APEX
Apophis Probe Experiment

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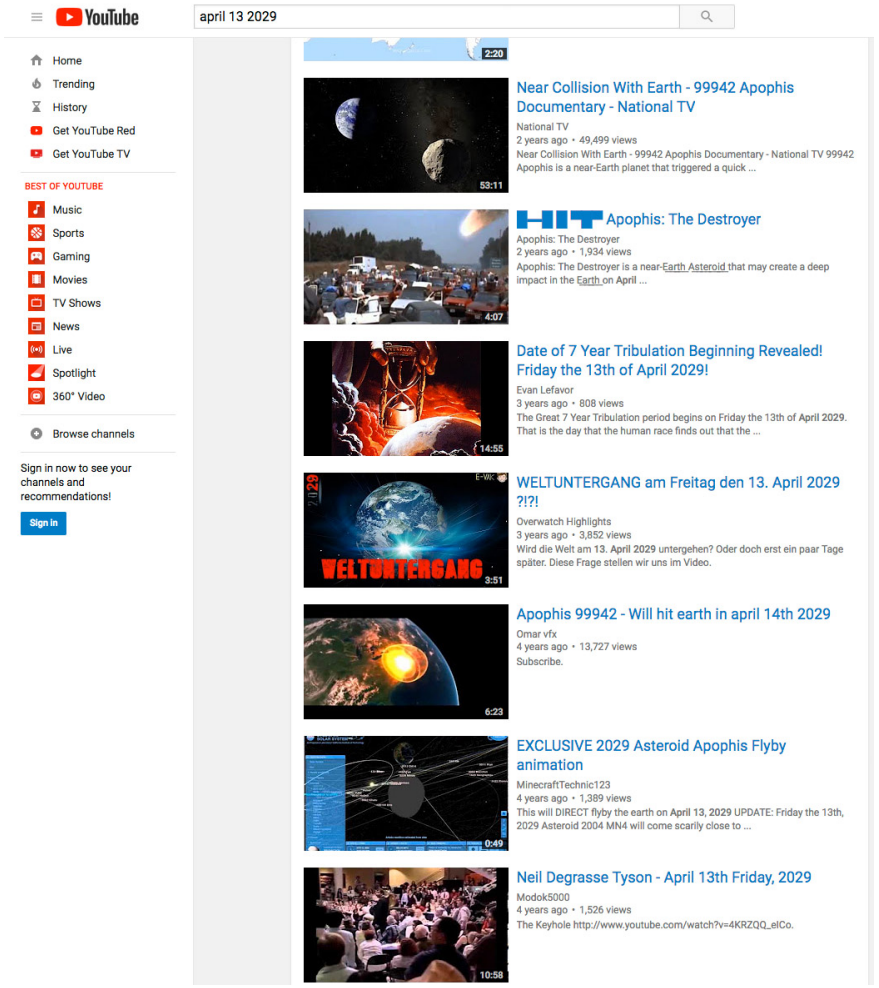
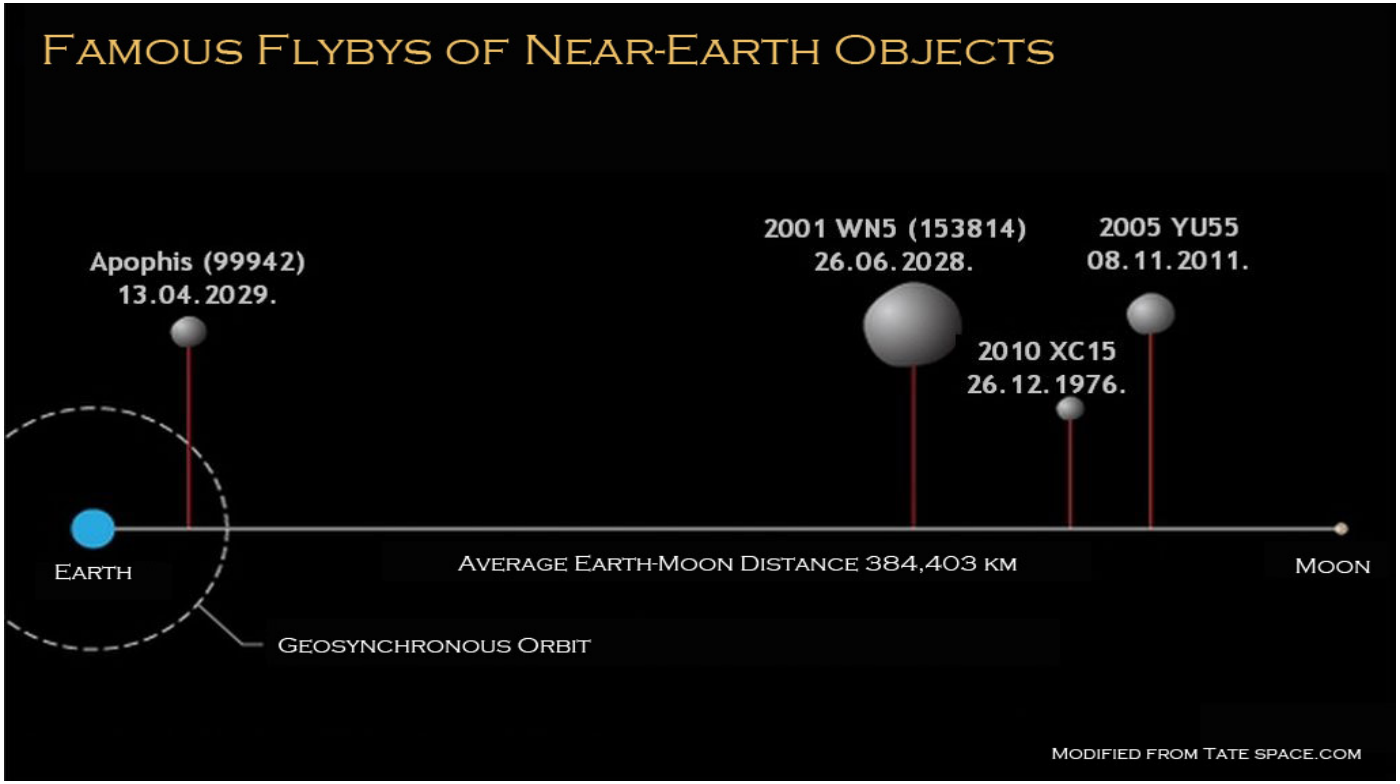
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

APL

Apophis – Friday the 13th April 2029



Apophis Earth Encounter

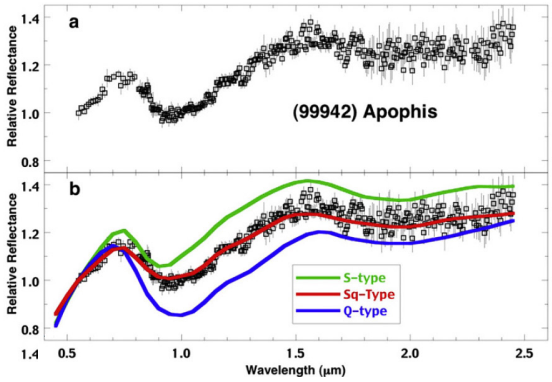


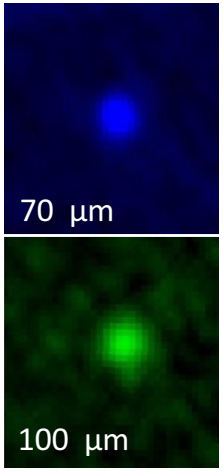
Apophis

Dimensions:	410 x 350 x 317 m
Equivalent Diameter:	340 m
Surface Area:	0.39 km^2
Volume:	0.02 km^3
Gravity:	0.00027 m s^{-2}
Thermal Inertia:	200-800 J m^{-2} $s^{-0.5}$ K^{-1}

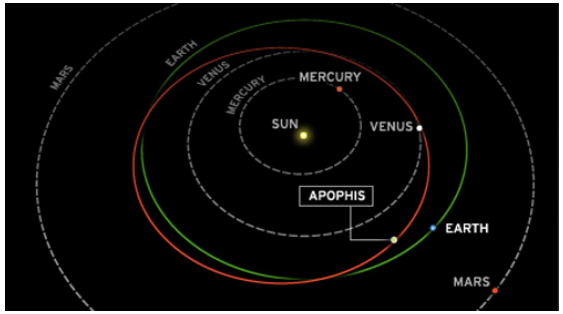
Sq type (Uncommon spectrally immature inner belt asteroid with olivine and pyroxene bands)

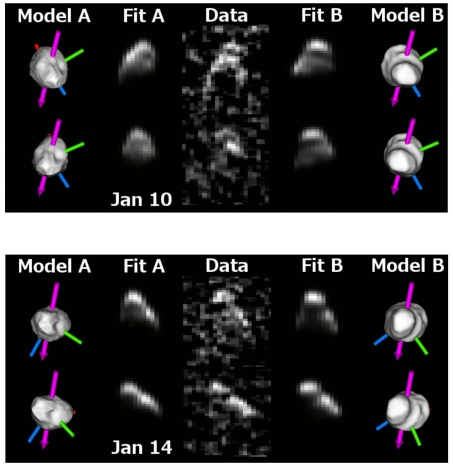
Rotation:	30.4 hr (retrograde) tumbling
Precession:	262.7 days
Non Principal Axis Rotation	
Orbital period:	324 days
Eccentricity:	0.19
Inclination:	3.33°





Herschel





Goldstone radar

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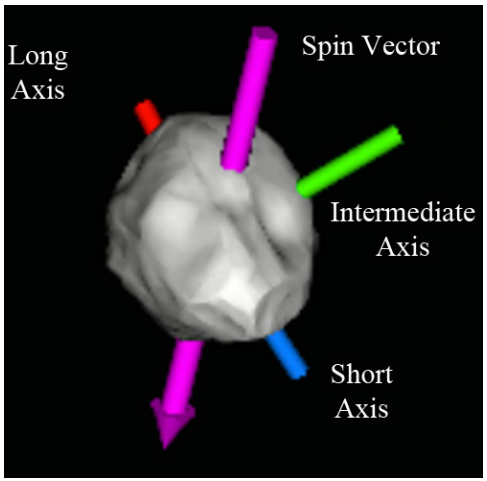
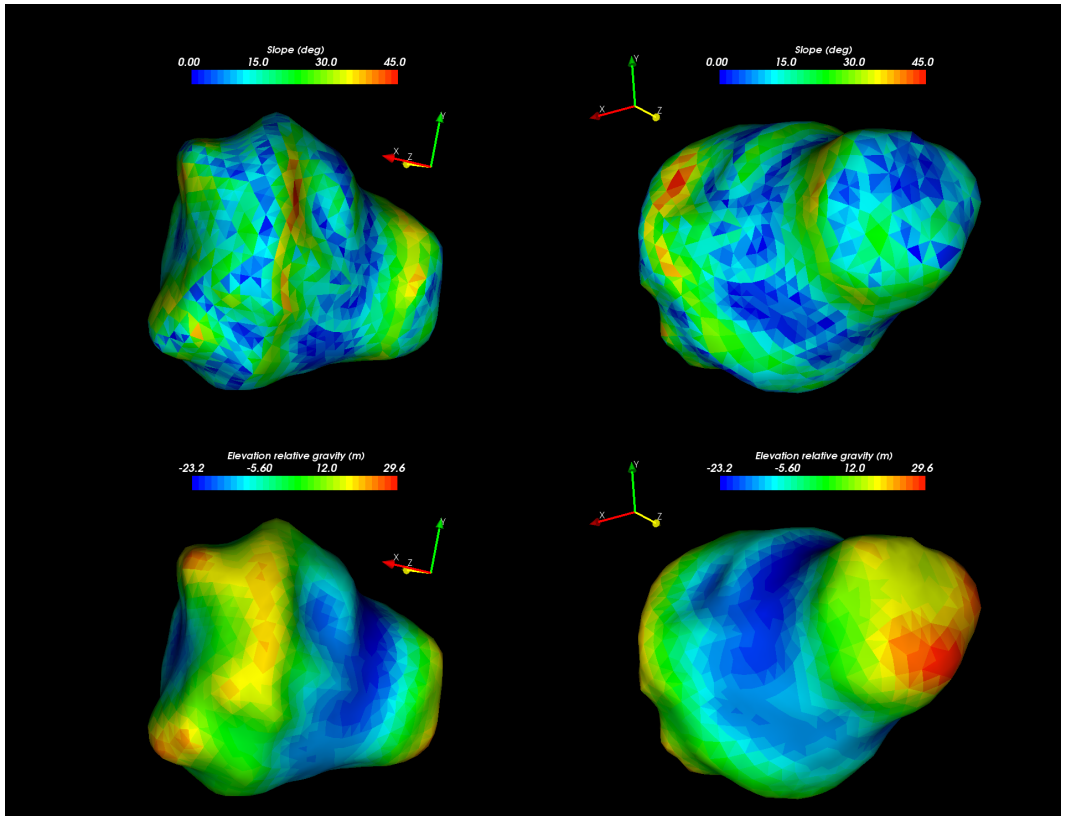
Apophis Shape / Gravity





Slope

Gravity

Assumes bulk density 2400 kg m^3

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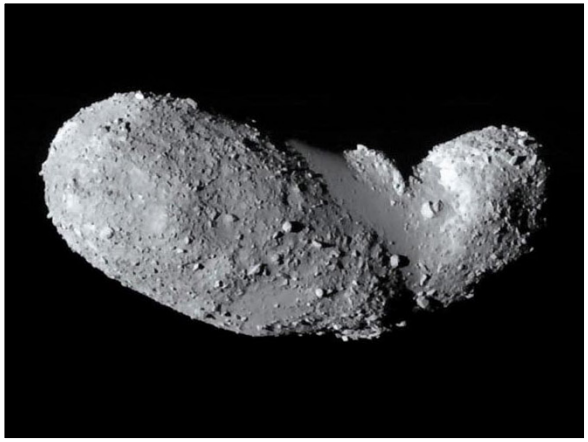
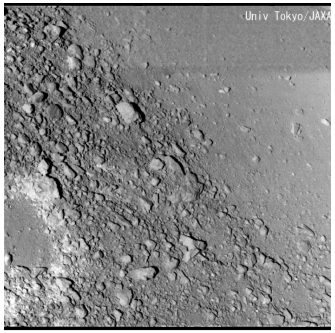
Expectations



Itokawa: 535 x 294 x 209 m



Lutetia 121000 x 101000 x 75000 m

Steins: 6670 x 5810 x 4470 m

Eros: 34400 x 11200 x 11200 m

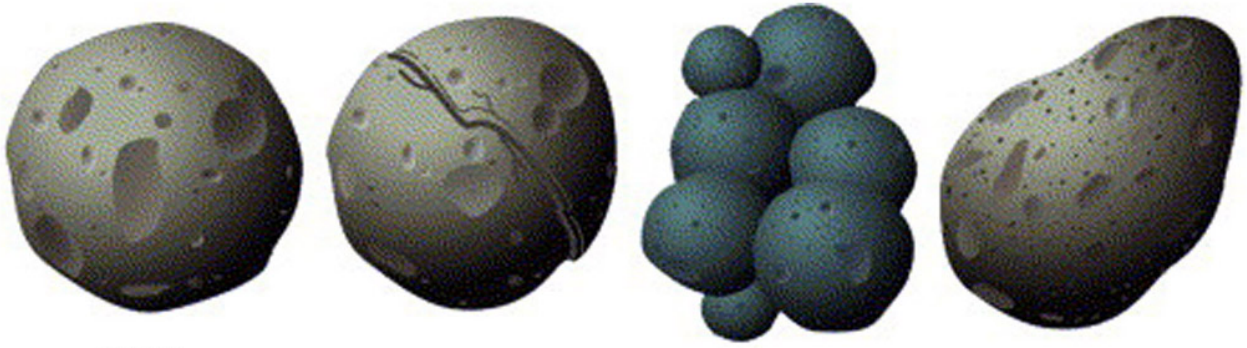
Science Requirements

Examine the tidal distortion effects of a close encounter with the Earth in April 2029 to understand the structure – implications for history and planetary protection.

- Determine the rotational dynamics
- Establish the physical dimensions
- Determine the shape / topography
- Determine the interior structure
- Define the surface morphology
- Define the mass

- Orbital change: semi-major axis 0.92 to 1.1 AU Aten to Apollo Family

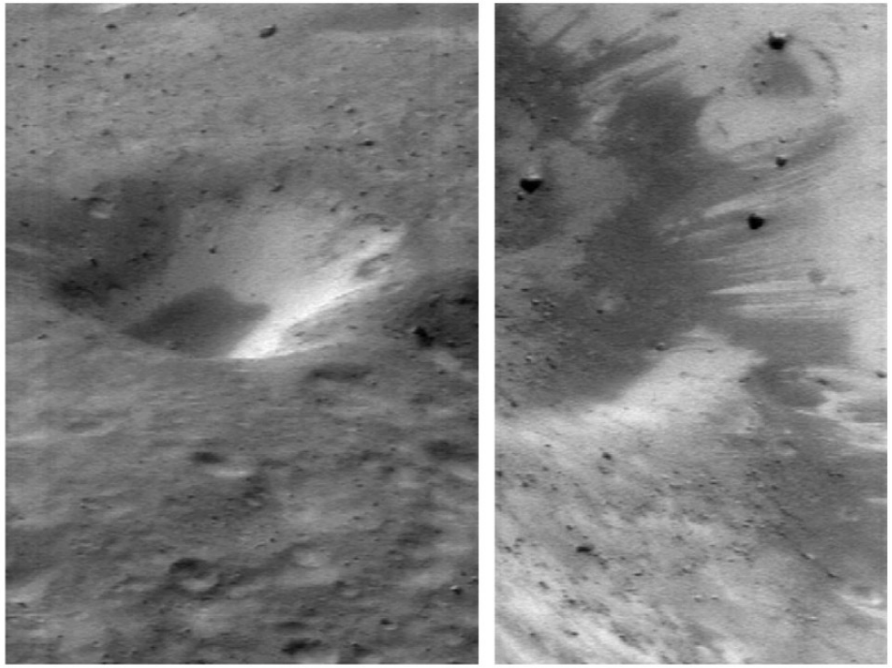
Internal Structure



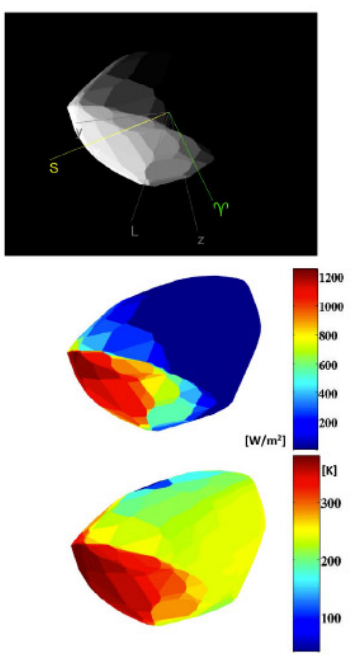
Walker et al (2006)

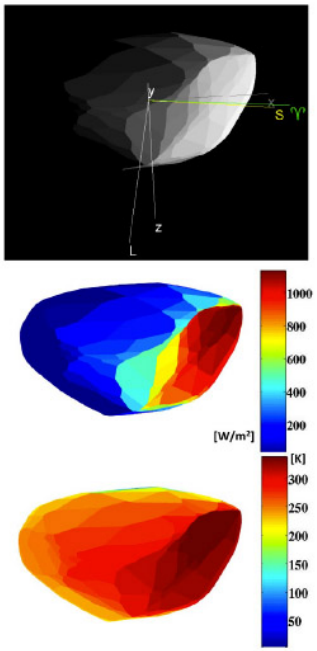
Solid - regolith covered - heterogeneous (large internal blocks / large internal voids)
Non-tidal induced seismicity
Thermal cracking
Impacts

Surface Character and Modification



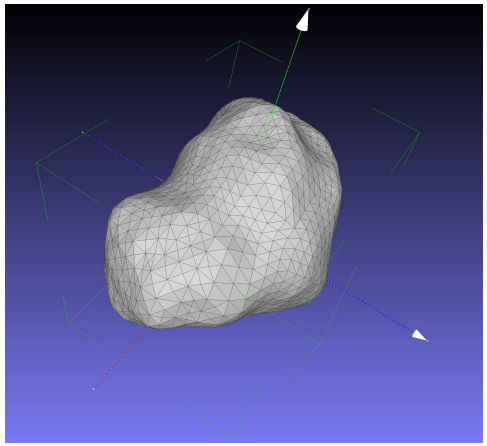
NEAR MSI 0154622520 / 0154409710

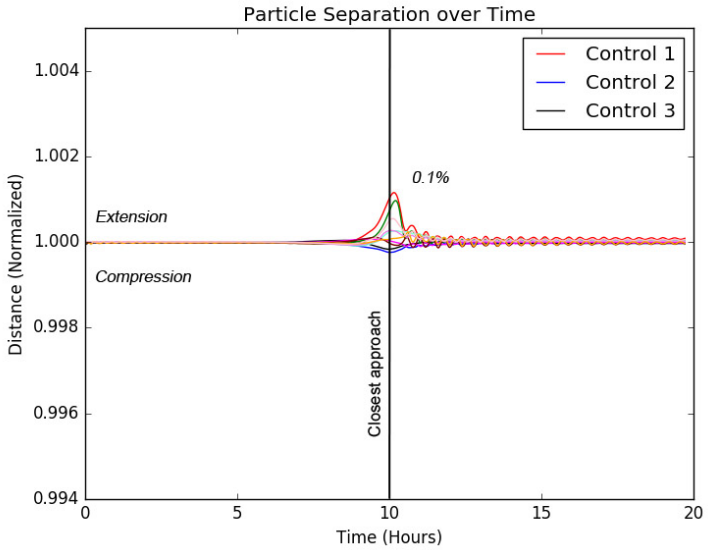


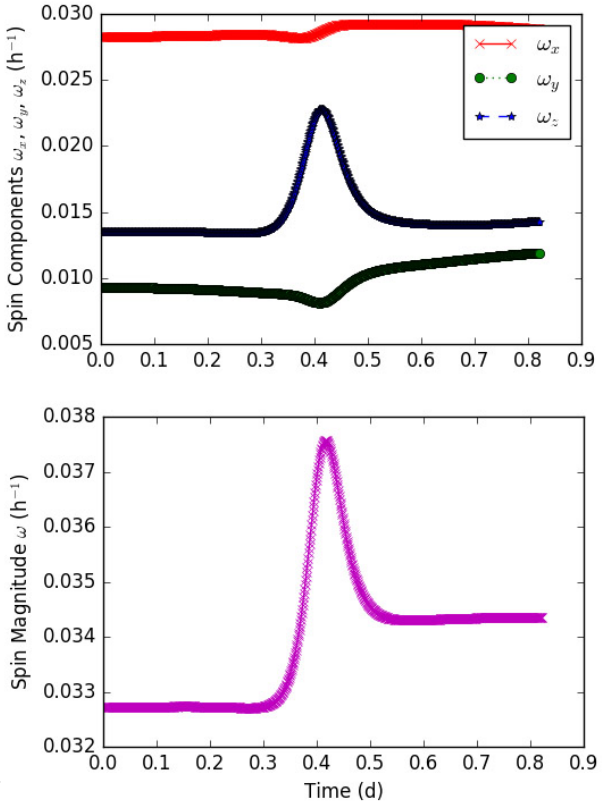


Expose fresh (unweathered) material
Movement downslope

Tidal Changes – Earth Encounter

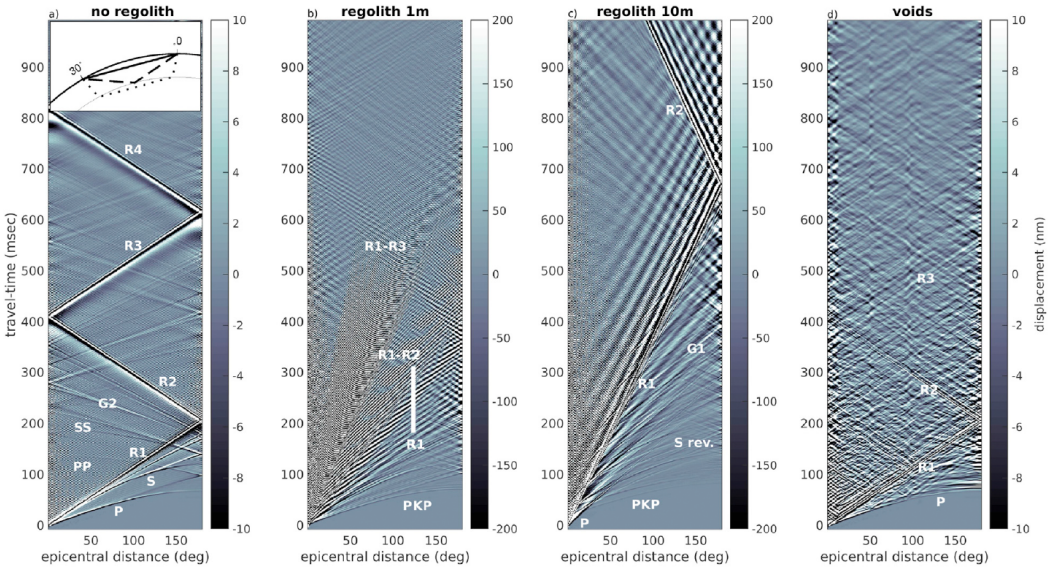




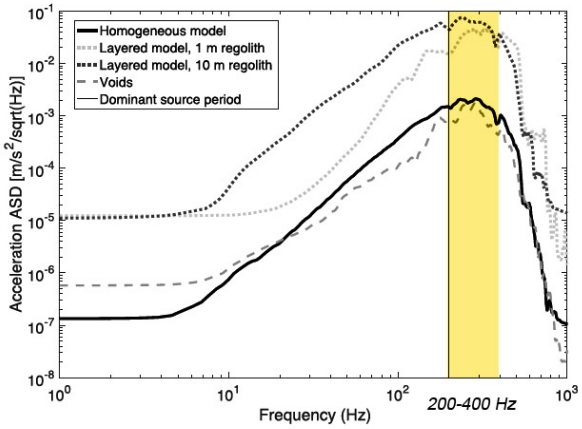


Magnitude depends on orientation, mass, density distribution, particle size-frequency

Seismology (Didymoon)

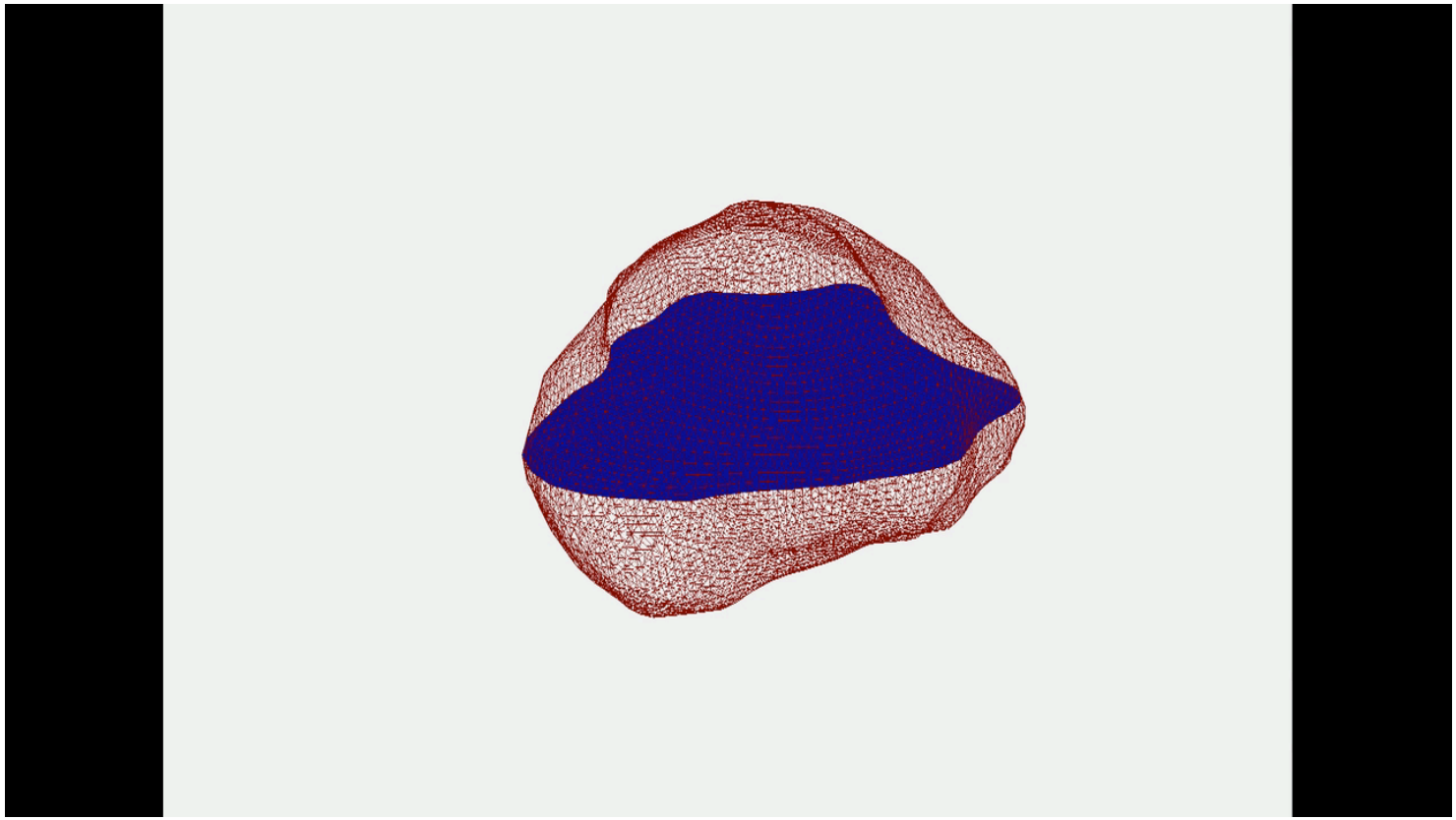


Murdoch et al. 2017 variable regolith thickness and 5 m voids



Δ90° for 1 mg impact at 6 km/sec

Seismology

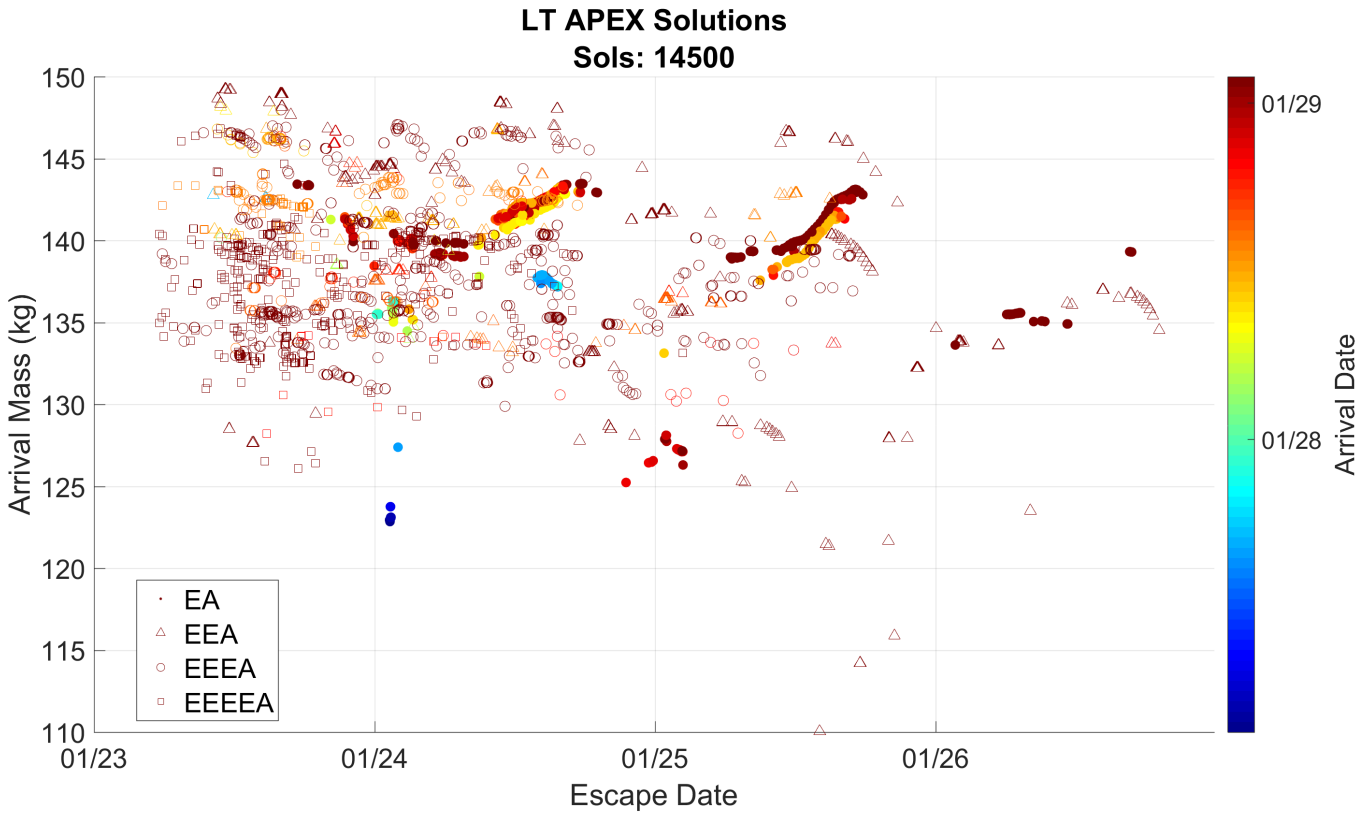


Trajectory Down-Select

Solution	Sequence	Departure Date	Arrival Date	Time of Flight (years)	Final Mass (kg)
7105	[E]L[A]	9/3/2024	10/18/2028	4.1	143.3
8120	[E]L[A]	8/27/2025	10/23/2028	3.2	141.8
398	[E]LE[A]	6/10/2024	8/12/2028	4.2	146.8
1152	[E]LE[A]	8/26/2024	2/1/2029	4.4	148.0
670	[E]LE[A]	6/21/2025	2/1/2029	3.6	146.7
446	[E]LE[A]	7/4/2025	8/5/2028	3.1	142.9

Highlighted trajectories are mass optimal for mid-2025 launch with arrival dates several months prior to Earth close approach

Trajectory Analysis



Trajectory Solution 8120 [E]L[A]

Launch into holding orbit

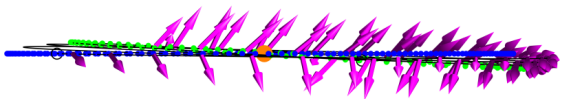
Lunar gravity assist: 8/29/2025

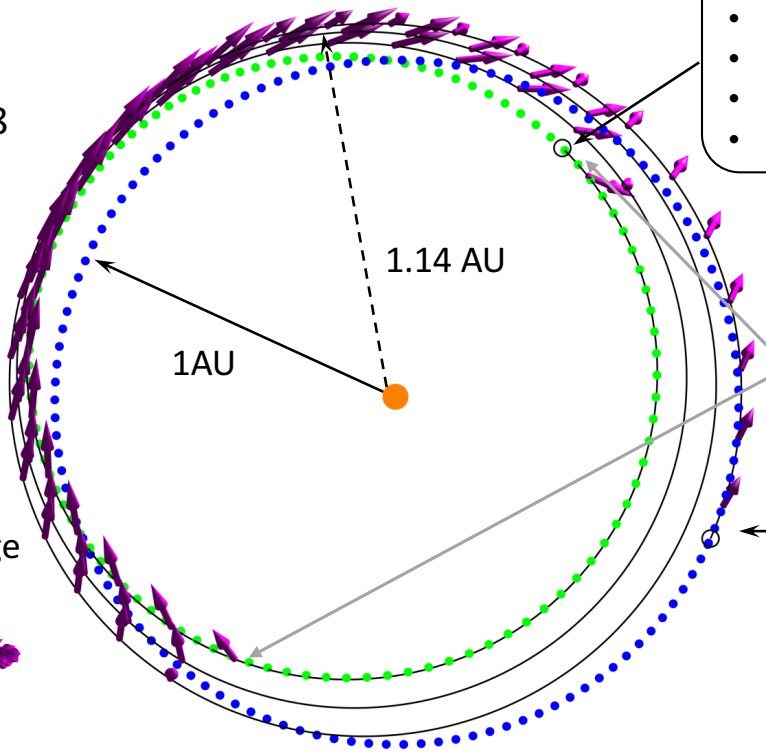
Arrival date flexible: 10/28/2028

Earth flyby: 4/13/2029

Apophis Orbit = Green
Earth's Orbit = Blue
S/C Orbit = Black
Thrust Vectors = Magenta

SEP system provides plane change





2. Apophis Rendezvous
- 10/26/2028
- TOF = 1,154.5 Days
- Mass = 141.5 kg
- V_∞ = 0.0 km/s

Arrival Date easily floats along this long coast duration

1. Earth Escape via LGA
- 8/29/2025
- TOF = 0.0 Days
- Mass = 180.0 kg
- C3 = 1.0 km^2/s^2

Mission Requirements / Challenges

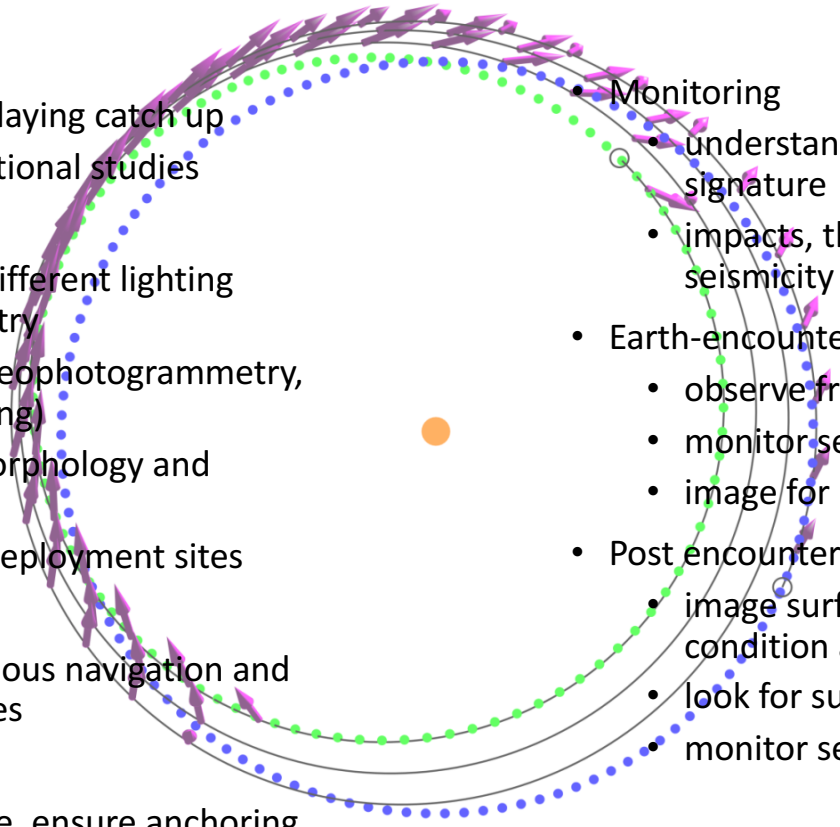
- Rendezvous with Apophis sufficiently before Earth-encounter to map the surface and emplace a seismometer on the surface.
- Image the entire surface, in stereo, such that a DTM can be produced and the rotational dynamics established.
- Deploy seismometer on the surface to detect seismic signals induced by thermal, rotational and tidal deformation forces. Monitor baseline seismic signal and encounter signal.
- Baseline payload:
  - panchromatic imager
  - seismometer
- Additional possibilities:
  - multiband imager
  - thermal imager
  - gamma ray spectrometer

Mission Requirements / Challenges

- Rendezvous and station-keep / orbit with a small body ~375 m diameter, at 1 AU, at close range (1 km). Solar forces > gravity
- CONOPS
  - "Orbit" Apophis to map the surface
  - Deploy a seismometer on the surface, ensure instrument is coupled to the surface. Touch the surface.
  - Autonomous operations
  - PROXOPS – terrain recognition
- Deployment mechanism
  - Space qualified stick - Use spacecraft to anchor the surface package
  - Launched penetrator
- Seismometer must be an independent instrument – power (solar cells and batteries), communications, electronics. Must survive for multiple months.
- Communications: Apophis to s/c, s/c to Earth
  - Data volume: Seismometer 40 Gb / Apophis day (30.4 hrs)
  - RF vs. Optical comm. for data
- PSDS spacecraft – <180 kg, low solar cell area – low power, small structure – small antenna
  - ESPA ring mount

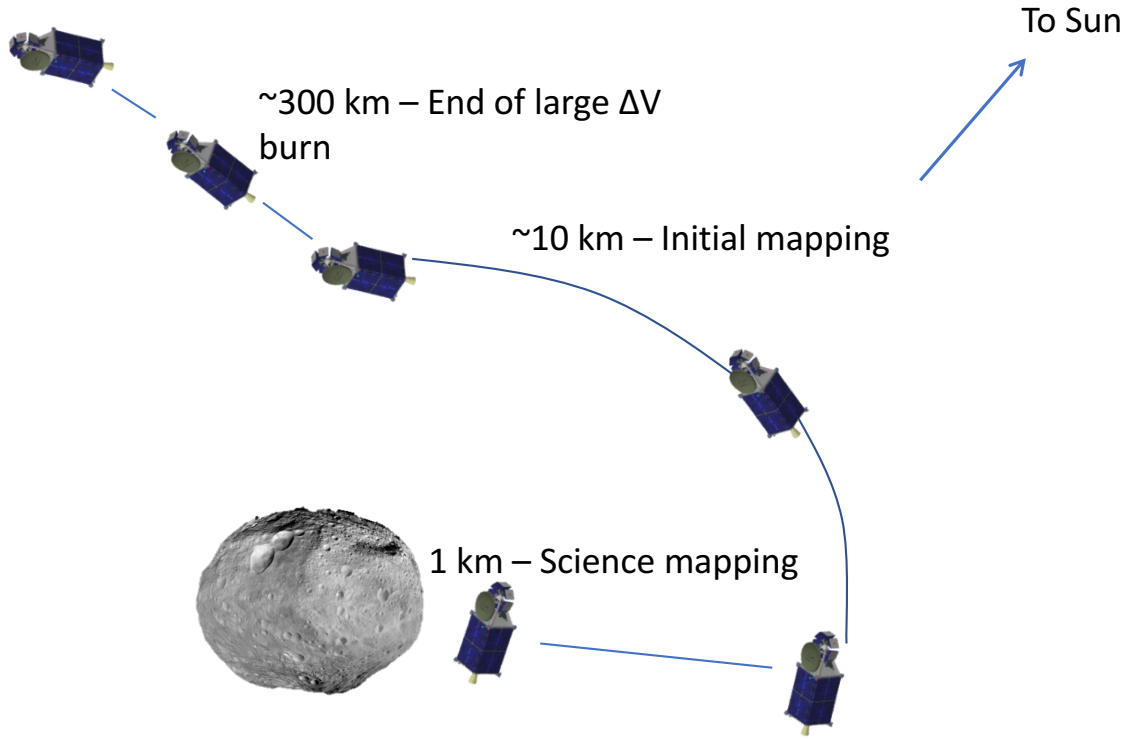
CONOPS

- Approach
  - relative velocity low, playing catch up
  - begin imaging for rotational studies
- Rendezvous
  - image surface under different lighting conditions and geometry
    - build a DEM (stereophotogrammetry, shape from shading)
    - define surface morphology and properties
    - locate potential deployment sites
- Rehearsal
  - demonstrate autonomous navigation and deployment procedures
- Deployment
  - deploy surface package, ensure anchoring

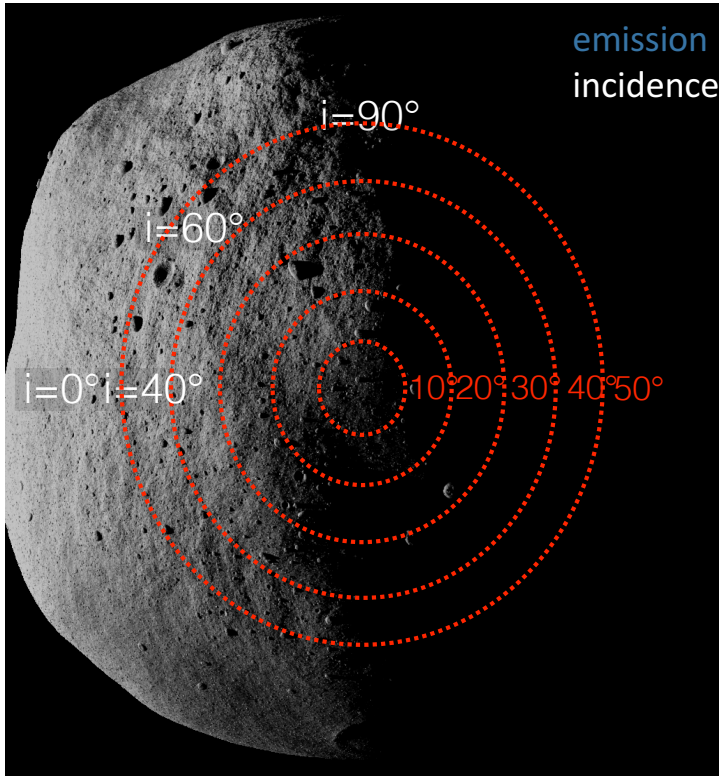


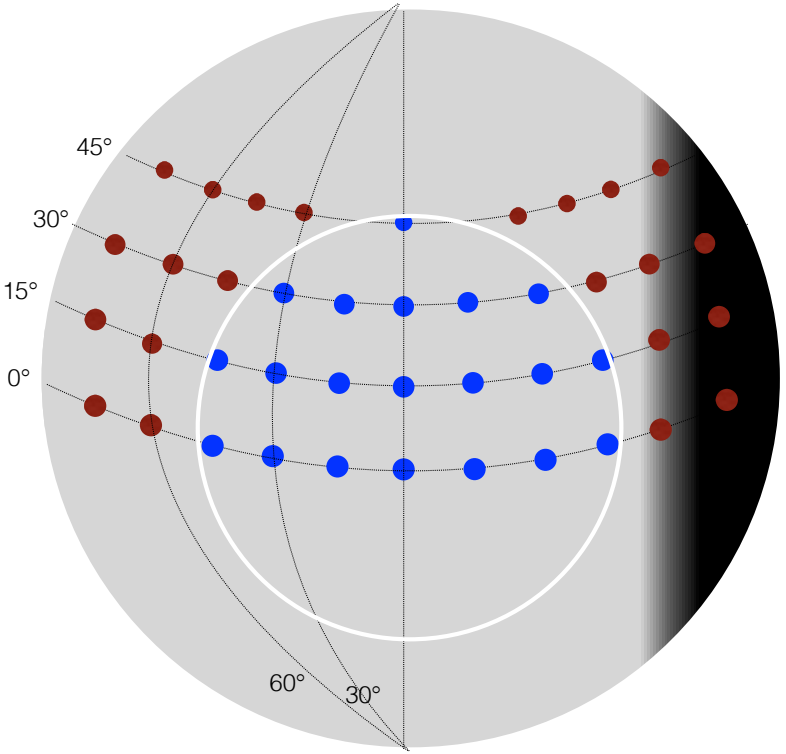
- Monitoring
  - understand the background seismic signature
    - impacts, thermal cracking, internal seismicity
- Earth-encounter
  - observe from safe standoff distance
  - monitor seismicity
  - image for rotational changes
- Post encounter
  - image surface under different lighting condition and geometry
  - look for surface changes
  - monitor seismicity

CONOPS - Approach and Rendezvous



Imaging Campaign

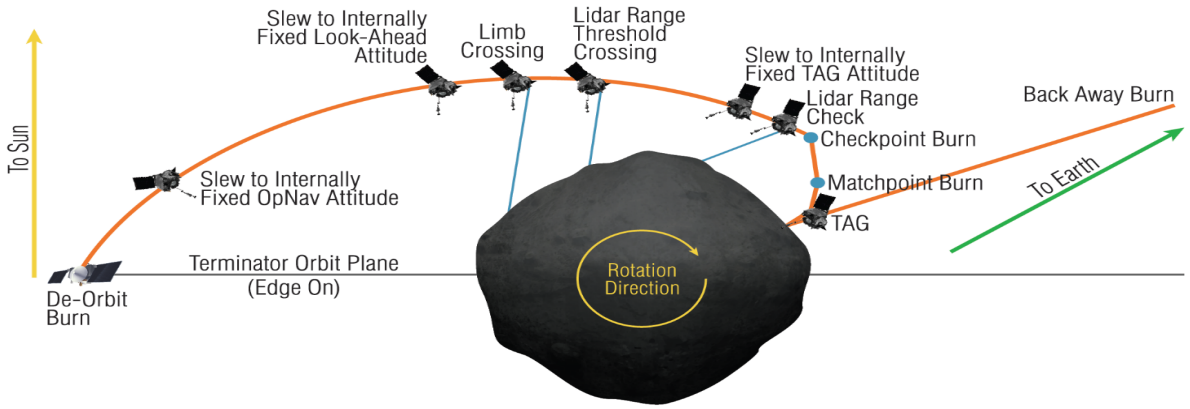




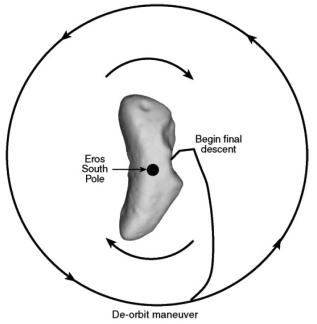
Viewing from multiple incidence angles and emission angles and with different geometry
Nominal mapping pixel scale

"Courtesy" of OSIRIS-REX

CONOPS Surface Package Deployment

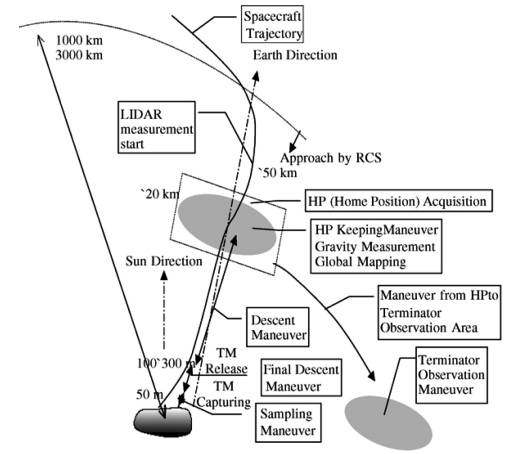


OSIRIS-REX



Eros - NEAR Dunham et al. (2002)

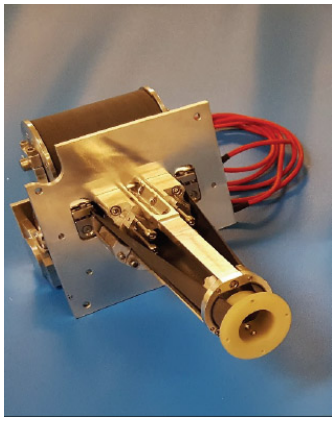
NEAR



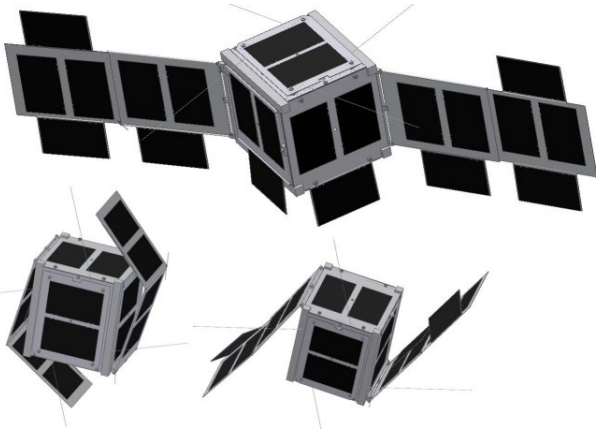
MUSES-C Kubota et al. 2003

Hayabusa

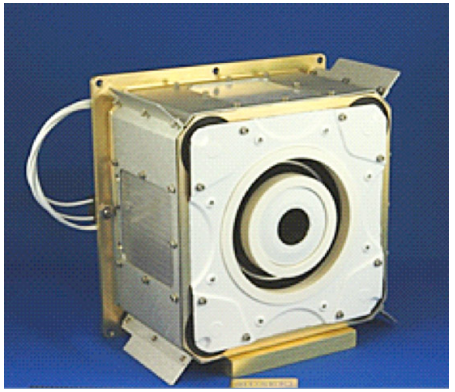
Technologies



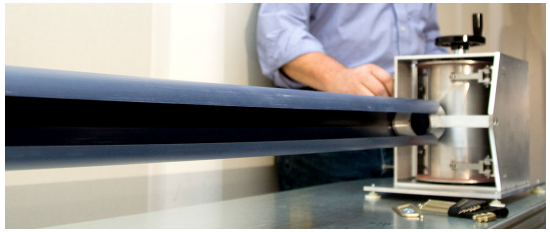
Strong, deployable, light weight extendable boom

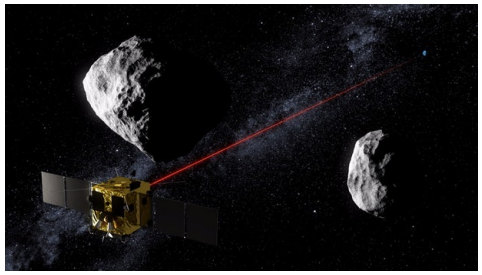


Deployable solar array



Propulsion: SEP Xenon vs. Iodine





Laser communications

Frontier lite radio

APEX - Mass and Power Budgets

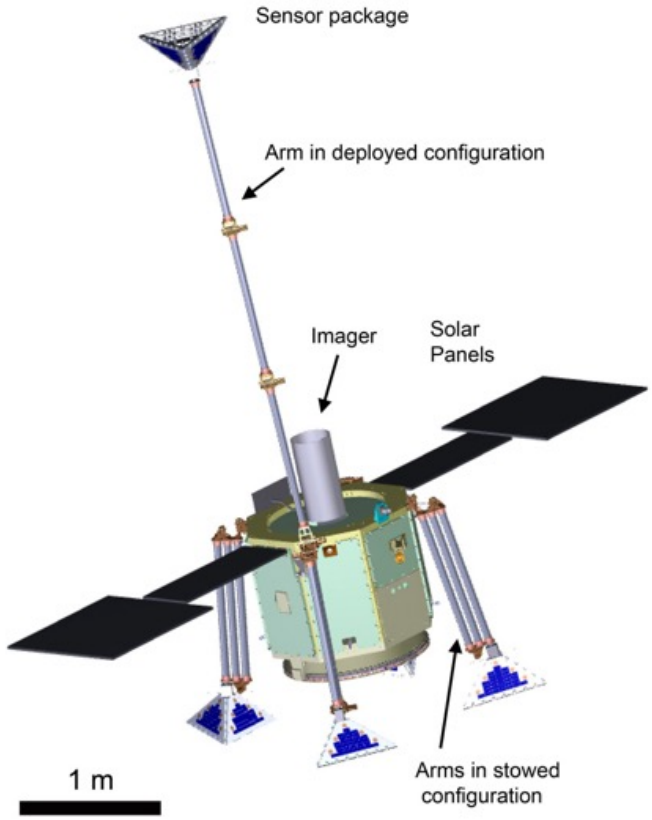
- Power – Key Drivers
  - Electric propulsion
    - 200 W required at 1.14 AU
  - Radio communications
    - Up to 50 W required for high-rate downlink (ongoing trade)
- Current Power Level:
  - 240 W at 1.0 AU
  - No need for deployed solar panel

- Mass – Key Drivers
  - Propellant loading
    - Need for flexibility in Prox Ops
  - Seismometer deployment
    - Stand-off distance under study
  - Redundancy Decisions
    - What level of redundancy required?
- Current Estimate: 265 kg

APEX Spacecraft Mass Budget	Mass (kg)
Spacecraft Bus	115
Primary Structure	25
All Other Structures	10
Propulsion Hardware	8
Avionics	25
Power Electronics	5
Solar Cells	3
Battery	4
Attitude Control (all sensors)	8
RF Communication	8
Harness	10
Thermal	2
Payload	11
Imaging System	6
Seismometer Surface Package	6
Contingency (30%)	37.8
Propellant	100.8
Total Mass	**264.6**
ESPA (180 kg)	-84.6
ESPA Grande (300 kg)	35.4

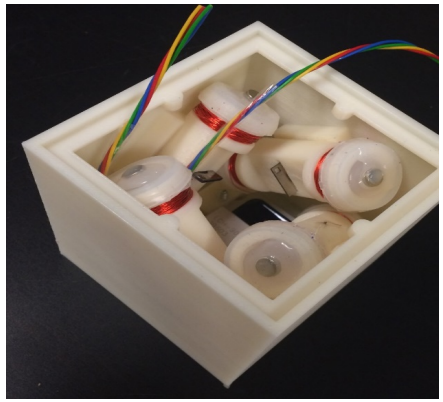
NIAC

Table 1. Flight System Mass Summary			
Subsystem	**CBE (kg)**	**Cont. (%)**	**MERV (kg)**
Structures	52	10	57
Integrated Propulsion	16	3	17
Avionics	11	4	11
Electrical Power	27	7	29
Attitude Determination Control	12	7	12
Thermal Control	4	15	4
RF Communications	4	6	4
Harness	11	10	12
Spacecraft Bus	136	8	146
Instrument packages	42	15	49
Total Dry Mass	**174**	**10**	**195**
Usable Hydrazine Propellant*			109
Propellant Residual & Pressurant			5
Total Mass*			**309**
Launch Capability*			**358**
* These values are for target 1991VG. Maximum expected resource value: MERV Contingency = Maximum expected resource value - current estimate of resource value % Contingency = [Contingency / (MERV-Contingency)] *100			



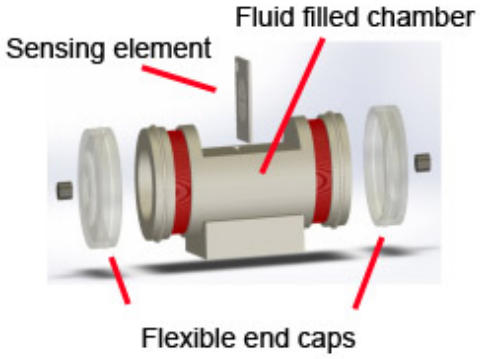
Seismometer

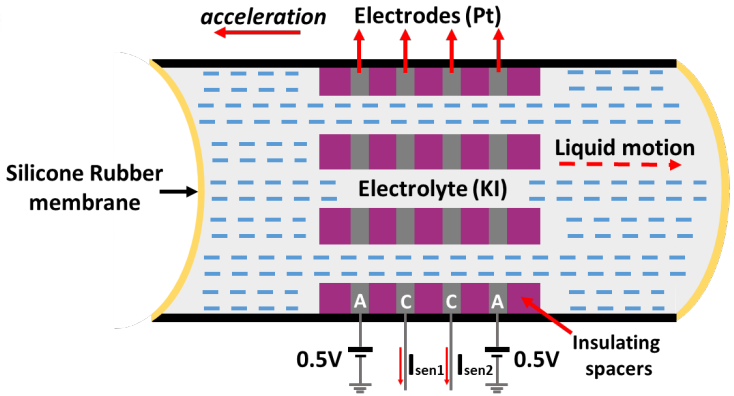
Molecular Electric Transducers work as a novel motion sensing mechanism by integrating mass-spring system and electro-chemical reaction.



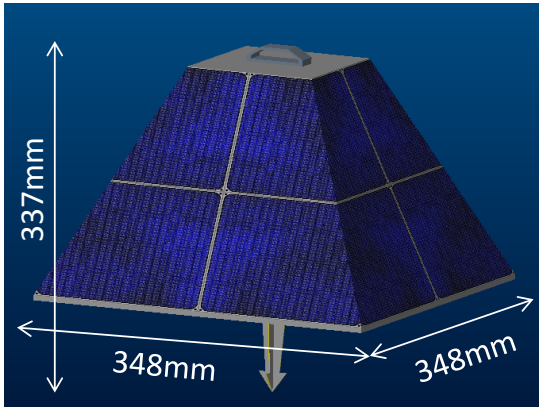
Molecular electronic transducer

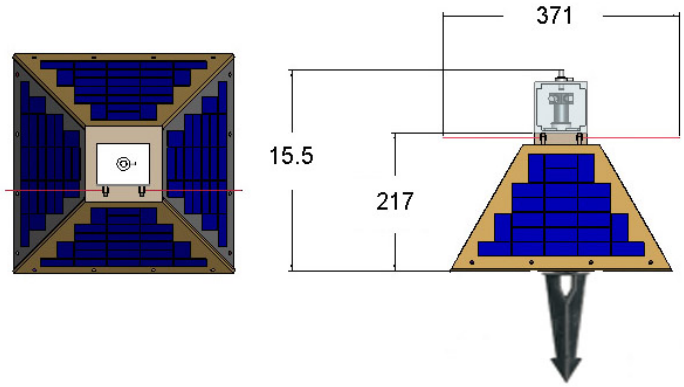
- 4 electrodes (Pt)
- Inter-electrode spacers
- Channels
- Iodine ion solution
- Flexible diaphragm

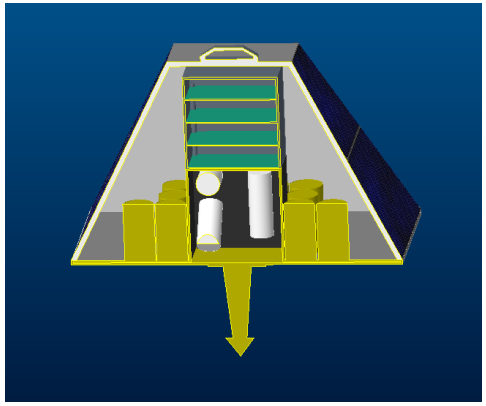




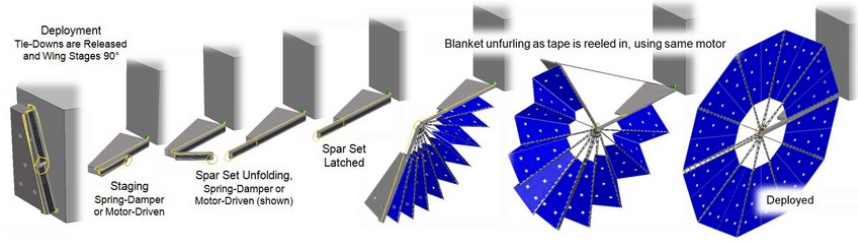
APEX Seismometer Surface Package Design





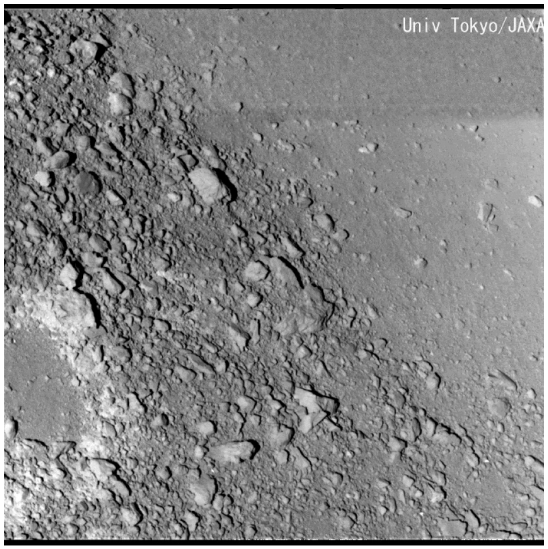


Alternative solar cell concept – circular array, also acts as sun shade for thermal control



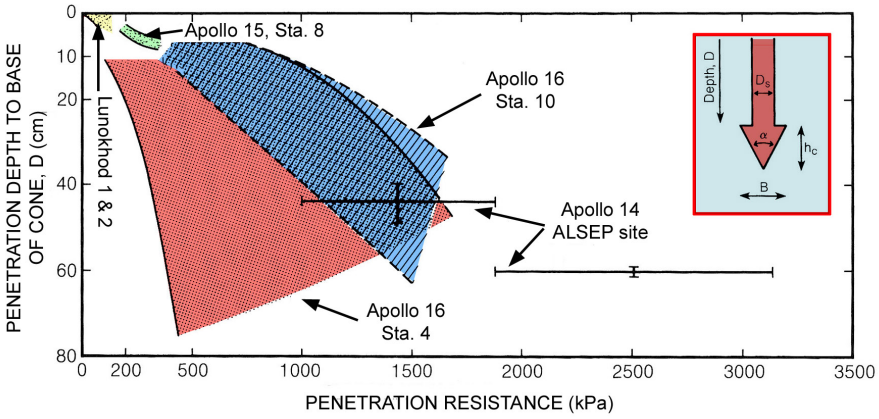
Surface Package Anchoring

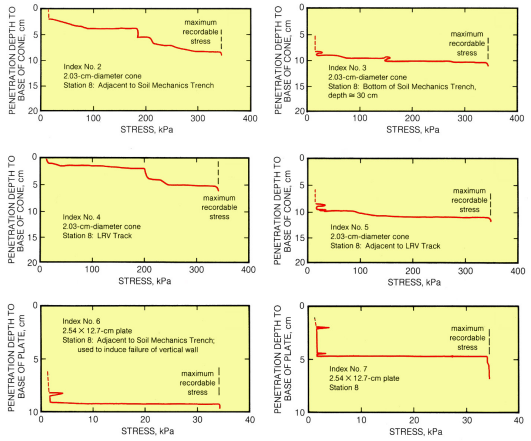
Itokawa



Assume fine-grained regolith occurs.
Thermal inertia suggests fine-grained material present.
Thickness unknown

Penetration Resistance Data





Apollo 15 Cone Penetrometer Data - mare

Summary - APEX

- Important science, unique opportunity
- Challenging mission within PSDS constraints
- CONOPS at a small no-g body – Autonomous operations
  - Rendezvous
  - Touch the surface
- Emplacement of seismometer (tiny self-contained “spacecraft”) – ensure coupling
- Data downlink – high data volume from seismometer (40 Gb / Apophis day)
- Close to the Earth, close to the sun

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