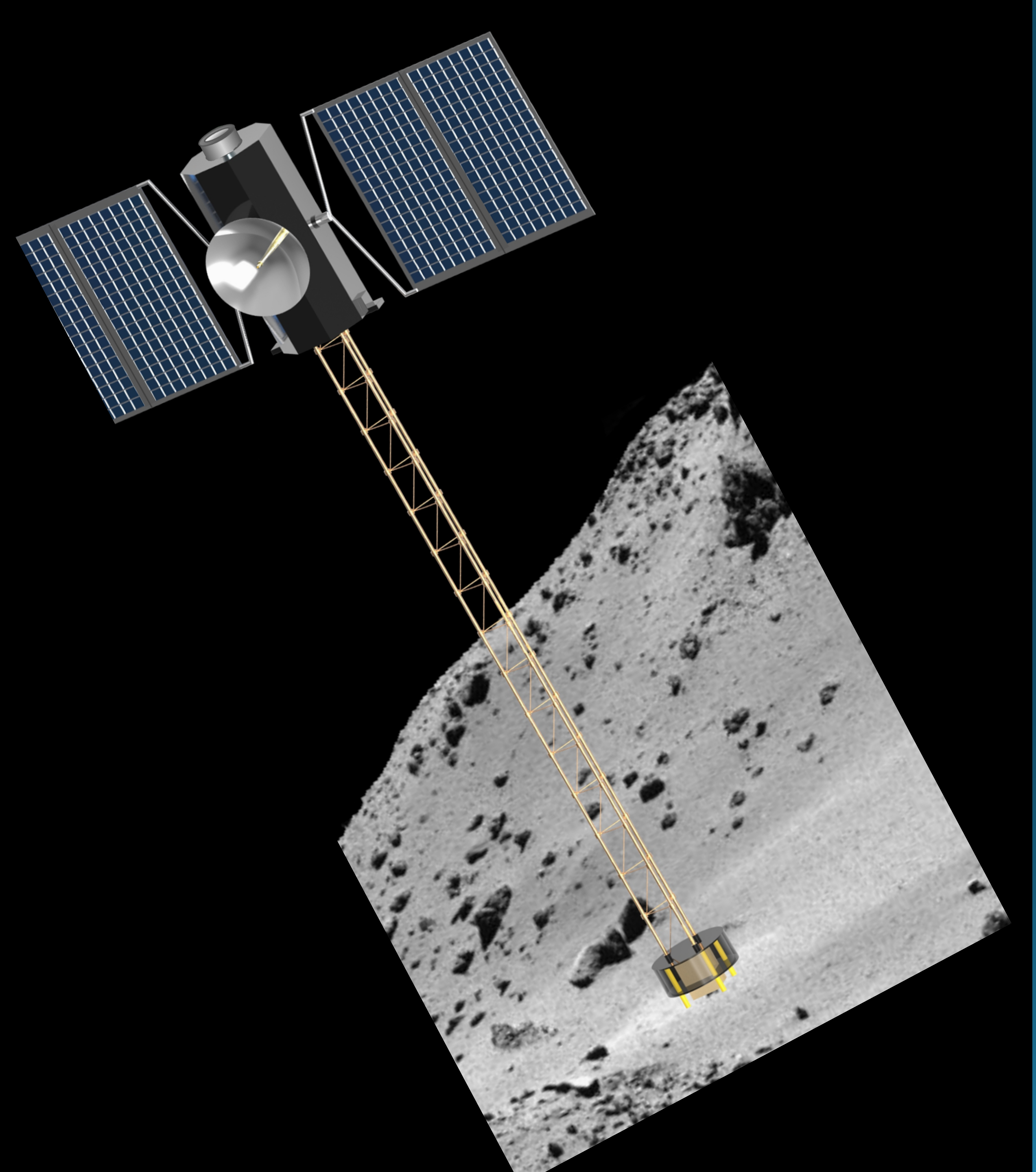


Spacecraft Penetrator for Increasing Knowledge of NEOs

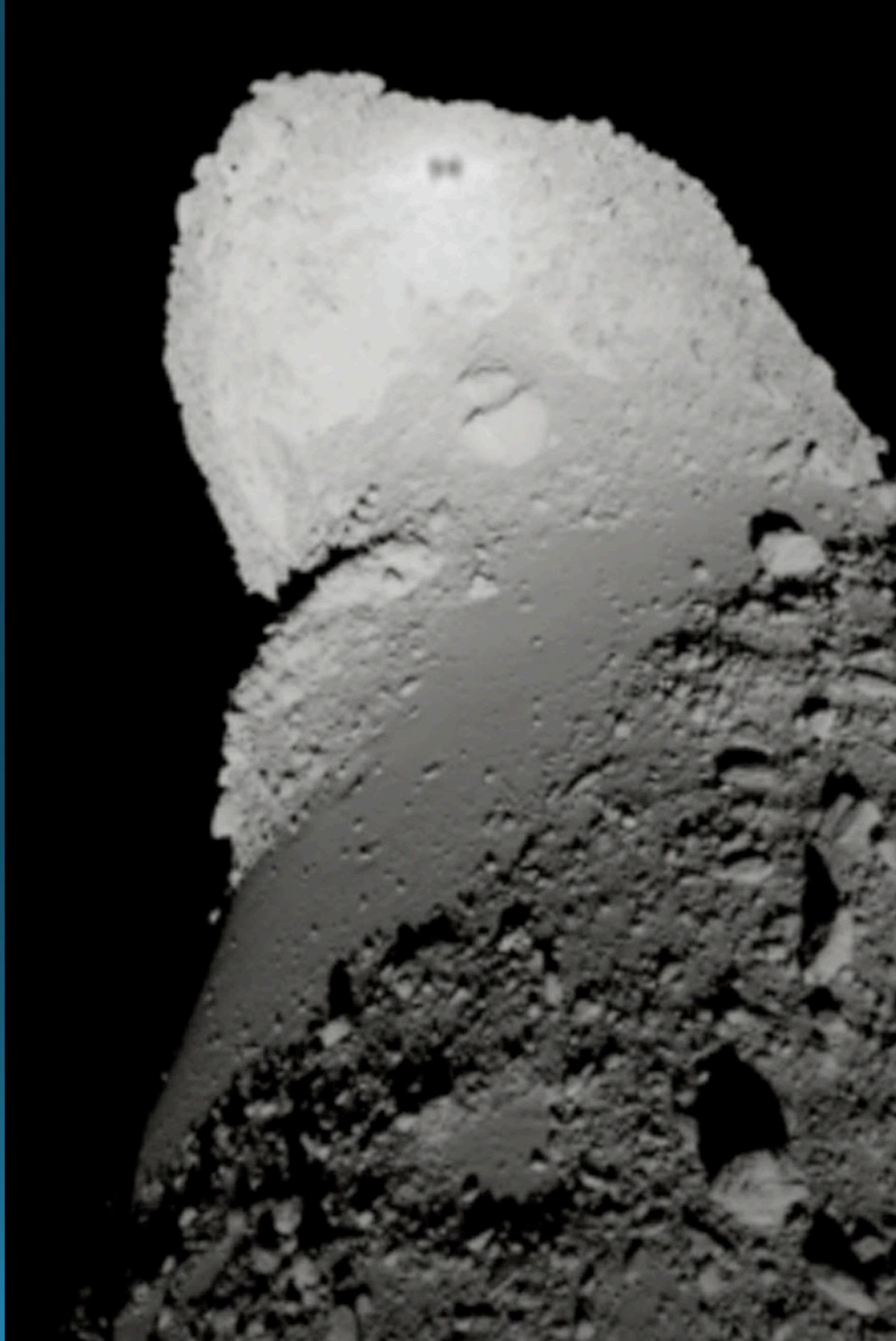
SPIKE

Erik Asphaug, Jekan Thangavelautham, Stephen Schwartz (ASU)
Roberto Furfaro, Tim Swindle (UA)
Paul Sava (CSM)
Dan Scheeres (CU)
Mathieu Choukroun, John Baker (JPL)

ASU Boulder MINES NASA Jet Propulsion Laboratory California Institute of Technology SpaceTREx

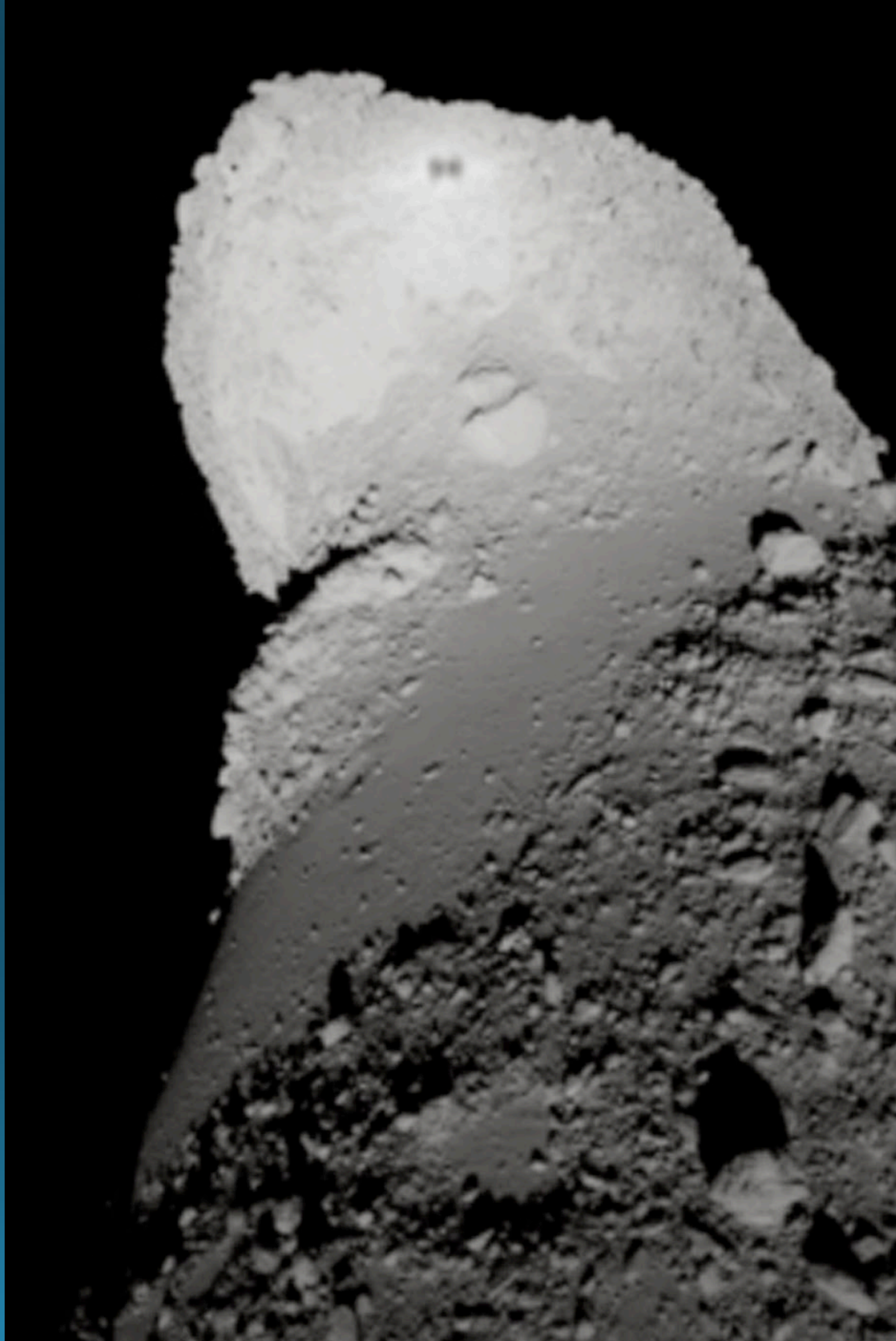
Why SPIKE?

- We require a comprehensive understanding of a wide variety of common NEOs
  - A scientifically significant sampling will require *tens of rendezvous missions*
  - Each investigation must acquire <u>subsurface geophysical and compositional data</u>
    - beyond remote sensing
  - Best achieved by *multiple identical smallsats* built and launched at <u>low cost</u> (<$100M per sat)
    - Each capable of in situ, comprehensive subsurface exploration e.g. GCMS, seismology, force sensing
    - Each spacecraft equipped with a capable, flexible, efficient and robust propulsion system



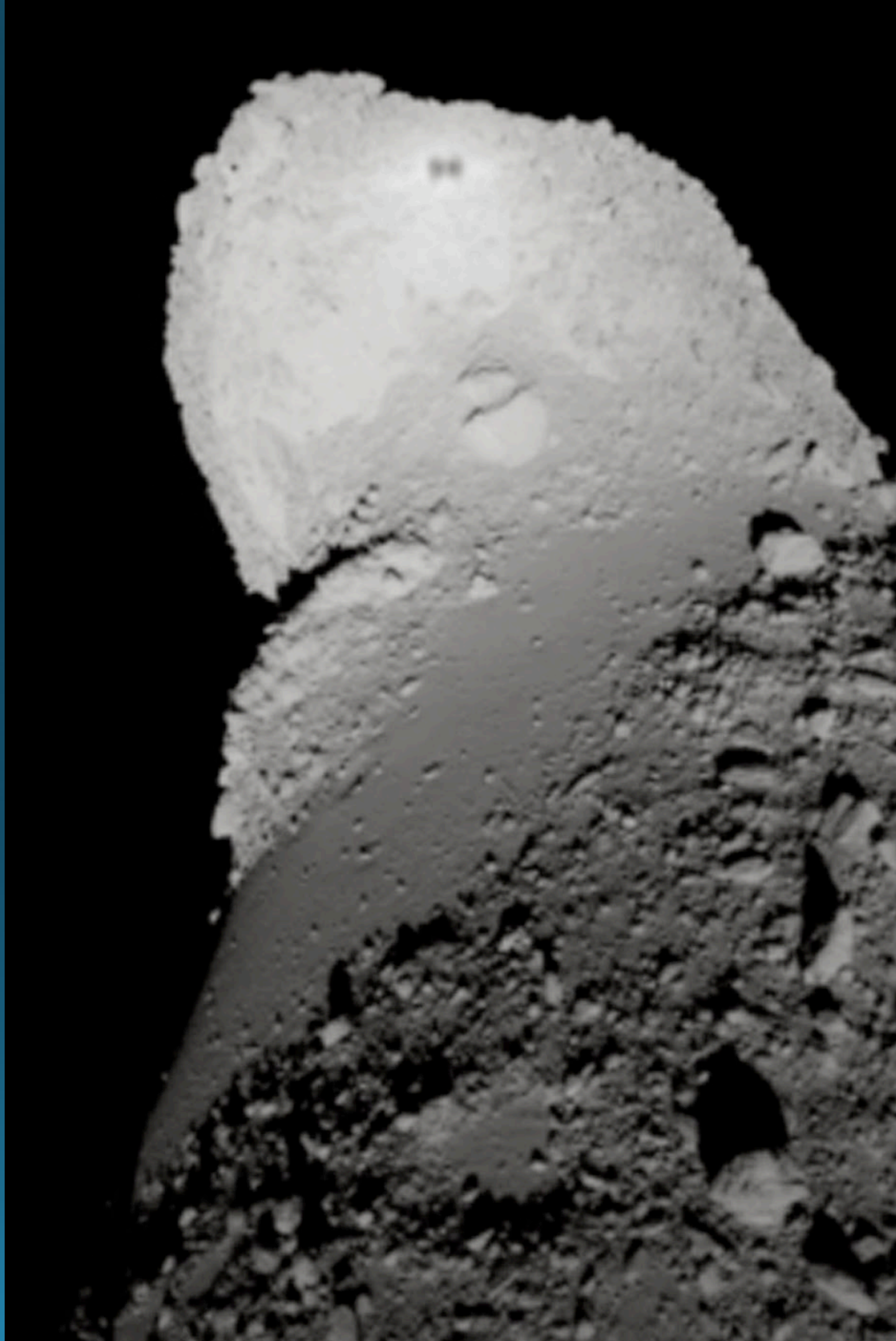
Why SPIKE?

- Reduce cost further using spare launch capacity
  - While reaching diverse NEOs in diverse orbits
    - Solar Electric Propulsion (SEP)
    - Any Earth-escaping launch will suffice
  - Further optimization → ESPA Ring deployment
- Comprehensive subsurface exploration requires high power and high bandwidth communications
  - *How to fit this capability into a small surface deployable?*



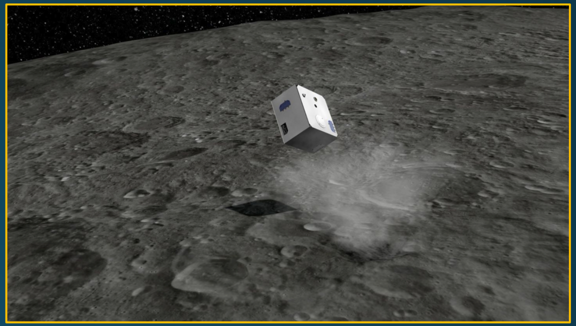
Why SPIKE?

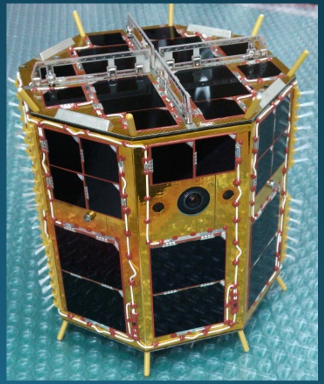
- Reduce cost further using spare launch capacity
  - While reaching diverse NEOs in diverse orbits
    - Solar Electric Propulsion (SEP)
    - Any Earth-escaping launch will suffice
  - Further optimization → ESPA Ring deployment
- Comprehensive subsurface exploration requires high power and high bandwidth communications
  - *How to fit this capability into a small surface deployable?*
- *The SEP bus becomes the lander*
  - A long deployable boom keeps the bus protected
  - Supports a capable penetrating science payload
  - Emphasis on 0.1-1 km NEOs → can eliminate the need for chemical propulsion → long mission lifetime



Asteroid and Comet Landers

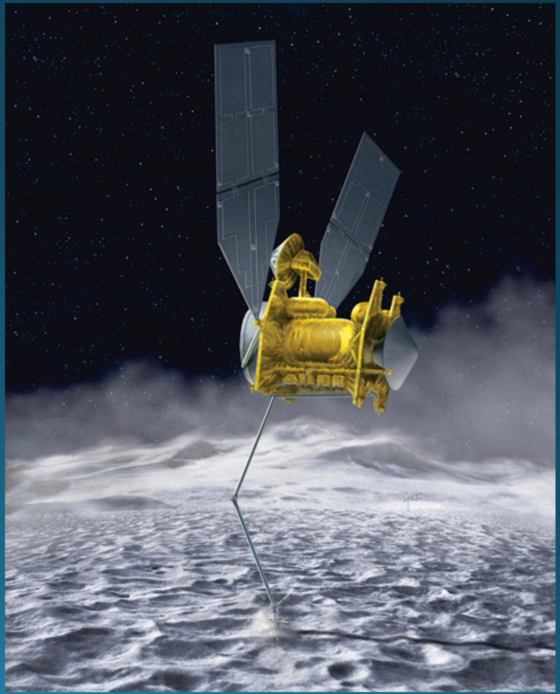
- A typical mission concept for asteroid regolith and interior exploration is to attain rendezvous and deploy one or more subspacecraft landers
  - Hayabusa: MINERVA, MASCOT
  - Rosetta: Philae
- Although *g* is small, landing is not easy!
- Small landers are severely limited
  - Require miniaturized science payloads
  - Solar power may be useless (dirt, burial, thermal cycle)
  - Battery life is limited to hours-days
  - Operations are high risk
    - Might land upside-down, or sink beneath the surface, or get jammed by dirt, or experience static discharge, or high thermal loading
  - Data transmission is limited and requires orbiter relay





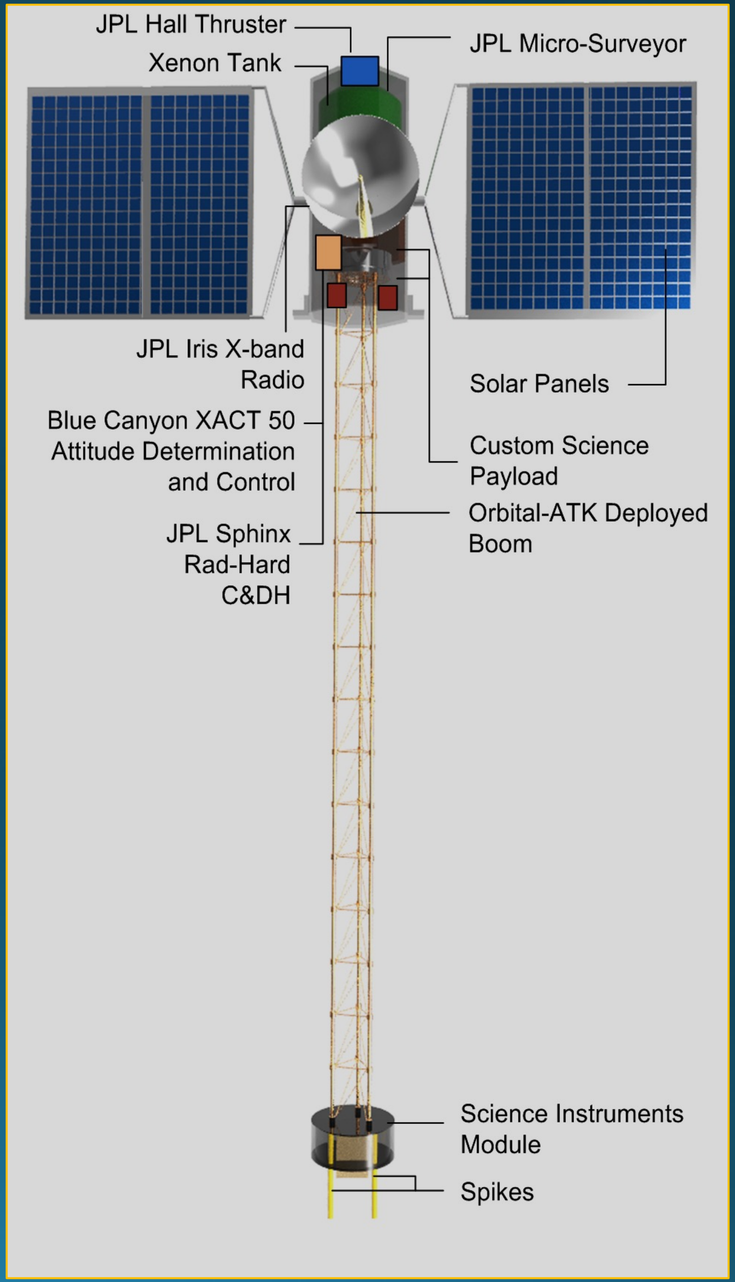
Touch-and-Go

- Hayabusa-1, Hayabusa-2
- OSIRIS-REx
- Comet sample return

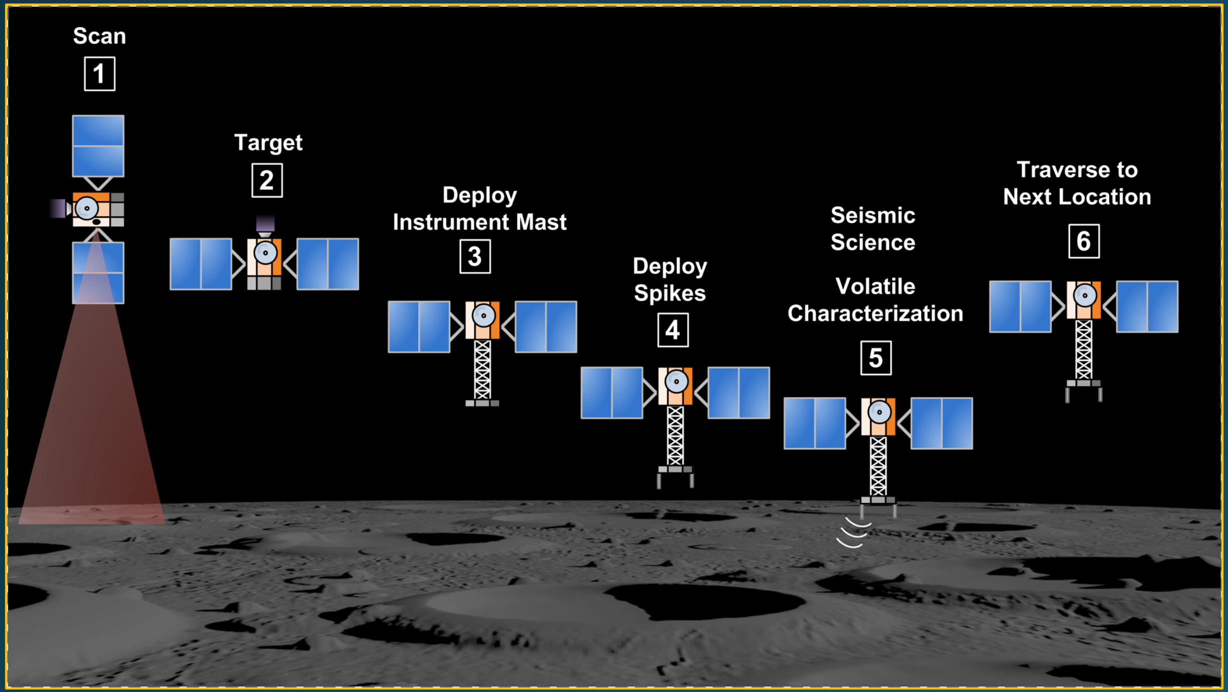


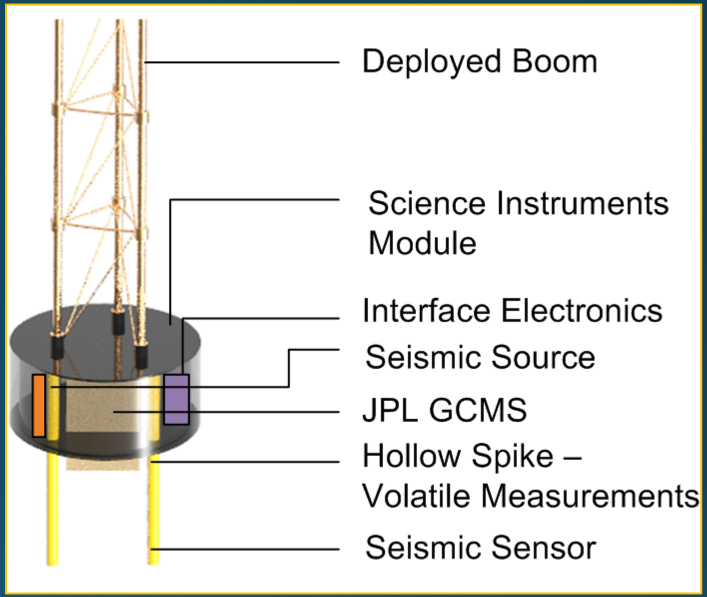
Touch-and-Stay-a-While!

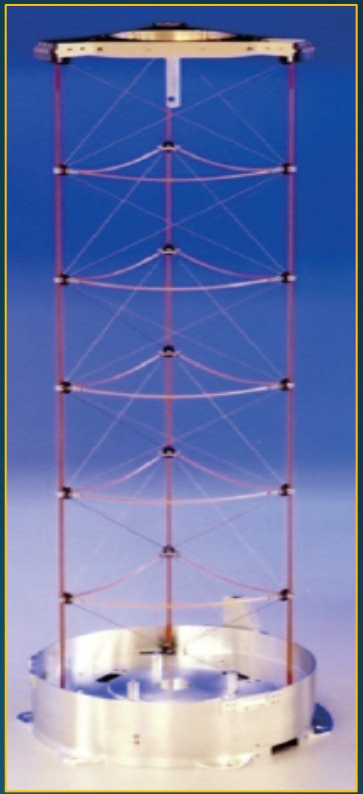
- Instead of a retractable arm with sampling capability, use a fixed rigid ~3-m boom with conduit for power and data
  - Keeps the asteroid away from the bus/panels
  - Supports a free-fall landing at ~1-10 cm/s
  - Powers the science instruments module
- Balancing is easy! (in principle)
  - Inverse-pendulum maintained using reaction wheels → no chemical propulsion required
  - *Can we eliminate chemprop entirely?*



Inverted Pendulum Lander





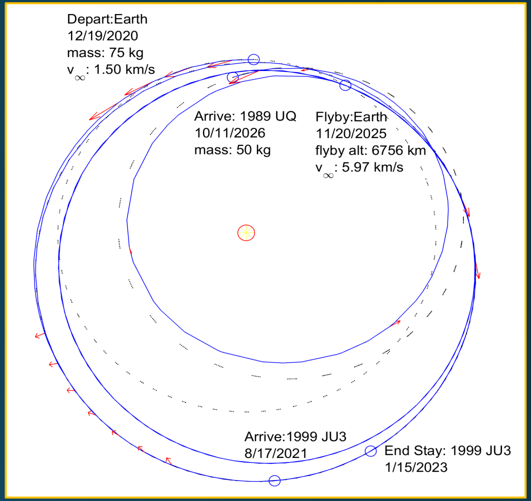


Initial design point: extremely lightweight truss (Orbital-ATK) withstands 180N loads.

- Lightweight boom is sufficient to support free-fall (1-10 cm/s) landing stresses
- The spacecraft mass (~75 kg) enables slow *inertial penetration*
- Low impact velocity and high momentum = buried instrument suite

SEP: A Perfect Match for Small NEOs?

- Rendezvous with a NEO can require high delta-V
  - SEP has the highest I_{SP} of any mature technology
  - Small, long-duration SEP systems are becoming available
    - Example: MaSMi Hall thruster (Xe)
- Can utilize any Earth-escaping launch opportunity
  - SEP can 'take it from there' to attain many NEOs
  - Single smallsat could visit 2-3 asteroids (mini-Dawn tour)
- Once at the asteroid, solar arrays provide ample power
  - ~750 W BOL; enables robust science and data transmission
- *SEP thrust exceeds surface gravity of a small (<1 km) NEO*
  - *In principle, can avoid the use of chemprop systems*



Example: dual rendezvous based on 75 kg (wet) 750W MicroSurveyor (JPL)

Goals	Measurables	Observables	Payload	Capability
Volatiles & Organics	Bound and free water content in the regolith	Abundance of H_2O ice in the regolith	Gas Chroma-tograph and Mass Spectrometer (GCMS)	Collector to acquire volatiles and organics from >30 cm below surface
	Spatial and chemical distribution of identified organic species	Abundance and composition of carboxylic acids, PAHs and amino acids		
Seismology	Seismological properties of asteroid and local regolith	Seismic reflections detected for >1 minute	• Geophone • Thumper • Vibrators • Accelero-meters	Sensors buried to >30 cm depth into seismically competent material
	Regolith response to tactile forces, compactions, vibrations and jolts	Landing/takeoff forces and accelerations Vibration response Penetration depth	• Camera Imaging	Navigation

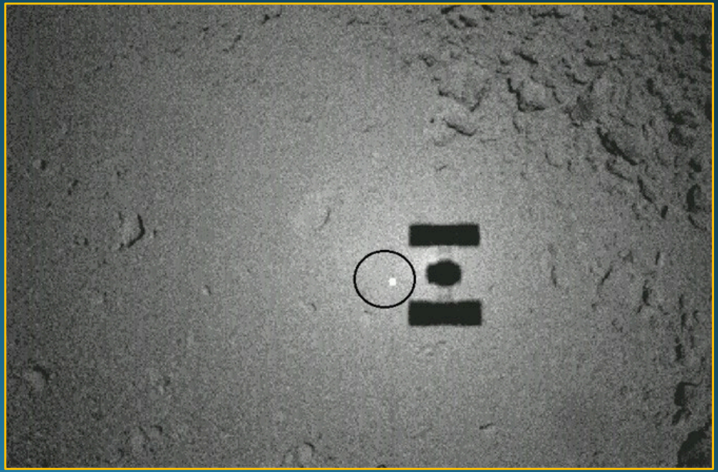
Candidate Payload

- **GCMS.** The SPIKE miniature gas chromatograph (GC) mass spectrometer (MS) is based upon the Spacecraft Atmosphere Monitor (SAM), a technology demonstration that will fly to the International Space Station (ISS) in 2018. SAM is intended for assessing trace volatile organic compounds and the major constituents in the atmosphere of present and future crewed spacecraft. As such, SAM will continuously sample concentrations of major air constituents (CH_4, H_2O, N_2, O_2, and CO_2) and report results in two-second intervals. SAM will provide on-demand reporting on trace volatile organic compounds at ppm to ppb levels of 40+ species relevant for astronaut health. SAM is the first instrument to have successfully demonstrated a fully electrostatic micro-electro-mechanical system (MEMS) GC, requiring no pneumatics for its MEMS valves. The GC is coupled to a quadrupole ion trap mass spectrometer (QITMS). SAM can operate at sub-atmospheric pressures relevant to extra-vehicular activities, which makes it amenable to operation on airless bodies. For the SPIKE embodiment the total instrument mass is projected at 6 kg with power consumption estimated at 35 W.
- **Seismology.** The seismic experiment consists of four components, to be assessed during the study. For activation, we will use a mechanical thumper integrated into the base of the SIM, directly above the spikes. We will also integrate tunable piezoelectric vibrators to both spikes, as a signal source and to facilitate disengaging from possibly cohesive regolith. For science we will use MEMS accelerometers in the seismology spike, plus one or more geophones. Our initial choice is to begin rigorously testing and space qualifying the 24 bit NuSeis NRU-1C by GTI, which has 120-123 dB dynamic range for 1-2 ms sampling.

Target Requirements: Small NEOs

Target Requirement	Probability
First asteroid target must be primitive (B, C or D)	Certain; many candidates
Regolith bed at least 1 m deep exists somewhere on the asteroid	Almost certain for NEOs >100 m diameter; can be verified by groundbased IR/radar
Clast sizes <30 cm in the target footprint (dust ponds, gravel beds are ideal)	Unknown for the smallest (~50 m) bodies considered; almost certain for 0.3–1 km
Regolith cohesion < 10 kPa in the target footprint	Could be greater if ice-cemented materials (unlikely), or as low as 10–100 Pa
Surface *g* < 0.3 mm/s² for gentle landing and to allow SEP-powered escape	Certain for <1 km diameter

Any asteroid ~0.1-1 km will do

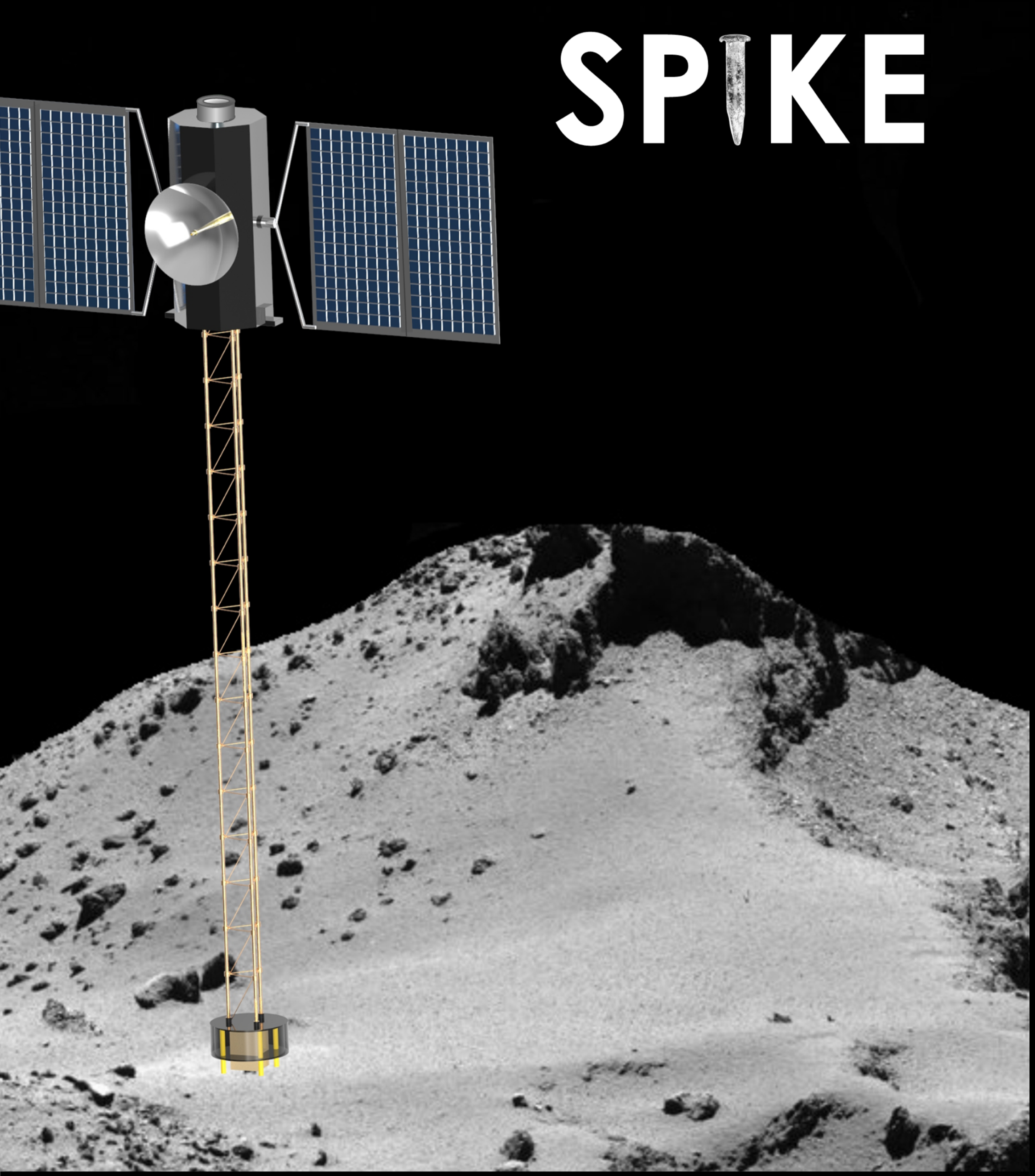


Example Mission Concept

- Launch up to 6 identical smallsats in an ESPA ring configuration
  - Or, a single <$100M mission
- Each unit goes to 2+ NEOs → landed science at a dozen asteroids
  - Discovery cost cap <$500M
- At each NEO:
  - 3 or more landings per asteroid → comprehensive knowledge of the body
  - Each landing explores *surface physics*, conducts *global seismology*, and measures the *volatile and organic* subsurface composition
    - Other instruments of course possible, e.g. IR/VIS/XGRS/ND
- After each landing:
  - The spacecraft jumps (~1 cm/s), thrusts (SEP) to stationkeeping, and lands/impacts again
  - Or, departs to the next asteroid

Risk Mitigation / Design Study

Risk	Likelihood	Impact	Mitigation (study effort)
Spike tip breaks	Low	Medium/ Severe	Explore penetrator materials/designs; develop failsafe mode for immediate departure
Boom mechanism collapses	Low	Severe	Obtain engineering copy early to begin exhaustive testing
Bus and arrays encounter dust	Medium	Medium	Design preprogrammed auto-depart sequences and status monitors/cameras
Wobble of spacecraft	High	Low	Develop one-minute science acquisition strategies; model in detail
Spikes encounter big boulder	Medium	Medium	Design mission to low-TI targets; develop algorithms to survey for buried rocks
Spacecraft cannot extract	Medium	Medium	Develop event sequence using vibrators and thumpers and springs to get clear.
Asteroid lacking regolith	Low	Medium	Attempt landing in area of lowest thermal inertia; use thruster to increase penetration



Questions?

Comments/Opinions/Advice?

ASU | Boulder | MINES | NASA Jet Propulsion Laboratory, California Institute of Technology | SpaceTREx