ASI CubeSat Workshop

Zodiac Pioneer

An interplanetary small satellite platform for asteroid reconnaissance

July 2024

TYVAK™ INTERNATIONAL
A Terran Orbital Corporation

Introduction

- **As part of the Planetary Defense roadmap, the European Space Agency is evaluating the implementation of a mission to Apophis to characterize the close-encounter effects on the asteroid properties**
- **Two scenarios are being studied**
  - RAMSES I – Hera concept re-use
  - RAMSES II – Alternative concept (open competition)
- **Tyvak International (Italy) is prime contractor for ESA for the execution of a feasibility study for a mission to Apophis, alternative to Hera, leading a consortium made by Politecnico di Milano, GMV, and OHB-Italy.**

Introduction (2)

- **RAMSES II Launch need: May 2027 (Baseline), November 2027 (backup)**
- **Implementation challenges**
  - Supply chain securing, considering missions funding scheme
  - Risk vs solution maturity was considered by the Agency too high to enable a mission implementation to Apophis, and selected RAMSES I as baseline to pursue leveraging on the Hera heritage and solution maturity
- **RAMSES II redirected to additional targets in the list of the ESA Planetary Defense roadmap**

RAMSES II → **ZODIAC PIONEER**

Target:
Apophis
(close encounter in 2029)

Targets:
Known NEAs with high interest for Planetary Defense and reasonable rendezvous possibility in the next 8 years

Asteroid	a [AU]	e [-]	i [deg]	T [y]
2006CT	1.097	0.231	2.74	1.15
2011CG2	1.177	0.158	2.76	1.277
2019NC1	0.992	0.128	6.807	0.989
2009SC15	1.265	0.179	6.841	1.423
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2008JL24	1.038	0.107	0.551	1.058

Zodiac Pioneer Mission Objectives

Mission goals and objectives

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- **Zodiac Pioneer Science goals**

ID	Description
ZP-SG-110	Determine the **global properties** of the asteroid and their implications on its past and future orbital evolution and on planetary defense planning.
ZP-SG-120	Determine the **geophysical properties** of the asteroid and how this relates to its formation, evolution, and their implications related to planetary defense.
ZP-SG-130	Study the **chemical composition** of the asteroid, and how this relates to its formation, space weathering, and the transportation of volatiles to Earth.

- **Zodiac Pioneer Scientific objectives**

ID	Description
RAM-SO-110	Determine the **mass** of the asteroid.
RAM-SO-120	Measure the **shape and thermal properties** of the asteroid and determine their impact on the translational state.
RAM-SO-130	Determine the **rotational motion** of the asteroid and its impact on the heliocentric orbit.
RAM-SO-140	Determine the **global shape and surface features** of the asteroid.
RAM-SO-150	Determine the **interior structure** of the asteroid.
RAM-SO-160	Determine the **cohesion** of the surface material.
RAM-SO-170	Measure the **chemical properties** of the asteroid.

Mission goals and objectives

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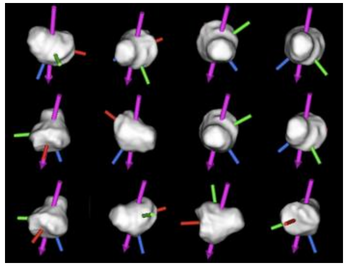
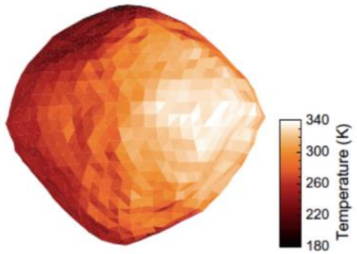
Main S/C

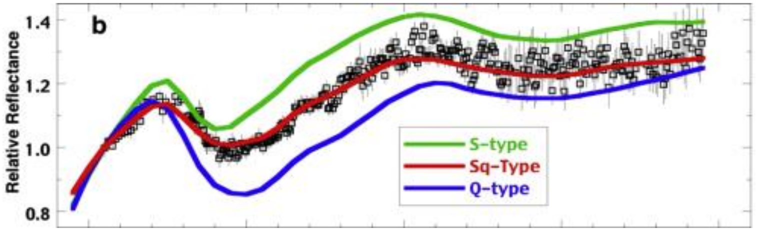
- **Optical imager:**
  - Surface features and shape model.
  - Rotational state.
- **Multi-/hyper-spectral imager:**
  - Spectral properties.
  - Space weathering.
  - Detection of water/volatiles.
- **Thermal imager:**
  - Thermal properties.
  - Surface composition.



Brozovic et al. *Icarus.* 2018

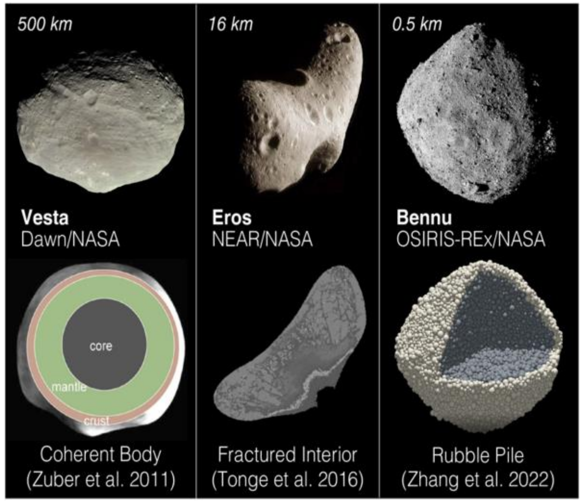


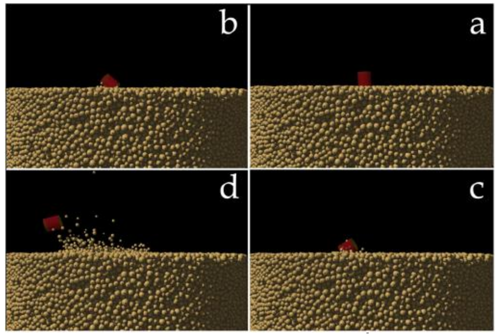
Emery et al. *Icarus.* 2014



CubeSats/Landers

- **Mono/bi-static radar:**
  - Internal structure.
- **Seismometer:**
  - Seismicity.
  - Internal properties.
- **Gravimeter/IMU:**
  - Landing and bouncing.
  - Surface mechanical properties.
- **ISL:**
  - Gravity field estimation.



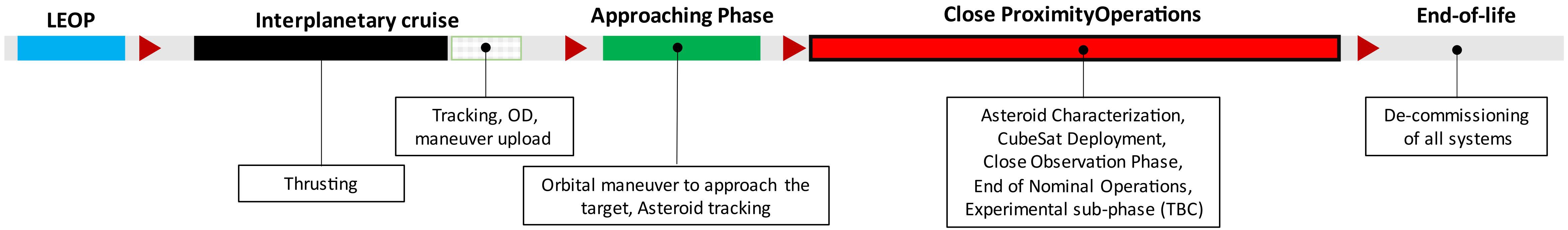


DellaGiustina et al. *MNRAS.* 2024

Zodiac Pioneer Mission Overview

Mission Timeline

- **Launch considered timeframe: between 01/2029 and 12/2030**



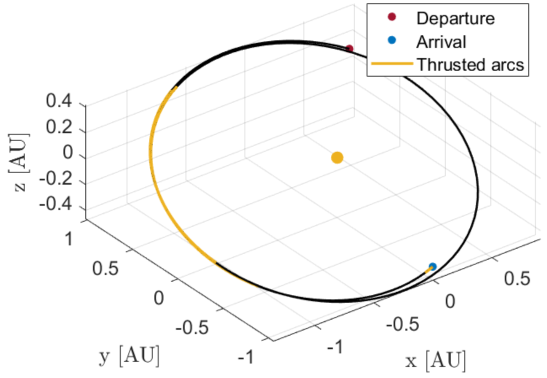
- **LEOP (2 months)**
  - Platform Power Up, Attitude Stabilization, Solar Arrays Deployments, Bus and Payloads Commissioning, Two-way Communication Check
- **Interplanetary cruise (up to 36 months)**
  - Continuous thrust arcs using electric propulsion (5-6 days TBC), including trajectory corrections for navigation and momentum wheel management
  - Coasting arcs (1-2days TBC), for communication with Earth and Flight Dynamics operations
- **Approaching phase (1-2 months)**
  - Asteroid Detection & Tracking and Orbital Maneuvers
- **Close Proximity Operations (6 months)**
  - Asteroid Characterisation Phase (ACP) – 2 months
  - CubeSats Deployment Phase (CDP) – (within ACP)
  - Close Observation Phase (COP) – 4 months
  - End of Nominal Operations
  - Experimental Phase
- **End of Life**
  - Passivation of the communication subsystems
  - Passivation of stored energy sources, propellant depletion.

Zodiac Pioneer
Mission Analyses

Interplanetary Trajectory and Geometrical Analysis for Selected Targets (PoliMI)

- **Selection of 3 best-ranked trajectories for each of 16 targets according to mission constraints and platform requirements**
- **For the best-ranked trajectory of each target, a geometrical analysis is carried including:**
  - Thrust Profile
  - Distance to Sun and Earth Profiles
  - Target phase angle Profile
- **14 out of 16 available targets are reachable within the mission scope**

Selected trajectory for asteroid 2006CT
(Illustrative example)



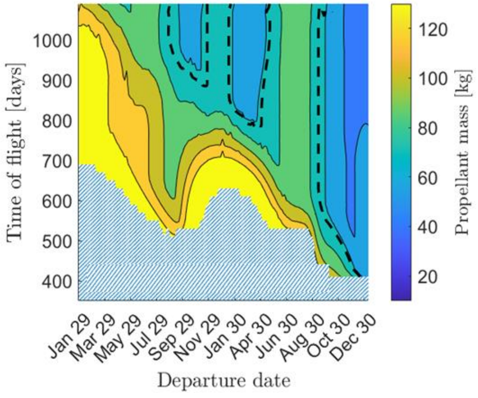
Time Constraints
Departure: 1/1/2029 to 31/12/2030
Time of Flight: up to 1100 days

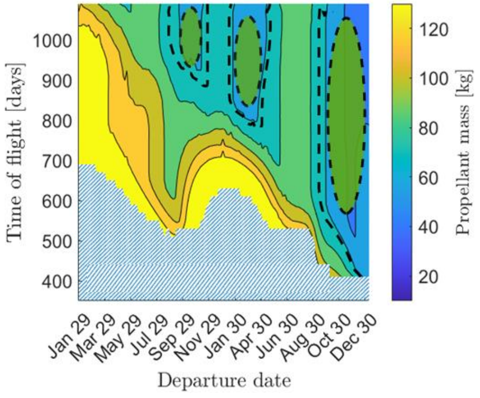
Xe Propellant mass: < 76 kg
SC-Sun distance: [0.75, 1.4] AU

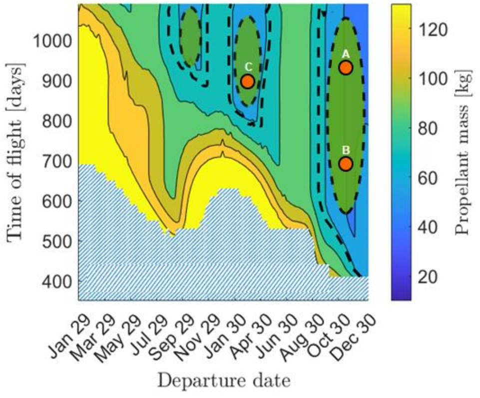
Priority given for trajectories closest to Earth during science phase

1 Compute reachable trajectories → Porkchop → 2 Identify feasible trajectories according to requirements → Possible Trajectories → 3 Ranking of trajectories → 4 Geometrical analysis

3 best ranked trajectories
(phase angle, earth distances, etc..)







Close Proximity Operations (GMV)

Estimation of **Asteroid Mass** values was needed to compute **the propellant budget for Proximity Operations**:

Starting point: Absolute magnitude (only known value)

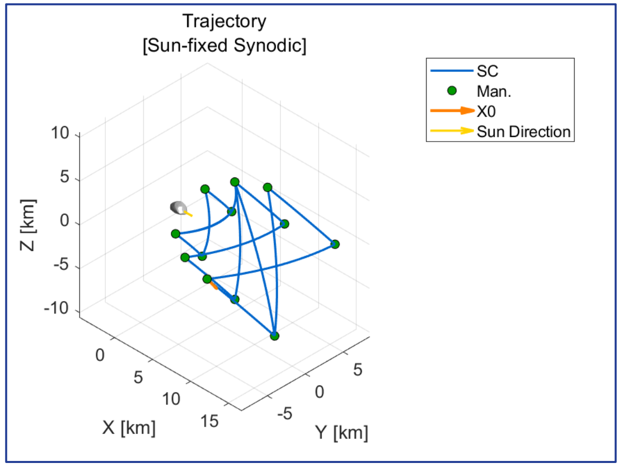
Typical albedo intervals → Max/Min Diameter → Typical density intervals → Max/Min Mass → **Delta V budget**

Asteroid Characterisation Phase (2 months)

- First Asteroid Characterisation (e.g. gravity, shape model, rotation state)
- GNC System and Payload Commissioning

Strategy

- **High uncertainty**, conservative strategy (collision-free trajectory)
- **Hyperbolic Arcs** (safe if a manoeuvre is missed)
- Manoeuvres in 3-4 day cycles (week synchronicity)
- **Decreasing distances (15km → 10km → 5km)**
- **Initially attitude and manoeuvres commanded by ground (15km)**
- At closer distances the attitude is commanded by the GNC

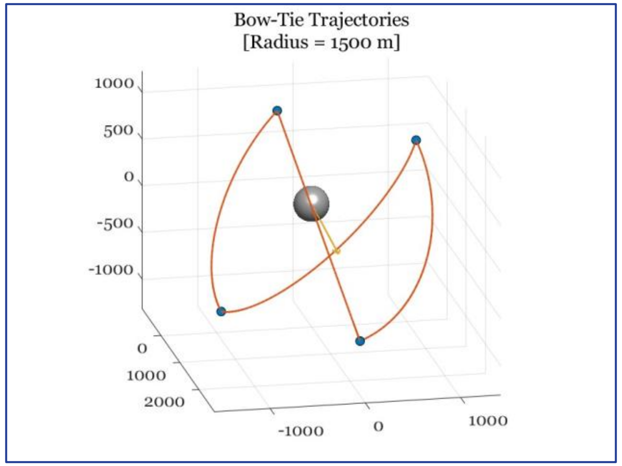


Close Observation Phase (4 months)

- Global coverage at 10cm/pixel
- Different illumination conditions

Strategy

- **Elliptic Arcs (active collision avoidance system ensures safety)**
- Manoeuvres in 10-14 h cycles (day synchronicity)
- Constant distance of 1.5 km (altitude 1.3-1.4km)
- **Both manoeuvres and attitude commanded on-board**
- Foresees 8h of communication per day for monitoring and science transmission



Zodiac Pioneer Overview

Zodiac Pioneer Spacecraft Overview

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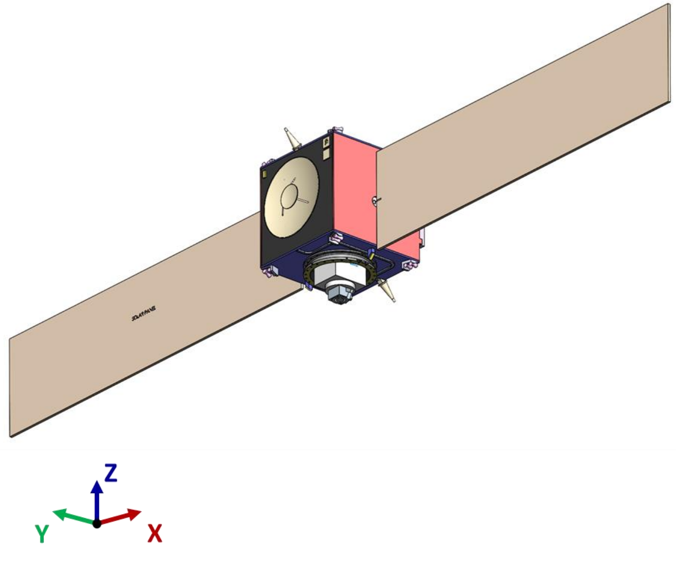
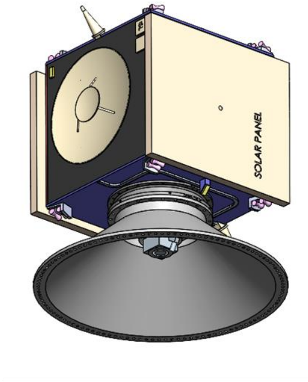
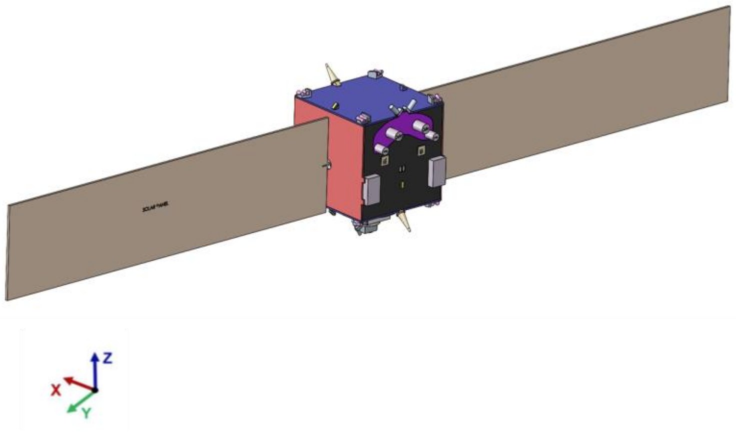
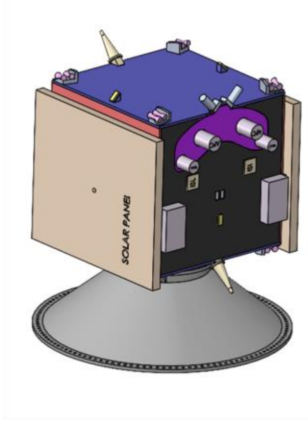
<u>Main Spacecraft Features</u>

- **Tyvak Core Avionics**
- **Target Specification Mass 525 kg**
  - Including propellant (Xe) 102 kg
  - Including 20% System Margins
- **1.8 kW class solar array** (@1AU)
- **Payload Capacity: ~ 45 kg** (including 2x CubeSats)
- **HET Electric Propulsion: 30-90 mN** gimballed main thruster
- **X–Band link via 75 cm class HGA**
- **X–Band link with 2x LGAs (Omni Coverage)**
- **Monopropellant RCS** enabling momentum management and proximity operations









Approx size:
Main body: 1m x 1m x 1m
Solar wing: 3.5m x 1m

Baseline systems

- **A RFI campaign was executed aiming at identifying baseline architecture**

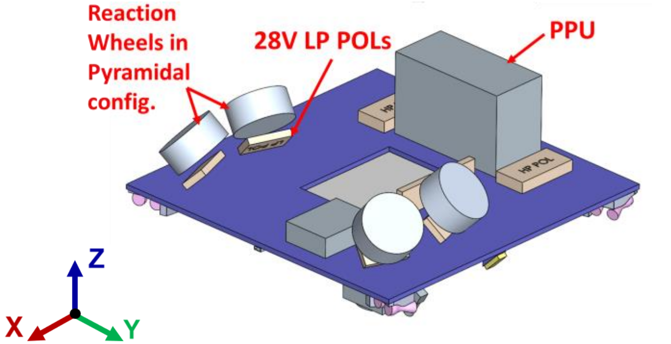
- **Selection drivers:**
  - Technical solution and requirements compliance
  - Technology Readiness Level / Qualification Status
  - Programmatic (lead time and cost)

- **First RFI round did not include:**
  - Opportunity Payloads
  - CubeSats and related systems (i.e. Deployers, InterSatellite Links)
    - Hera heritage to be maximised (e.g. Milani CubeSat, developed by Tyvak International, and related MECH and EE interfaces)

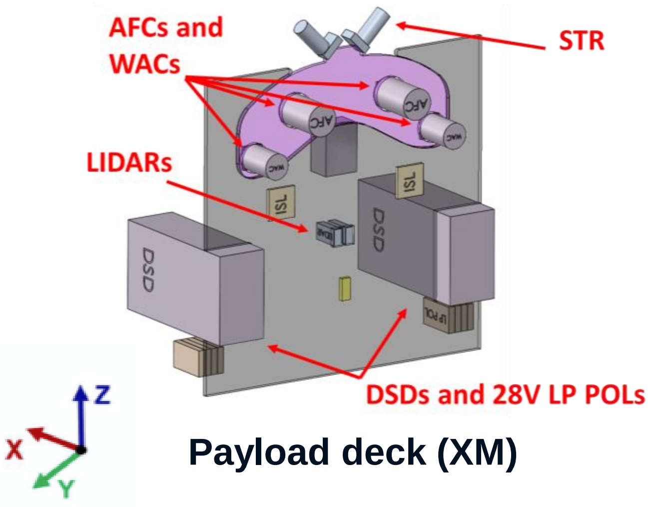
Preliminary Internal Accommodation

Internal configuration uses a set of ribs and panels to support the loads and all the modules inside the spacecraft

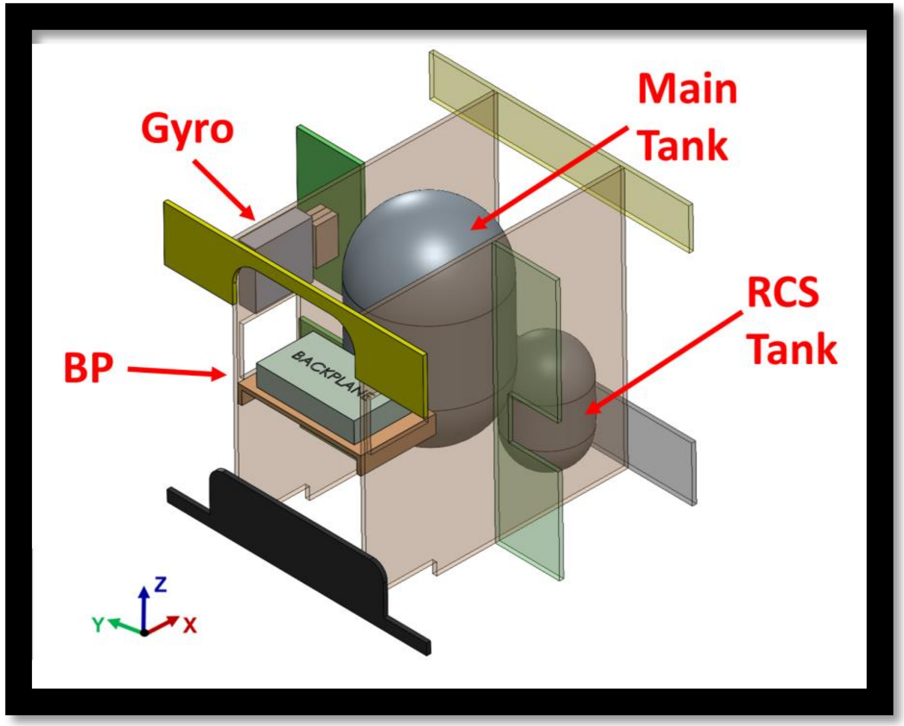
- Main propulsion system tank in the center
- Subsystems accommodation on the different panels aiming at optimizing AI&T flow, harnessing complexity and thermal performances

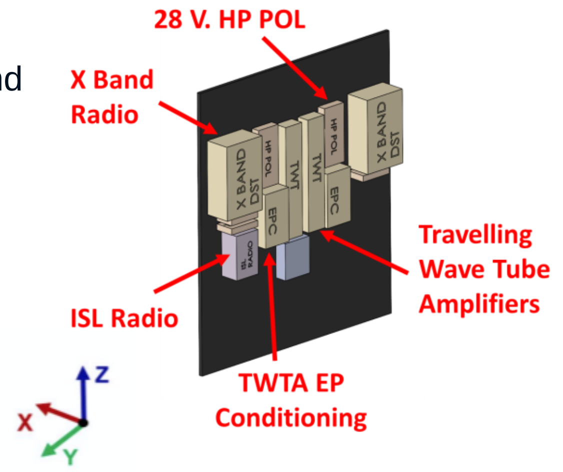


Lower deck (ZM)

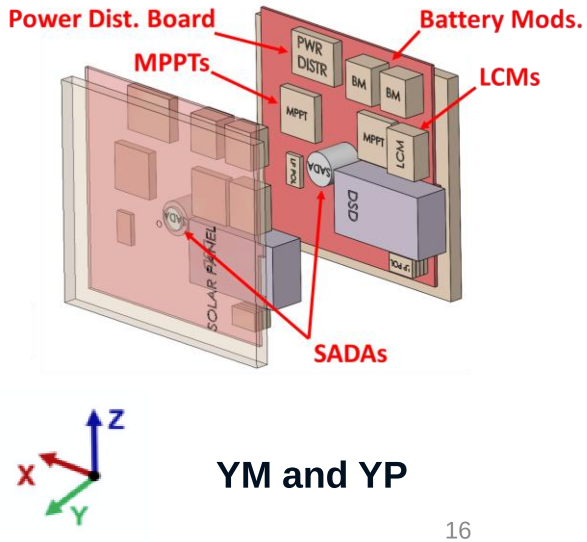


Payload deck (XM)





Comsys deck (XP)



YM and YP

Preliminary External Accommodation

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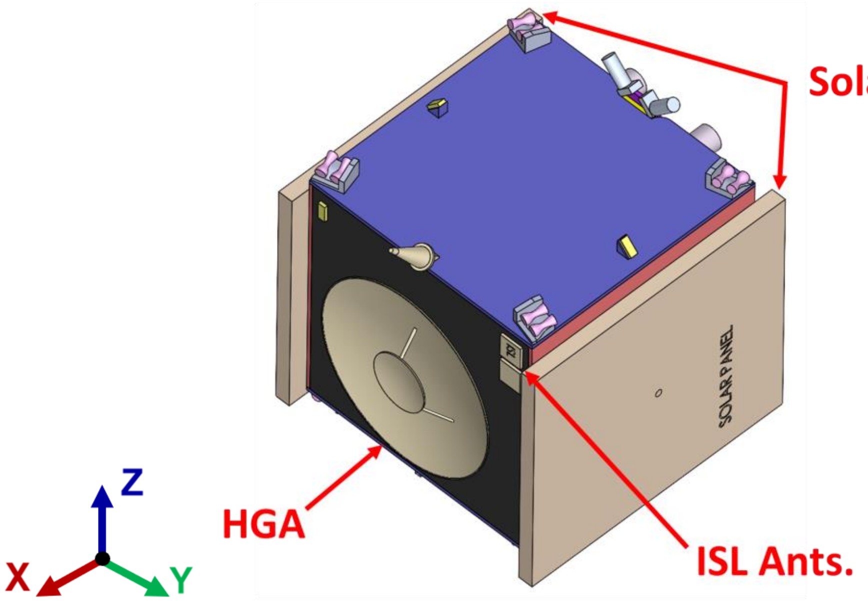
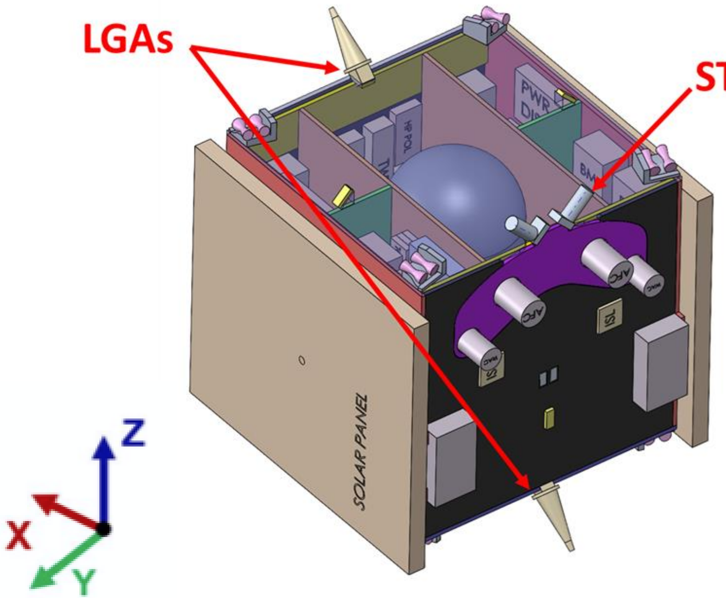
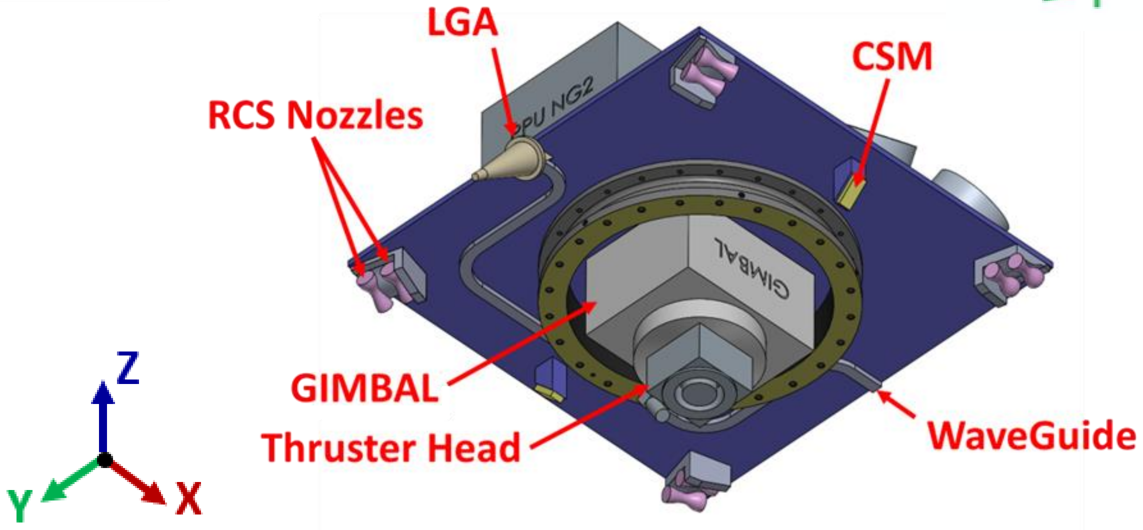




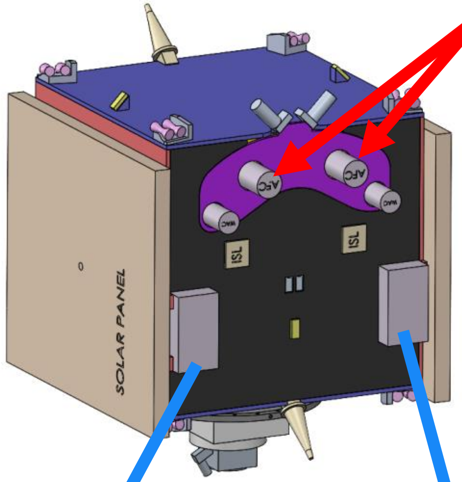


Current Payload suite

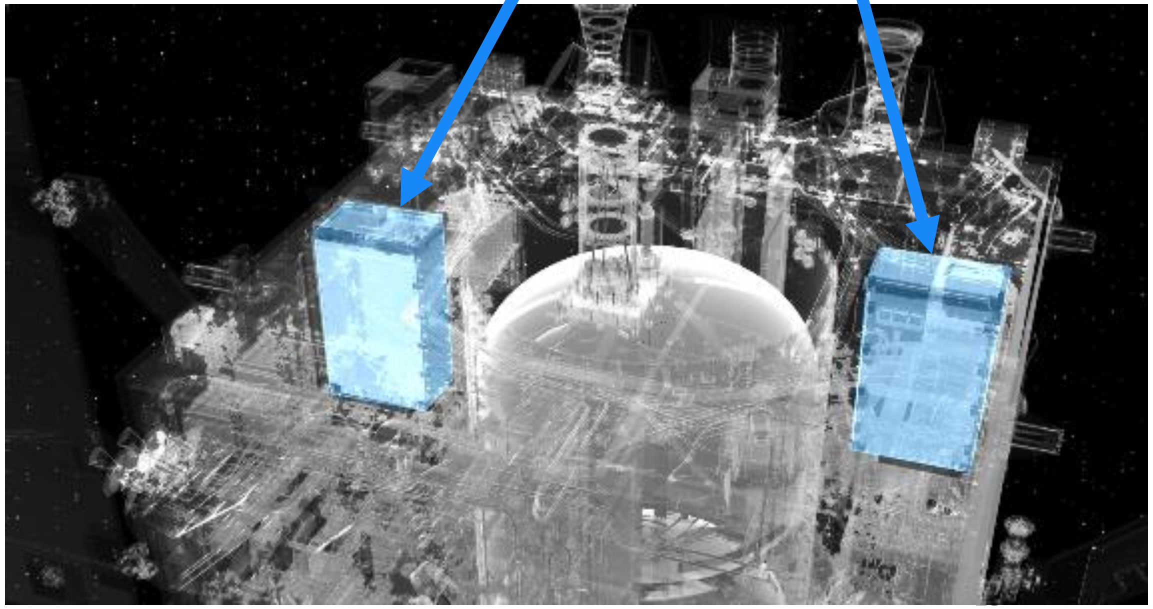
- **2x 6U CubeSats**
  - Based on HERA design and heritage
  - Baseline CubeSat payloads: low-frequency radar, gravimeter, seismometer, high-resolution camera, dust detectors, retroreflectors
  - Deep Space Dispensers + “Life Support Interface Boards” + CubeSats + ISL Radios and antennas
  - Total system + support mass: ~**39 kg**
- **2x Asteroid Framing Cameras**
  - These are the Narrow Angle Cameras, dual use as navigation cameras
  - Cold redundant system
  - Total system mass: ~**1 kg**
- **2x Wide Angle Cameras**
- **Additional Payloads to be defined**
  - Extra SWaP reserved for this purpose
  - Total mass available for Additional Payloads: ~**6 kg**

Total Payload Mass Allocation: 46 kg

Asteroid Framing Cameras



Hera CubeSat configuration reference



Zodiac Pioneer Operational Envelope

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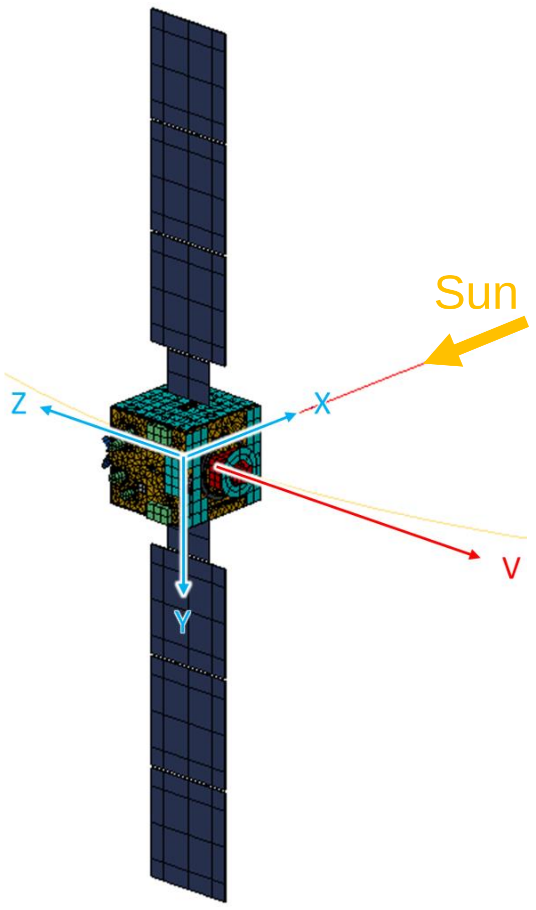
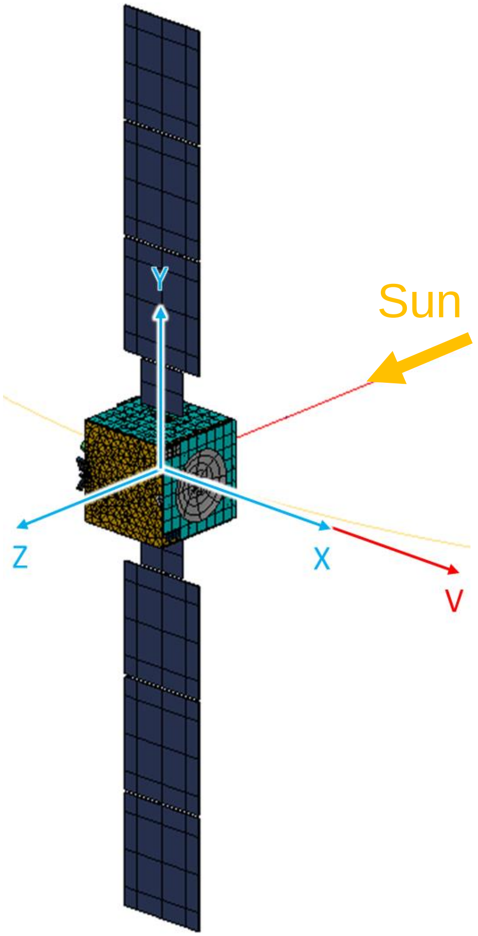
The design concept aims to define an **operational envelope** to assess the platform usage feasibility for future asteroid missions. The operational envelope has been analyzed in terms of:

- **Communication and Data Downlink Capabilities,** considering HGA and LGA as a function of distance from the Earth
- **Payload mass availability vs Propellant mass request** considering the variation of the spacecraft's total mass.
- **Electrical Thruster capabilities** as a function of the power generated by the Solar Arrays at different distances from the Sun:
    - EP Power model numerically interpolated and computed with a 3rd-degree polynomial fit
- **Platform thermal behavior** in different scenarios and related TCS solutions

Thermal Analyses Conducted with respect to 7 operative scenarios



EP + Comms Operative Mode Attitude

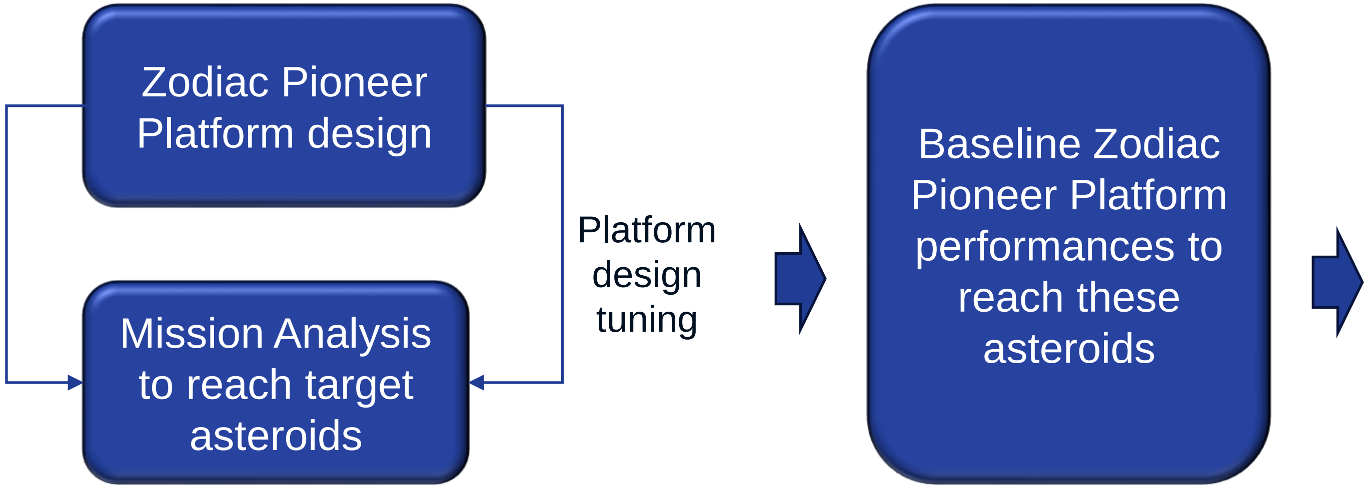


Normal Operative Mode Attitude

Conclusions

Conclusions

- **Objective was to identify a platform configuration able to reach the highest number of target with minimum design tuning / modifications**
- **Main outcome:**
  - Out of 16 analyzed targets, just 2 (2002LY1 and 2009SC15) are not reachable
  - Tunable Parameters of the Spacecraft within the reachable asteroids:
    - EP propellant and payload masses (optimized to the mission).
    - Transponder Tx data rates.
    - External radiator coatings (for Thermal Control System).



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2008JL24	1.038	0.107	0.551	1.058

Flawless Execution Sustains Growth

Contacts: isabella.pappagallo@tyvak.eu

Backup Slides

Communication and Data Downlink Capabilities

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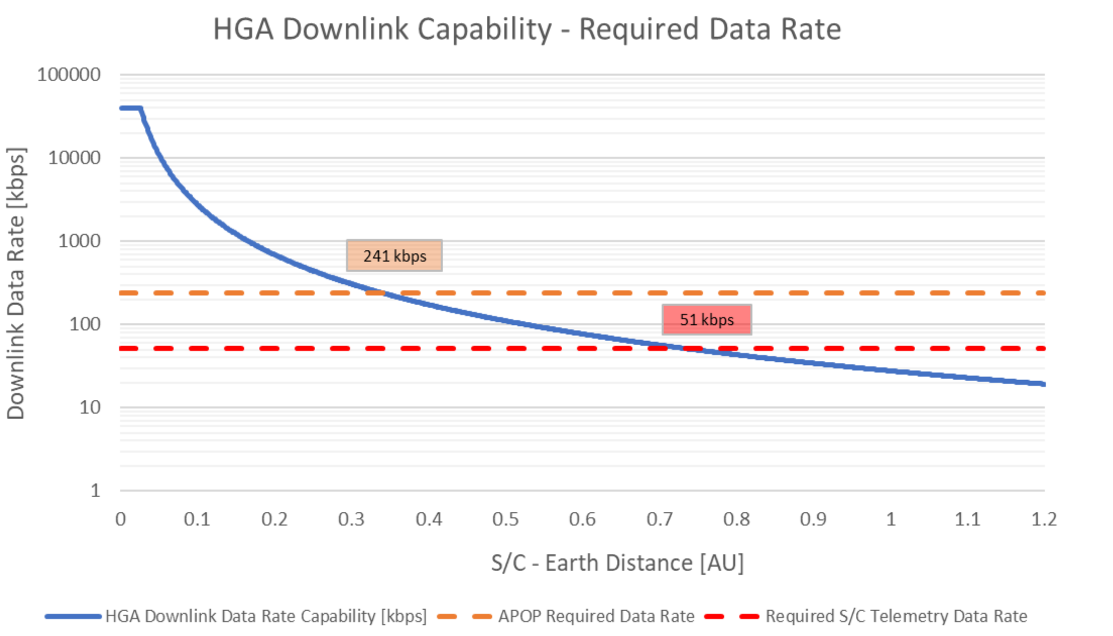
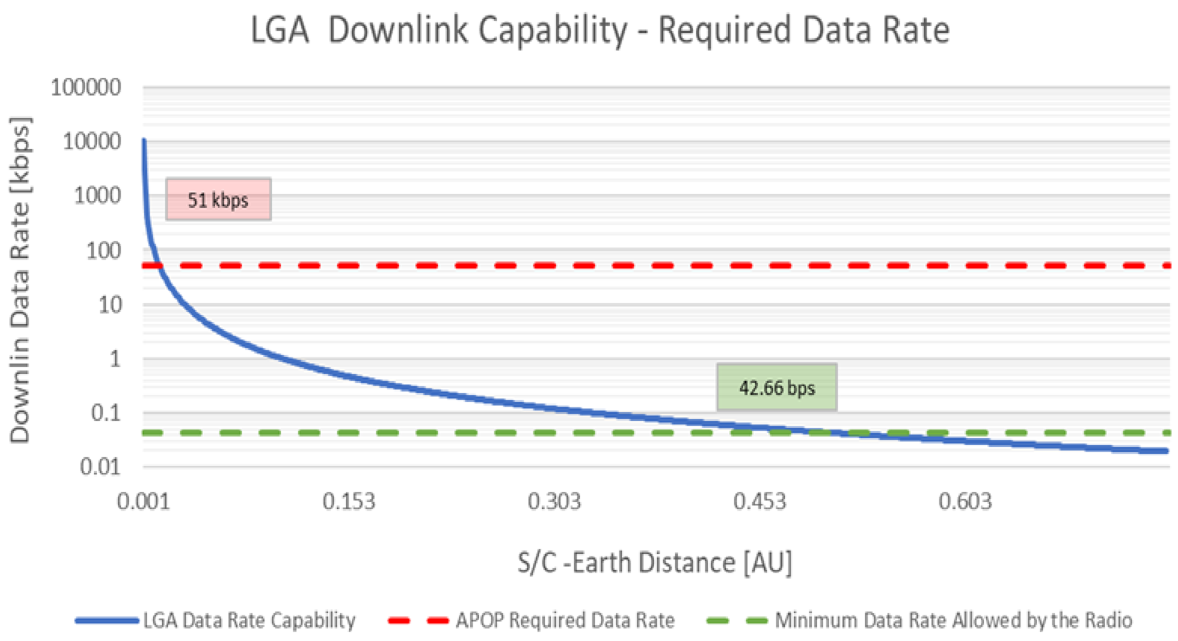
The link and data budget analysis for the HGA & LGA led to the identification of the boundary distances for the capability of data transmission **to comply with the 8-hour transmission window and considering Spacecraft and Science data requests.**



- Maximum Earth-Spacecraft Distance – Scientific Operations
- Maximum Earth-Spacecraft Distance – Spacecraft Full Set Telemetry

> 100 kbps at 0.5 AU from Earth	**> 360 MB at 0.5 AU from Earth**
> 25 kbps at 1.0 AU from Earth	**> 90 MB at 1.0 AU from Earth**
> 10 kbps at 1.5 AU from Earth	**> 36 MB at 1.5 AU from Earth**

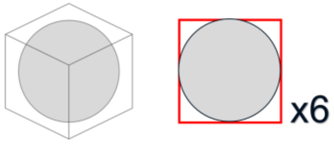
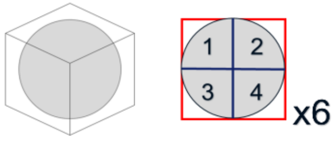
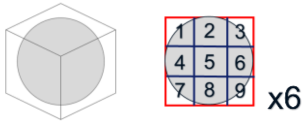


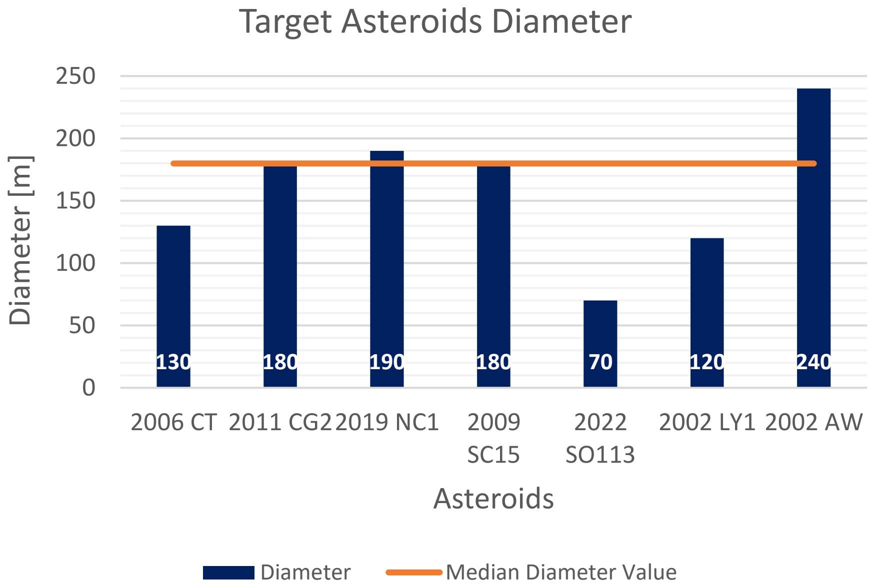
- Maximum Earth-Spacecraft Distance – Spacecraft Full Set Telemetry
- Maximum Earth-Spacecraft Distance – Spacecraft Min. Meaningful Data

Larger distances from the Earth can be supported by further tailoring of the telemetry to be downlinked.

Surface Mapping – Zodiac Pioneer Target Asteroids

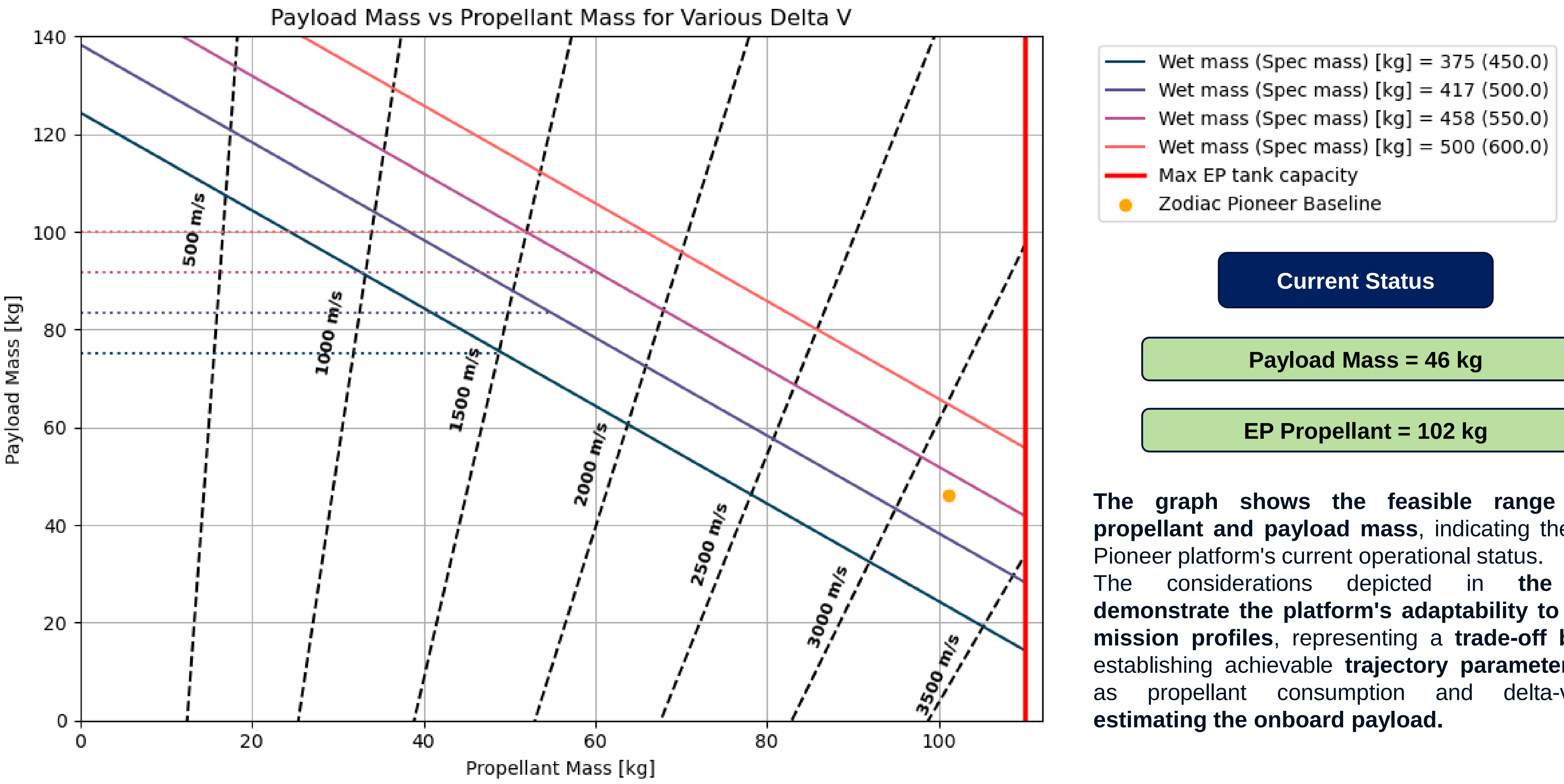
Asteroid Categorization – Number of pictures Required for Full Surface Mapping, considering acquiring images of the target asteroids with a **resolution** equal to or better than **10 cm (at the central pixel).**

Asteroids Range	**Diameter less or equal to 204.8 m**	**Diameter greater than 204.8 m and less than 409.6 m**	**Diameter greater than 409.6 m and less than 614.4 m**
Asteroids Percentage within the Category	86%	14%	-
Number of Pictures Required for Mapping	 **6**	 **24**	 **54**
Data Volume of Full Mapping	45.3 MB	181.2 MB	407.7 MB
Percentage Allocation of S/C Data Return Volume (Max. Value 180 MB of daily scientific data generation)	25%	101%	227%



Median Diameter Value: 180 m

Zodiac Pioneer Platform – Payload-Propellant Mass Envelope



Current Status

Payload Mass = 46 kg

EP Propellant = 102 kg

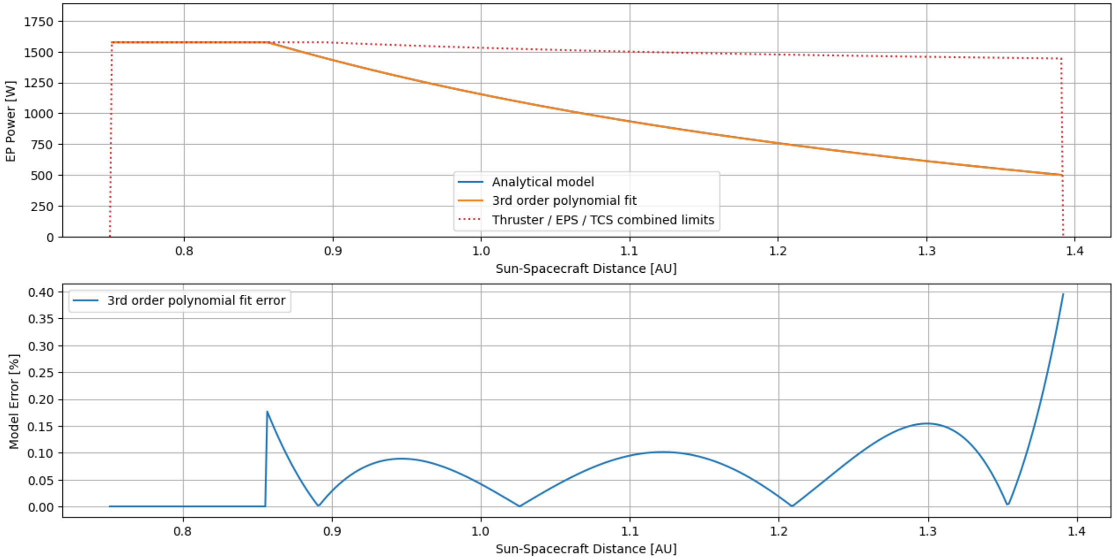
The graph shows the feasible range of EP propellant and payload mass, indicating the Zodiac Pioneer platform's current operational status.
The considerations depicted in **the graph demonstrate the platform's adaptability to various mission profiles**, representing a **trade-off between** establishing achievable **trajectory parameters** (such as propellant consumption and delta-v) **and estimating the onboard payload.**

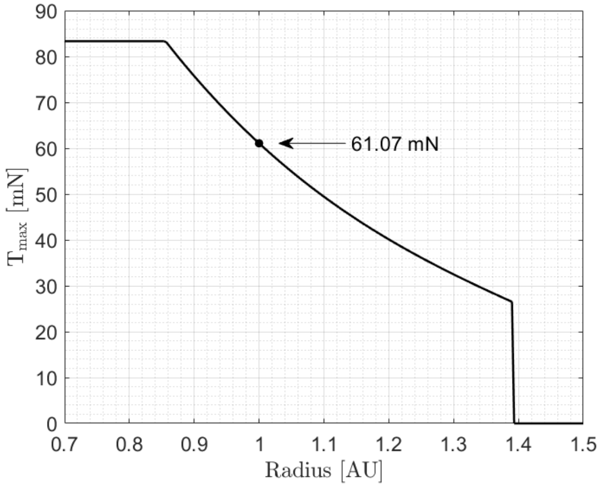
EP Power Model

Power model numerically interpolated and computed with a 3rd-degree polynomial fit.

- Power Generation – Power Consumption Matching (considering margins)
- Solar flux as a function of distance from the Sun
- Solar Arrays temperature considering out-of-plane and front-to-rear panel conduction
- Heaters Power Consumption as a function of the distance from the Sun

Valid in the range 0.8568 AU <= r <= 1.3922 AU, considering Isp = 1500s and T [mN] = 0.0529*P





Maximum thrust as a function of the distance from the Sun

- The Power is capped at 1575 W in the range 0.75 <= r < 0.85, as it is the maximum Discharge Power allowable for the PPU.
- The r upper limit of validity is given by the information of the minimum working point of the EP, at the time the model was generated.
- Polynomial fit error shows very good fidelity of the model (<1%) that however increases as the Sun distance increases, at it was possible to anticipate.

Thermal Model Operational Envelope

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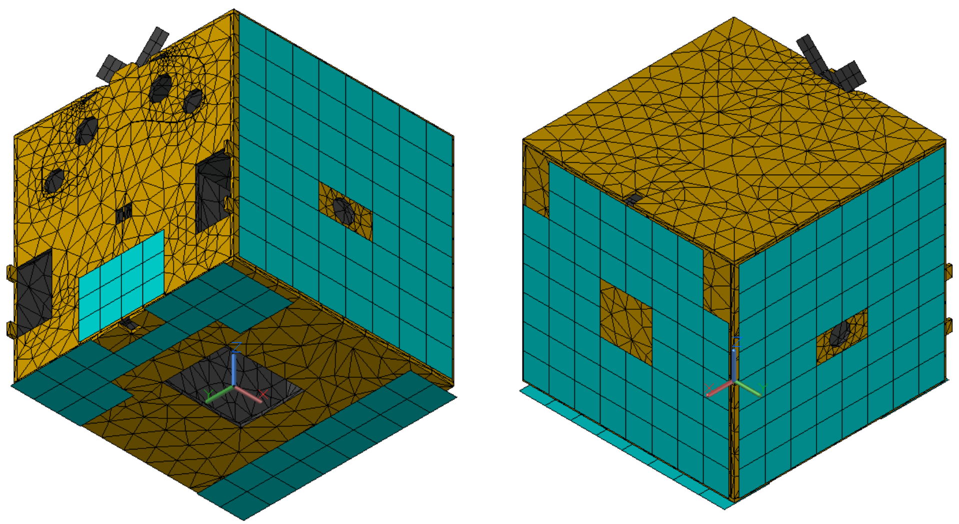
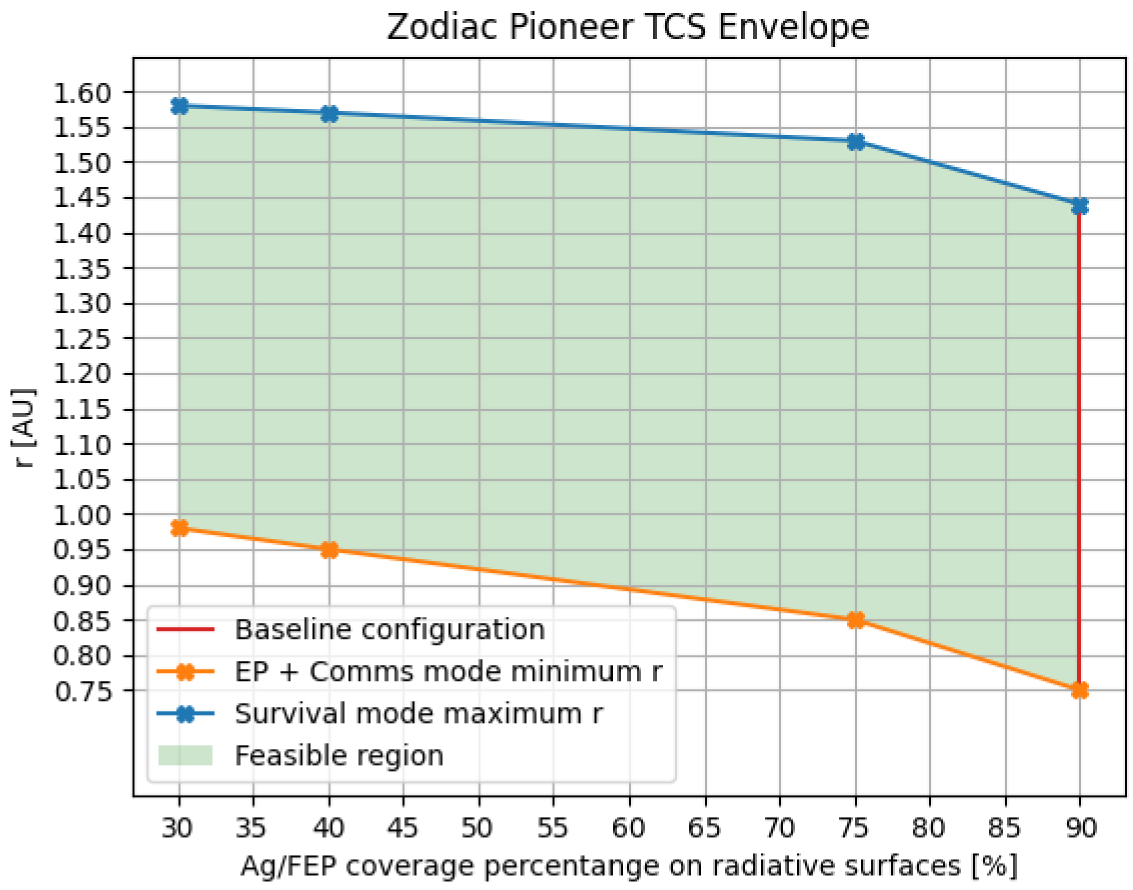
- The platform can operate in different environments with minimal changes to the thermal architecture, with the possibility of implementing them late in the project lifecycle
- Changing the fraction of radiator surface (cyan in the image) covered by second surface mirror tapes the operational range (in Survival mode) can be extended up to 1.58 AU, with respect to a baseline range of 0.75 AU to 1.44 AU.





Interplanetary Trajectory for Selected Targets

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- **The strategy carried for each target:**

Time Constraints
Departure: 1/1/2029 to 31/12/2030
Time of Flight: up to 1100 days

1 Compute reachable trajectories

Porkchop

Propellant mass: < 76 kg
SC-Sun distance: [0.75, 1.4] AU

2 Identify feasible trajectories according to requirements

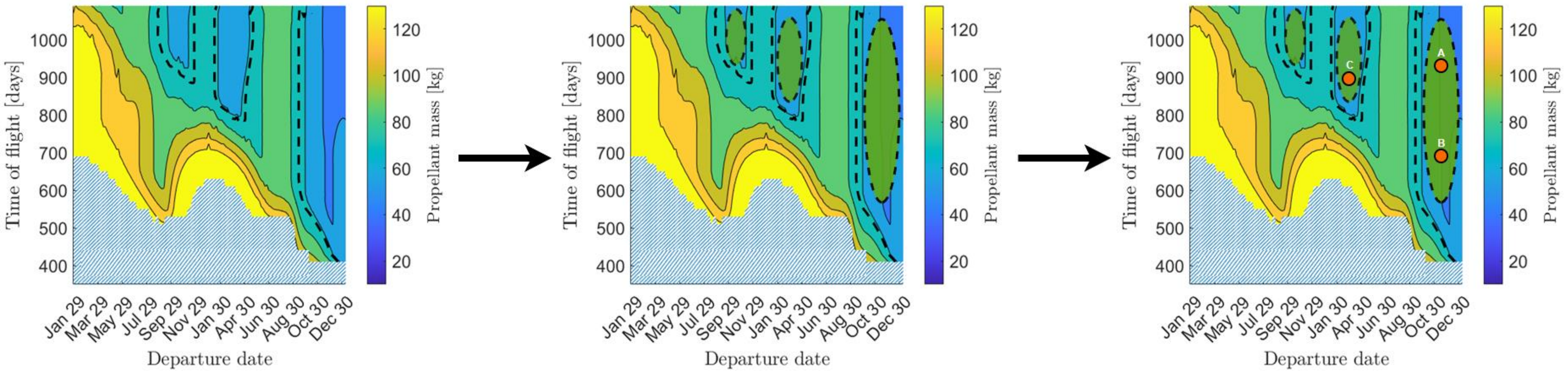
Possible Trajectories

Priority given for trajectories closest to Earth during science phase

3 Ranking of trajectories

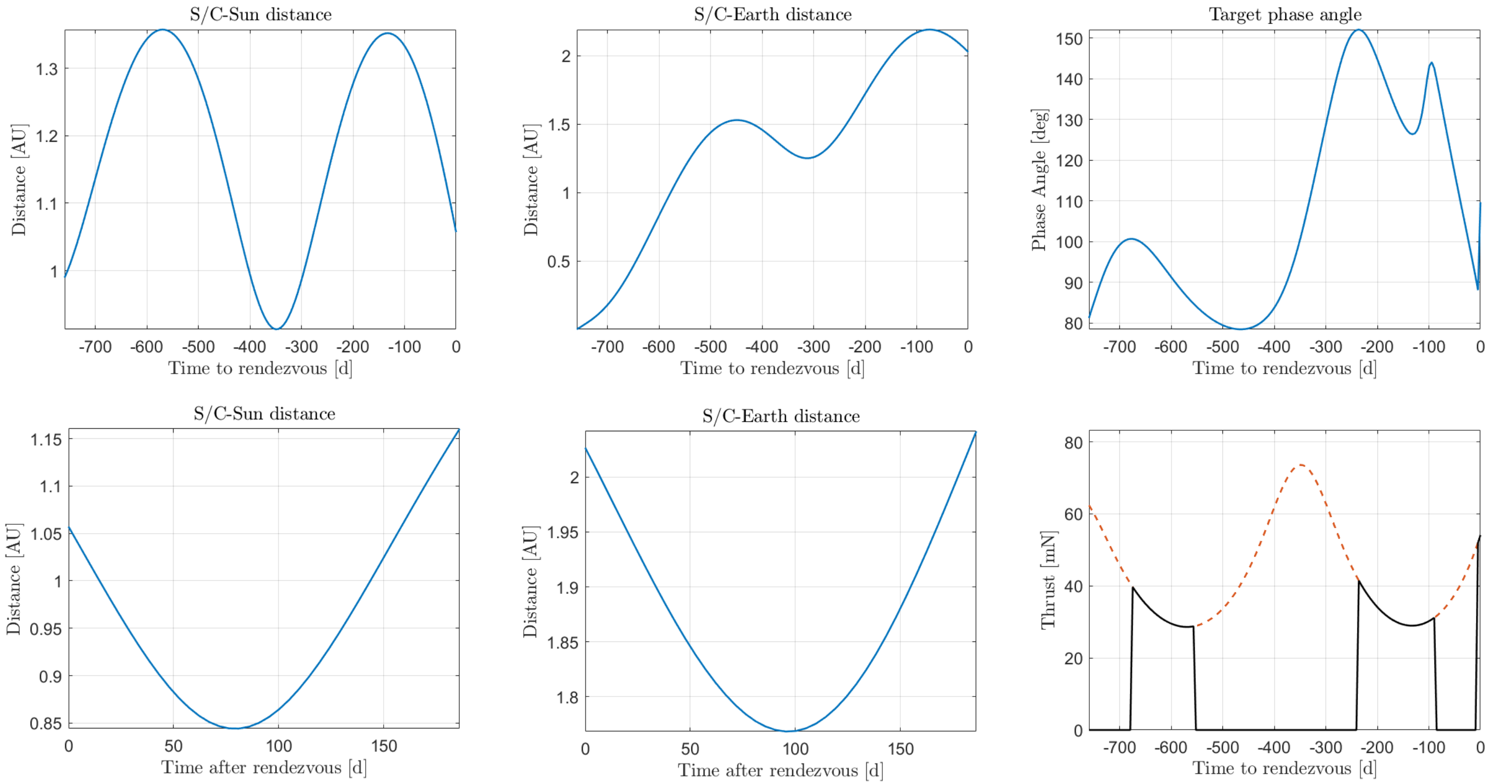
4 Geometrical analysis

3 best ranked trajectories
(phase angle, earth distances, etc..)

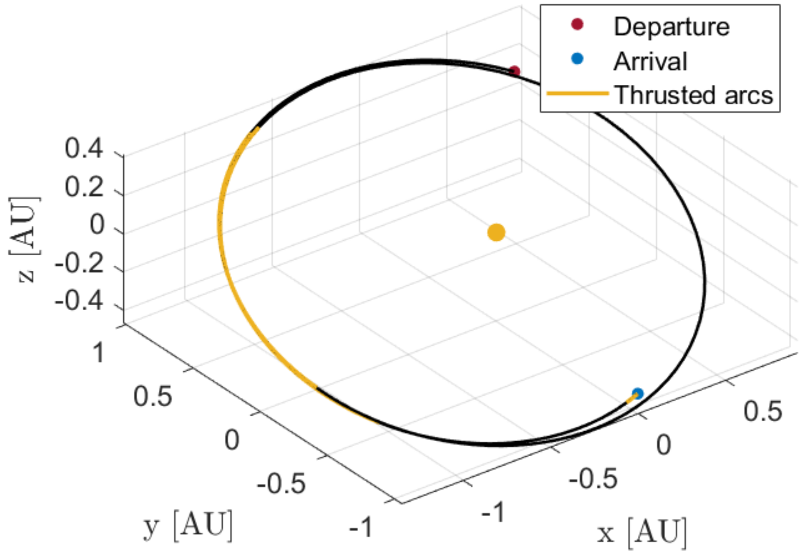


Results Interplanetary Trajectory and Geometrical Analysis

- **14 out of 16 available targets are reachable within the mission scope**
- **For the best ranked trajectory of each target, a geometrical analysis is carried including**
  - Thrust Profile
  - Distance to Sun and Earth Profiles
  - Target phase angle Profile



Geometrical analysis for asteroid 2006CT trajectory



Selected trajectory for asteroid 2006CT (Illustrative example)

Close Proximity Operations (GMV)

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- **Main Phases**
  - Asteroid Characterisation Phase (2 months)
  - Cubesat Deployment Phase (within ACP)
  - Close Observation Phase (4 months)
  - Experimental Phase – relies on leftover resources
- **Mass values were needed to compute propellant budget for Proximity Operations**
  - Starting point: Absolute magnitude (only known value)
  - Typical albedo intervals → Max/Min Diameter → Typical density intervals → Max/Min Mass (highlighted in orange) → Delta V budget

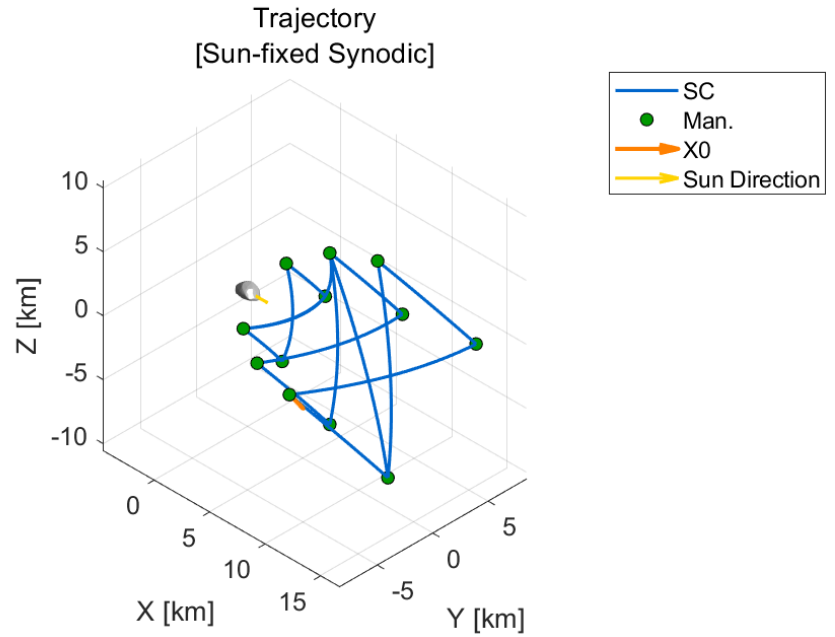
Target	Rot. Period [h]	Abs Mag [mag]	Min Rho [-]	Max. Rho [-]	D_Max [m]	D_Min [m]	Min. Mass [kg]	Max. Mass [kg]
2006CT	16.69h	22.28	0.05	0.4	208.0	73.5	1.561E+08	1.413E+10
2011CG2	10.813h	21.45	0.05	0.4	304.8	107.8	4.913E+08	4.447E+10
2019NC1	13.91h	21.4	0.05	0.4	311.9	110.3	5.264E+08	4.765E+10
2009SC15	10.354h	21.43	0.05	0.4	307.6	108.8	5.050E+08	4.571E+10
2022SO113	Not available	23.57	0.05	0.4	114.8	40.6	2.626E+07	2.377E+09
2002LY1	Not available	22.4	0.05	0.4	196.8	69.6	1.322E+08	1.197E+10
2002AW	4.647h	20.81	0.05	0.4	409.3	144.7	1.189E+09	1.077E+11
2000SG344	Not available	24.7	0.05	0.4	68.2	24.1	5.512E+06	4.989E+08
2012UV136	Not available	25.6	0.05	0.4	45.1	15.9	1.590E+06	1.439E+08
2014YD	2.12h	24.3	0.05	0.4	82.0	29.0	9.579E+06	8.670E+08
2009BD	Not available	28.1	0.05	0.4	14.3	5.0	5.027E+04	4.550E+06
2015KK57	Not available	27.62	0.05	0.4	17.8	6.3	9.757E+04	8.831E+06
2008JL24	0.054h	29.6	0.05	0.4	7.1	2.5	6.329E+03	5.728E+05

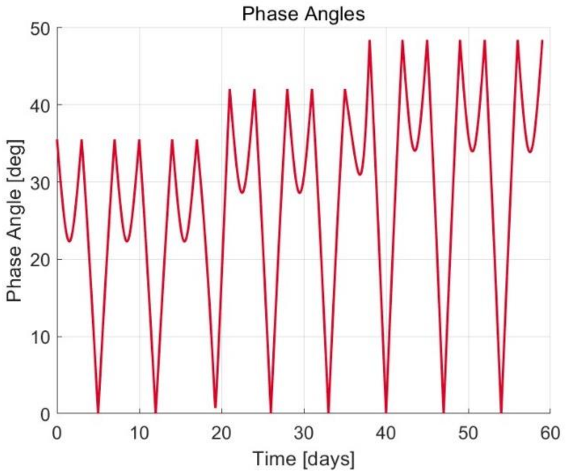
Asteroid Characterisation Phase

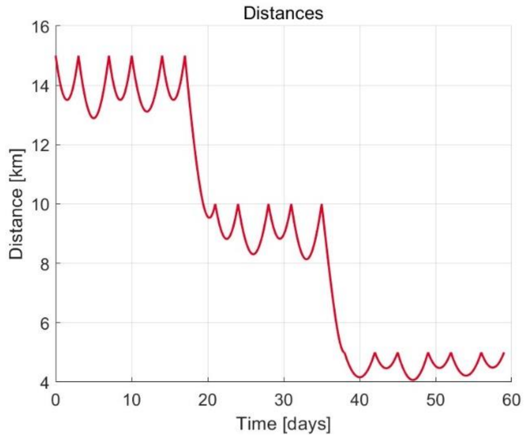
- **Main Phases**
  - **Asteroid Characterisation Phase (2 months)**
  - Cubesat Deployment Phase (within ACP)
  - Close Observation Phase (4 months)
  - Experimental Phase – relies on leftover resources

- **Objectives:**
  - First Asteroid Characterisation (e.g. gravity, shape model, rotation state)
  - GNC System and Payload Commissioning

- **Strategy**
  - High uncertainty, conservative strategy (collision-free trajectory)
  - Hyperbolic Arcs (safe if a manoeuvre is missed)
  - Manoeuvres in 3-4 day cycles (week synchronicity)
  - Decreasing distances (15km → 10km → 5km)
  - Initially attitude and manoeuvres commanded by ground (15km)
  - At closer distances the attitude is commanded by the GNC







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