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Zodiac Pioneer: An interplanetary small satellite platform for asteroid reconnaissance

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Abstract

One of the next priorities in ESA's Space Safety Programme related to Planetary Defense is the implementation of class of fast rendezvous satellites to characterize potentially dangerous asteroids. The scientific community and the Agency regularly monitor Near Earth Asteroids. The main objective of the ongoing study is to conceive a small satellite baseline design with high delta-V capability enabling an asteroid scout mission to a wide range of targets. Considering the European framework, the novelty of the architecture of the Zodiac Pioneer deep space platform is the main propulsion system being electric. The rationale is to lower the overall vehicle mass for a given mission, thus enabling the use of lighter and cheaper launch vehicles, or conversely to enable a greater flexibility for target selection, and less rigid launch windows, for a given launch opportunity.

Keywords: Planetary Defense, Asteroid, Deep Space, Platform, targets

Acronyms/Abbreviations
Asteroid Characterisation Phase (ACP)
Narrow Angle Cameras (NAC)
Asteroid Framing Cameras (AFC)
Asteroid Proximity Operations Phase - APOP
Close Observation Phase (COP)
Earth to Asteroid Cruise Phase - EACP
End of Mission Phase - EOM
FCS (Flight Control System)
Launch and Early Operations Phase – LEOP
Minor Planet Center (MPC)
Power Control and Distribution Unit (PCDU)

1. Introduction

Asteroids are characterized by different mass, volume, shape, composition, system and trajectory, this last one affected by solar radiation pressures, fly-by of celestial bodies (e.g. planets), and intra-asteroids impacts. Such variety makes crucial the maintenance of the asteroid database including all the related information. Asteroid detection and assessment are two crucial steps to identify any Earth collision risk, and the more the asteroid is characterized, the most accurately the mitigation / deflection strategy can be defined. Since the warning time increases with the asteroid mass (bigger the asteroid, higher the warning time), asteroids with diameters larger than 1km are amost all known, and it is possible to assess with reasonable confidence that they do not represent a threat to Earth in the near Future; this confidence decreases for lower sizes asteroids. Specifically, the hundreds of meters diameter class, is the most concerning one, considering the combination of the relatively low warning time (years) and the consequences of a potential Earth impact. For this reason, the scientific community and the Agency regularly monitor Near Earth Asteroids and characterization is crucial to inject additional data and information in the currently available – and constantly evolving – models, increase the knowledge of these objects and ultimately be able to identify the most suitable mission in case of an Earth collision risk.

Although the detection can be done with large ground and space telescopes, detailed characterization requires space missions in proximity of the asteroids, to measure mass, density, porosity, size distribution of surface material, dynamical properties, strength of near-surface material, interior structure, etc. Large part of these measurements can be done by orbiting around the asteroid, while some specific characterization such as seismic system response can be done considering a landing on the asteroid.

This type of missions would be realised by large spacecraft, characterized by significant programmatic impacts such as development schedule, satellite cost, launch cost. A disruptive mission which started to change this trend in the European scenario, is the Hera mission from the European Space Agency, which was developed in less than four years and will be launched in October 2024 to the Didymos asteroid. As part of the Planetary Defence roadmap, ESA is preparing a mission to Apophis, which Earth fly-by is foreseen in April 2029.

Besides the Apophis opportunity, characterized by a challenging implementation schedule to reach the asteroid before the close encounter, as said previously the Agency is constantly monitoring the NEAs and is studying dedicated missions, possibly able to reach more than one target. Furthermore, in order to further decrease the programmatic implementation constraints (i.e. costs), the Agency is seeking for innovative solutions enabling a lower mass at launch.

Zodiac Pioneer study aims at answering these needs through the feasibility assessment of a rendezvous mission to characterize potentially dangerous asteroids, based on a flexible small satellite platform based on electric propulsion, able to reach multiple targets in a single mission. The study started in June 2023 and is led by Tyvak International (Italy), prime contractor of a consortium composed by Politecnico di Milano (Italy), GMV (Spain) and OHB-Italy. The study completion is foreseen in June 2024.

The main objective of this study is to generalize the baseline design of a small satellite with high delta-V capability enabling an asteroid scout mission to a wide range of targets. Considering the European framework, the novelty of the architecture of the Zodiac Pioneer deep space platform is the main propulsion system being electric.. The rationale is to lower the overall vehicle mass for a given mission, thus enabling the use of lighter and cheaper launch vehicles, or conversely to enable a greater flexibility for target selection, and less rigid launch windows, for a given launch opportunity.

Primary goals of the mission are the determination of the target asteroid orbit, spin state, orientation, internal structure, presence of sub-millimeter dust particles. In the event of an asteroid Earth fly-by, it would be interesting to determine shape and surface changes of the asteroid

2. Mission Design

The mission timeline for the Zodiac Pioneer Mission is divided into four main phases, according to the following schematic representation.

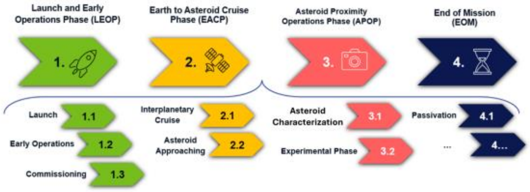

Figure 1. Mission Phases.

Following the successful commissioning of the system after launch, an Interplanetary Cruise phase using the electric propulsion system starts. It will be characterized by continuous trust arcs alternated with coasting arcs with allocated communication windows to exchange essential spacecraft telemetry. This phase will continue until the asteroid is approached so that the Proximity Operations Phase can start. This phase will be marked by activities to characterize the target asteroid selected, and an eventual experimental phase.

The characterization phase of the asteroid will take place using at least the Asteroid Framing Camera (AFC) and possibly additional scientific payloads. Any CubeSats for further closer characterization will also be released. In this phase, incremental level of risk can be accepted in the operations concept, and an experimental phase, for technology demonstration reasons or to increase the scientific return of the mission with additional measurements, could be considered.

The mission will come to an end with the successful passivation of the system. The task of each phase is detailed below.

Launch and Early Operations Phase - LEOP

During the LEOP, the spacecraft will be launched and initial operations to check out and commission all the subsystems are performed.

The LEOP shall consist of the following key tasks:

- Launch and ascent phase until separation of the spacecraft from the launcher.
- Initial autonomous satellite switch-on and power-up (TBC).
- Attitude stabilization and Safe Mode acquisition.
- Deployment of solar arrays and any spacecraft appendages (TBC).
- Commissioning of all subsystems, including payload.
- Two-way contact with ground and health check of the essential units.

Earth to Asteroid Cruise Phase - EACP

During the interplanetary phase, the spacecraft transfers from the Earth to the asteroid using an electric propulsion system. Long coasting arcs (i.e., with the thruster off) and thrusting arcs are expected, also to allow for flight dynamics operations. The interplanetary cruise shall consist of the following key tasks:

- Continuous thrust arcs using electric propulsion.
- Communication with ground during coasting segments.
- Link exchange of key housekeeping parameters.
- Trajectory corrections for navigation during the continuous thrust phases and momentum wheel management.
- Regular health checks of onboard Payloads not in use during this phase (e.g. CubeSats)

During the approaching phase, the spacecraft will detect the asteroid and prepare for the rendezvous. This phase shall consist of the following key tasks:

- Orbital maneuver to approach the asteroid.
- Asteroid tracking.

Asteroid Proximity Operations Phase - APOP

In this phase, the spacecraft will orbit the asteroid, performing the main scientific operations in close proximity. APOP shall include the following sub-phases:

- Asteroid Characterization Phase (ACP).

- CubeSat Deployment Phase (CDP).
- Close Observation Phase (COP).
- End of Nominal Operations (ENO).
- Experimental Phase (EXP) (TBC).

End of Mission Phase - EOM

Following the operations of the spacecraft, at the EOM the spacecraft shall be disposed appropriately preceded by:

- Passivation of the communication subsystems.
- Passivation of battery.
- Passivation of stored energy sources, via propellant depletion.

2.1 Mission Operations Concept

The choice of mission trajectories for the Zodiac Pioneer Mission is determined by the outcomes of the mission analyses, spanning both Interplanetary Cruise Phase and Close Proximity Phase. These analyses are being complemented by an evaluation of the radiative space environment that the satellite will encounter in both phases. For the radiation analysis effort Tyvak leverages on the support of Politecnico di Torino, DAUIN department. The interplanetary mission analysis aims at identifying the best trajectories options to reach the asteroid, and it considers:

- Mission time constraints, such as departure date, time of flight, latest arrival, etc.
- Spacecraft properties, such as spacecraft mass specification and EP Thruster capabilities. The latter is computed as a function of the available power generated by the Solar Arrays.
- Launchers assessment and launching conditions (i.e. escape velocity, launch geometry characteristics).

The details of the results of the Interplanetary Cruise Phase are reported in the next section. The first run of close-proximity mission analysis goal is the design of the trajectories and related feasibility studies that will lead to the asteroid characterization.

The analysis has been conducted evaluating:

- The mission Reference Frames.
- The specific asteroid Dynamical Environment.
- The Platform with the evaluation of actuators and sensors, and the attitude constraints.
- The Trajectory and maneuvers design.
- FCS (Flight Control System) Strategy of the mission.

An assessment of the space environment for the journey has been conducted to evaluate the nature and quantity of radiations to which the spacecraft would be exposed based on the mission phases and trajectory considered. This will lead to the adoption of mitigation action to reduce the radiation effects on the spacecraft avionics components.

2.2 Proximity Mission Analysis

The nominal proximity operations mission phase will consist of two distinct sub-phases. First, the Asteroid Characterisation Phase, based on the HERA heritage, will employ hyperbolic arcs to estimate the asteroids dynamic environment. Afterwards, lower altitude bow-tie trajectories will be used in the close operations phase, where the main scientific return will be achieved. An overview of the Proximity Operations phase is shown in Table 1.

Table 1 Proximity Operations Timeline.

Phase	**Duration**	**Objectives**
Asteroid Characterisation Phase (ACP)	2 months	First two weeks @10km: ○ Early characterization of the dynamical system ○ Commissioning of the autonomous GNC system Detailed Characterisation @5km: ○ Detailed Dynamical System Estimation ○ Scientific Return Approach and insertion for Phase COP
Cubesat Deployment Phase (CDP)	Part of ACP	Safe release of the cubesats into hyperbolic arcs from ACP-like trajectories.
Close Observation Phase (COP)	4 months	Meet Scientific Resolution and Coverage requirements (100% coverage at 10cm/pxl)
End-Of-Life Phase (EOL)	TBD	Safely dispose of the spacecraft

Asteroid Characterisation Phase (ACP)

After rendezvous with the asteroid, the first two months will be spent flying hyperbolic arcs increasingly close to the asteroid, starting from a distance where the gravity is almost negligible. Throughout this phase, the dynamic environment of the asteroid will be modelled and continuously updated, based on the increasing accuracy in results. These trajectories will be designed such that they can be flown from ground and that they are passively safe.

Close Observation Phase (COP)

Once the model is sufficiently accurate after two months of observation, the mission will continue with the Close Observation Phase. In this phase, bow tie trajectories will be used for achieving the scientific objectives. Such a trajectory is a set of elliptic arcs, connected by ballistic legs, an example of which is shown in Figure 2. The required manoeuvres will be computed autonomously on board. Although they are not passively safe, i.e. collisions can occur after a prolonged period of inactivity, the relatively long duration of these arcs is beneficial for earth communication.

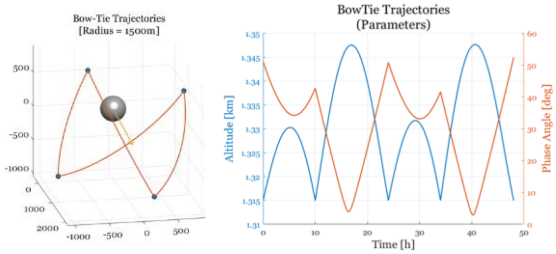

Figure 2: Bow-tie trajectory and associated parameters
Left: Bow tie trajectory example @ 1.5 km
Right: Altitude and Phase Angle

2.3 Autonomy Approach

High level of autonomous operations is anticipated for the Zodiac Pioneer spacecraft, given the nature of the mission (i.e., deep-space mission) and related complexity. In this sense, autonomy will be maximized to handle contingency situations, and to facilitate proximity operations with the asteroid.

In particular, the spacecraft will carry on autonomous operation with respect to:

- Automatic sequence after deployment, specifically related to ADCS functions to bring the spacecraft in a power-positive state.
- Mode Transition to reach the highest possible Operative Mode (e.g., after deployment to Normal Mode).
- FDIR actions to isolate equipment when a fault occurs and to bring the spacecraft into Safe Mode or Survival Mode.
- Trajectory and momentum management through EP gimballing to reduce or eliminate the need of wheel offloading while developing the proper delta-V.
- Asteroid proximity operations and navigation, maintaining its instruments trained on the target, performing hovering and CAMs if necessary.

For all other operations, direct commands, planification from ground and ground support is advised.

The key autonomy processes can be identified within:

- The Executive application Flight Computer state machine, managing the Operative Modes, the transitions between them, and any periodic, self-scheduled, or event-driven activity.
- The GNC application state machine, managing the overall attitude and trajectory to varying degrees of autonomy.

The FDIR mechanisms built-in within each flight computer application managing the various subsystems.

3. Asteroid selection & interplanetary cruise

A priori, many small bodies could be potential targets for the Zodiac Pioneer Mission. If the Minor Planet Center (MPC) database* is considered as the source of information for the minor planets in the Solar System, more than 1 million objects are accounted as for April 2024. The database comprehends the designation and the orbit computation of all the discovered minor planets, and it is updated daily. The feasibility of the Zodiac Pioneer mission cannot be assessed performing the mission analysis for all these objects, for computational time constraints. For this reason, a reachability analysis covering the Interplanetary Cruise Phase has been performed towards a shortlist of them.

The first part of the shortlist is the list of known NEAs with high interest for Planetary Defense and reasonable rendezvous possibility in the next 8 years. The list is provided in the table below, in order of priority, and has been provided by the European Space Agency.

Table 2. Orbital elements for the alternative missions' targets selected by ESA [3] (ecliptic J2000).

Asteroid Name	SMA [AU]	RA [AU]	RP [AU]	Period [yr]	Eccentricity [-]	Inc. [deg]	Node [deg]	AOP [deg]
2006CT	1.097	1.350	0.844	1.148	0.230662	2.741	285.446	82.795
2011CG2	1.177	1.364	0.991	1.277	0.158422	2.757	293.176	283.942
2019NC1	0.993	1.119	0.867	0.989	0.127682	6.809	310.544	144.133
2009SC15	1.265	1.492	1.038	1.423	0.179124	6.842	178.582	333.986
2022SO113	1.196	1.439	0.953	1.307	0.202432	2.490	138.370	332.606
2002LY1	0.956	1.317	0.594	0.934	0.378715	2.895	247.768	134.331
2002AW	1.072	1.346	0.797	1.109	0.256729	0.575	161.797	119.377

Furthermore, to sustain the small satellite platform flexibility, a series of additional targets are considered for the study. Presented in Table 3, their selection came from a previous study of the M-ARGO CubeSat mission [1] which filtered and ranked a set of attainable NEAs.

Table 3. Orbital elements for the additional selected target asteroids[2] (ecliptic J2000).

Asteroid Name	SMA [AU]	RA [AU]	RP [AU]	Period [yr]	Ec]
2000SG344	0.977	1.043	0.912	0.966	0.0
2010UE51	1.055	1.119	0.991	1.083	0.0
2011MD	1.056	1.095	1.017	1.085	0.0
2012UV136	1.008	1.149	0.868	1.023	0.1
2014YD	1.072	1.165	0.979	1.110	0.0
2009BD	1.062	1.117	1.007	1.095	0.0
2001GP2	1.035	1.109	0.9600	1.053	0.0
2015KK57	1.090	1.159	1.022	1.139	0.0
2008JL24	1.038	1.149	0.928	1.058	0.1

The interplanetary mission analysis has been performed using a fast and reliable sequential convex programming

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* See https://minorplanetcenter.net/; last accessed in April 2024.

algorithm a previously developed method employed in the RAMSES mission towards the Apophis asteroid (see [2]). The assumptions applied are reported in Table 4. The analysis considers two-body problem dynamics, with the Sun as the central body. Considering the characteristics of the baseline launcher (Ariane 6), the infinity velocity at the Earth sphere-of-influence interface has been constrained to be lower than 4 km/s, leaving the declination and right ascension as free parameters (measured in the J2000 reference frame). Additionally, for the interplanetary cruise computations, only 73 kg of mass propellant are considered (unlike the max 95 kg reported in Section 4). This reduction is to consider additional costs derived from stochastic processes and margins which are added to the interplanetary propellant mass budget. Note that this value will be refined and finalized towards the study completion foreseen in June 2024.

Table 4. Interplanetary mission analysis assumptions.

Type	Description	Value
Time Constraints	Earliest departure date	January 1, 2029
	Max Time of Flight	800-1100 days
	Latest Arrival	December 31, 2030
Spacecraft	Initial wet mass	525 kg
	Thrust	60 mN
	Specific Impulse	1500 s
	Interplanetary propellant mass budget	73 kg
Launcher	Infinity velocity	≤ 4 km/s
	Azimuth	[-180, 180] deg
	Declination	[-90, 90] deg

With these assumptions, several interplanetary cruises for each of the 16 asteroids has been computed. For each feasible trajectory of each target in the identified time window, it has been computed:

- The optimal launch conditions (including infinity velocity, azimuth, and declination).
- The optimal propellant mass required to reach the asteroid.

The results are summarized in Table 5. The propellant mass value refers to the minimum amount of the average propellant mass value required by the trajectory in each of the feasible launch window identified. Additionally, the propellant mass interval refers to the minimum and maximum propellant mass used between all trajectories which are feasible. A feasible window is defined as a zone where the required propellant mass is less than the 73 kg constraint, as identified in Table 4 An asteroid is said to be “not feasible” if its porkchop shows no feasible launch windows. The feasibility of each asteroid is classified depending on the percentage of reachable trajectories which are feasible, each level defined as: slightly satisfactory if > 0%, satisfactory if ≥ 20%, good if ≥ 40% and very good if ≥ 60% respectively. The absolute percentage is reported for each asteroid.

Table 5. Results of the interplanetary mission analysis for each asteroid.

Asteroid	Feasibility Comment	Propellant mass (kg)	Propellant mass interval (kg)
2006CT	Good with 2 feasible launch windows (40%)	60.77	[36.96 to 73.00]
2011CG2	Good with 2 wide feasible launch windows (56%)	52.70	[20.50 to 73.00]
2019NC1	Satisfactory with 2 wide and 2 narrow feasible launch windows (24%)	50.51	[21.36 to 73.00]
2009SC15	Slightly satisfactory with 2 feasible launch windows (9%)	63.53	[51.92 to 73.00]
2022SO113	Satisfactory with 3 feasible launch windows (31%)	62.03	[41.38 to 73.00]
2002LY1	Not feasible, subject to further computations	-	-
2002AW	Satisfactory with 4 wide feasible launch windows (21%)	68.09	[61.80 to 73.00]
2000SG344	Feasible across all launch window (100%)	11.89	[0.52 to 30.18]
2010UE51	Slightly satisfactory with 1 feasible launch window (18%)	66.66	[43.62 to 73.00]
2011MD	Slightly satisfactory with 2 feasible launch windows (4%)	66.78	[59.85 to 73.00]
2012UV136	Very good with 3 feasible launch window (74%)	47.99	[15.04 to 73.00]
2014YD	Slightly satisfactory with 2 feasible launch windows (8%)	63.28	[51.79 to 73.00]
2009BD	Good with 1 wide feasible launch window (46%)	59.23	[37.71 to 73.00]
2001GP2	Slightly satisfied with 3 feasible launch windows (15%)	66.91	[55.99 to 73.00]
2015KK57	Very good with almost all launch window feasible (83%)	47.22	[19.12 to 73.00]
2008JL24	Very good with almost all launch window feasible (69%)	46.21	[19.17 to 73.00]

The results presented above show 15 out of 16 targets reachable, with a substantial amount of them showing positive feasibility windows. Consequently, this behaviour proves and supports the multi-purpose feasibility of the Zodiac Pioneer platform. Note, however, that the maximum time of flight of some asteroids was increased from 800 to 1100 in cases where no feasibility windows were initially detected. Figure 3 reports the porkchop plots related to the reachability of asteroids 2011CG2, 2022SO113 and 2012UV136 (from left to right) under nominal conditions. The x-axis represents the departure date, the y-axis the tune of flight, the colour code represents the propellant mass, and the dashed black line represents the available interplanetary propellant of 73 kg.

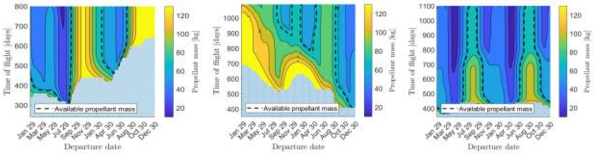

Figure 2. Propellant mass porkchop plot for asteroids 2011CG2, 2022SO113 and 2012UV136 (from left to right).

4. Baseline platform

The proposed Platform leverages on Tyvak avionics modules, designed to support satellite applications ranging from 6U nanosatellites up to 500+kg small satellites. The Spacecraft Bus envisioned for Zodiac Pioneer mission heavily leverages Tyvak's reference Nebula/Ambassador platforms, which evolved from Tyvak microsatellite class of buses. The core platform allows a scalable battery module and modular Power Control and Distribution Unit (PCDU) configuration and is suitable to accommodate a variety of propulsion solutions. Furthermore, the standard platform includes a dual-string redundant design that allows modular avionics architecture to tune the vehicle performance according to the mission needs. The Platform is equipped with a processing unit designed by Tyvak, with a radiation tolerant watchdog microcontroller for hot-swap redundant functionality. The processing modules also include on-board storage for housekeeping telemetry collection. The Guidance, Navigation and Control (GNC) software runs on the same processing unit, and interfaces with multiple AOCS sensors (star trackers, Inertial Measurement Unit (IMU), sun sensors) and actuators (reaction wheels, and propulsion system both selected according to the mission scenario). The Non-Recurring Engineering (NRE) effort for Zodiac Pioneer Spacecraft is expected to be focused on mechanical/electrical/thermal design, and specifically associated to the mission-specific propulsion and communication system integration, the main structure, and the payloads accommodation and interface. Finally, modifications to the AOCS subsystem and associated flight software will be needed for this mission, due to the synergistic development of the subsystem with an experienced partner such as GMV.

At the current stage of the study, the Zodiac Pioneer satellite high level configuration is summarized below (and shown in the following figures):

- Tyvak Core Avionics.
- 525 kg mass specification for the satellite
    - Including propellant (Xe) max capacity 95 kg.
    - Including 20% System Margins.
- Approximate size
    - Main body: 1m x 1m x 1m.
    - Solar wing: 3.5m x 1m.
- 1.8 kW class solar array (@1AU).
- Payload Capacity: 50 kg (including 2x CubeSats).
- Electric Propulsion: 45-90 mN gimballed main thruster.
- X-Band links with Earth via HGA + 2x LGAs (omni coverage).
- 75 cm class HGA dish.
- Total data volume: 305 MB.
- Monopropellant RCS enabling momentum management and agility near the target.

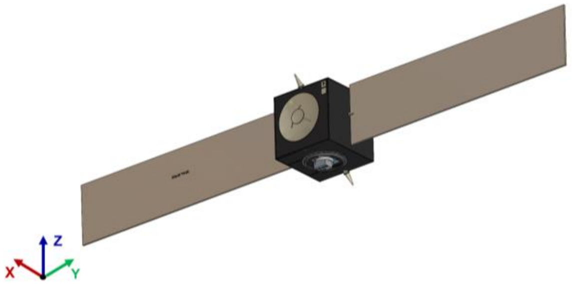

Figure 4. Zodiac Pioneer space vehicle first high-level concept, HGA face and lower deck (deployed configuration).

Figure 5. Zodiac Pioneer space vehicle concept, Payload and top decks (deployed and stowed configuration).

Some details on the various subsystems are hereafter presented.

Electrical Power System

- **Steerable Solar Array**, 2 wings with 1 DOF SADA each. Each wing has 3 panels + yoke. Power generation 1.8 kW @ 1 AU.
- **4x MPPT Modules**, 2x for each solar array wing.
- **4x Battery Packs**, for LEOP, detumbling, and contingency transitions. 660 Wh total capacity.
- Power distribution through dedicated DC rails and Point of Load modules for local switching and protection.

ADCS/GNC Sensors

- **2x Star Tracker** modules in hot redundancy.
- **1x Gyro Assembly** in (internal) hot redundancy.
- **Coarse Sun Sensors**, providing omnidirectional coverage.

- **2x** cold redundant **NACs (Narrow Angle Cameras)**, used as navigation cameras ± payload.
- **2x** cold redundant **WACs (Wide Angle Cameras)** to support navigation.
- **2x** cold redundant **Laser Altimeters** (supporting also the hoovering phase).

AOCS Actuators

- **4x Reaction wheels** in tetrahedral configuration**.**
- **Monopropellant RCS system,** with 8+8 thrusters in cold redundancy (A/B branches).
- **EP system with** Hall Effect Thruster, mounted on 2 DOF gimbal.

Communication System

- **2x X-Band Deep Space Transceivers**, with RX hot redundancy, TX cold redundancy, ESTRACK compatibility, ranging capability.
- **2x Low Gain Antennas (LGA),** each providing hemispherical coverage (contingency and low data rate communications).
- **1x High Gain Antenna (HGA),** with 0.75 m parabolic reflector (nominal TT&C and payload data downlink).
- **2x X-Band TWTAs, 70 W RF out each,** in to provide the required amplification both for the HGA and LGAs.
- **RF Distribution Network**, including diplexers, isolators, switches, wave guides, RF harness, etc.

As notable, Tyvak avionics use can be maximized, together with some Deep Space flight heritage (TRL9) equipment currently baselined (e.g. Reaction Wheels, IMU, Deep Space Transponder, etc.).
The subsystems definition is the result of a first round of an RFI (Request For Information) campaign to European suppliers that Tyvak International managed aiming at closing trade off and define a baseline configuration. The current selection is driven by the following main drivers: technical solution and requirements compliance, Technology Readiness Level / Qualification Status, programmatic aspects (lead time and cost).

Internal configuration uses a set of ribs to support the loads and all the modules inside of the spacecraft. Accommodation analysis effort is executed along with structural and thermal analyses. Indeed, although the main propulsion system tank is positioned in the center of the satellite, the different subsystems accommodation on the different panels needs to optimize the AI&T flow, the harness complexity and routing and thermal performances. As such, refinements are foreseen to be implemented towards the study completion (June 2024).

4.1 Payload Equipment

Although the study currently focuses on the definition of a baseline platform configuration for the proposed mission(s), a high-level assessment of the payload part is being tackled.
Current payload suite of Zodiac Pioneer Mission is composed by:

- 2x 6U CubeSats.
- 2x Asteroid Framing Cameras (AFC).
- Opportunity Payload to be defined.

2x 6U CubeSats

Based on HERA design and heritage, CubeSat can host a variety of additional payloads to add scientific value to the mission; as baseline, the following are considered: low frequency radar, gravimeter, seismometer, high resolution camera, dust detectors, retroreflectors. It is important to be noted that CubeSats were not included in the study objectives, so the CubeSats payload suite is to be defined. Tyvak International can leverage on the development of the Hera Milani CubeSat to propose suitable payloads and to estimate constraints and performances. Regarding the mass budget, considering Cubesats, Deep Space Dispensers and electrical interface (“Life Support Interface Boards”), the total CubeSat associated mass is ~39 kg.

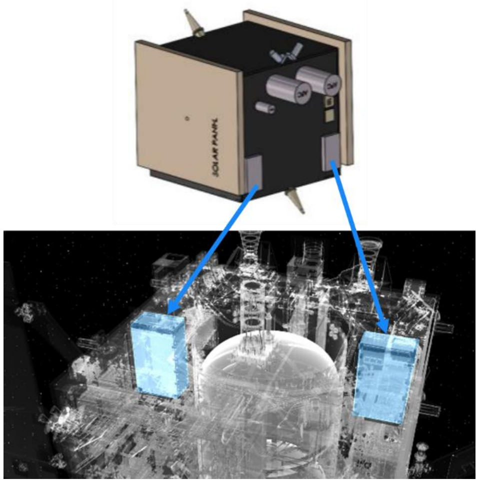

Figure 6. Zodiac Pioneer CubeSats (Hera CubeSats accommodation is shown in the bottom picture as reference).

2xAsteroid Framing Cameras (AFC) - Cold redundant system

2x Narrow Angle Cameras (NAC) - Cold redundant system
Zodiac Pioneer mission foresees two Asteroid Framing Cameras (AFC), used for the scientific asteroid proximity operations as well as Navigation Cameras with narrow field of view. RFI campaign for this system is executed by GMV, responsible for the GNC subsystem and final trade-off is under finalization and

will be completed for the study completion. Considering the worst-case equipment selection (from the mass point of view).

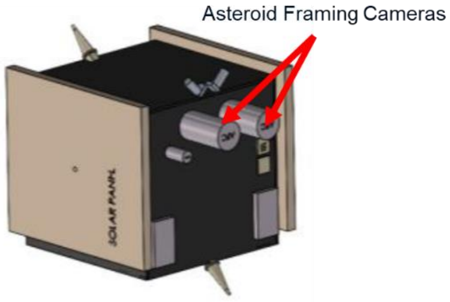

Figure 7. Zodiac Pioneer Asteroid Framing Cameras.

Opportunity Payloads to be defined

Extra mass and volume are reserved for the purpose of accommodating additional payloads. The total mass available for Additional Payloads is **~6 kg.**

4.2 System Budgets Assessment

The platform study includes system budget computation as part of the platform feasibility assessment for the Zodiac Pioneer mission. The system budgets considered are:

- Mass Budget
- Power Budget
- Link and Data Budget

The systems budgets are also correlated with specific sensitivity analysis to consider the variation of sensible mission parameters, and the impact of critical components.

The Margin Philosophy adopted follows the ECSS standard: maturity margins are applied on single items, depending on the equipment development maturity, plus a system margin of 20%.

Mass Budget. The budget considers the allocation of components, structure, and propellant mass to compute satellite dry (no propellant) and wet mass. This information is essential for the mission analyses computation, both for interplanetary analysis and trajectories down-selection and for the close proximity operations and manoeuvres analysis. These figures are important also to define an envelope for the available payload mass. The following subsystem-level assumptions have been made to define a baseline:

- Single-string EP system
- Redundant COMMSYS (except for antennas), no SPFs up to antenna ports
- Redundant core avionics (OBDH, EPS, ADCS), no SPFs at equipment level
- Redundant GNC/Payload sensors (Cameras, Altimeters)

Power Budget. The budget considers the main power modes associated with the key operative phases. The spacecraft is assumed to have 2-DOF control on the solar array orientation in most modes, thanks to the integration of the SADA. The EP reference operating point of at least 60 mN Thrust and 1500 s Isp has been considered. A model of the power available to the thrust as a function of distance from the Sun has been computed.

Power balance has been carried out considering two cases:

- A Hot Case at a chosen minimum distance from the Sun (set for now at 0.75 AU) in which the operating point of the thruster can be pushed to maximum power
- A Cold Case at a maximum distance from the Sun (set for now at 1.2 AU) in which throttling of the thruster can be considered.

Link Budget and Data Budget. The link budget is computed to assess the performance of the Earth-spacecraft communications link via HGA and LGA. The data budget is computed to identify the maximum distances allowed for the antennas to provide a downlink data-rate able to comply with the data return volume of the mission.

The Budgets have been computed considering:

- Maximum Earth-Spacecraft operating distance set at 0.75 AU
- Start of the Asteroid Proximity Operations Phase, determined at 0.23 AU

5. Launch compatibility assessment

One of the main driver of the study is to reduce the mass of the spacecraft and consequently the launch cost, and increase launch flexibility. Accordingly, a launch compatibility high level assessment was performed in the frame of the study. It has been performed in two steps:

- **Level One Compatibility**: Environmental conditions that the platform must be able to withstand, considered in the design of the platform (or checked once the design is almost finalized). They include vibration, shocks, and acoustic loads.
- **Level Two Compatibility**: Additional requirements that can be easily accommodated by most platforms but need to be accounted for. Among these, standard mechanical and electrical I/F, documentation, test activities, mock-up requirement, schedule etc. Finally, the info about the escape velocity of the specific launch vehicle.

The assessment was performed considering Zodiac Pioneers mission with a mass higher than 400 kg, noticing that the mass will be refined towards the study completion. The two main launchers considered are Falcon 9 and Ariane 6, based on reliability and flight frequency regarding multiple mini-sat launches. The Modal Analysis showed that the spacecraft’s first global frequencies comply with LV Stiffness Requirements, and Static Analysis showed acceptable displacements.

6. Results and Discussion

The main objective of this study was to identify a platform configuration able to reach the highest number of target with minimum design tuning / modifications. The main outcome shows that among the 16 considered targets, just 2 (2002LY1 and 2009SC15) are not reachable using the conceived design: 2099SC15 and 2002LY1.

To ensure the compatibility with missions to the reachable asteroids, a tuning of the following parameters would be required:

- EP propellant and payload masses (optimized to the mission).
- Transponder Tx data rates.
- External radiator coatings (for Thermal Control System).

7. Conclusions

Zodiac Pioneer program feasibility study phase was completed in June 2024. It represents a breakthrough in the Planetary Defence and small body exploration roadmap, which could lead to new and novel mission scenarios in the characterization of potentially hazardous objects. Furthermore, at the current state of the art, absence in Europe of a small satellite based on Electric Propulsion System for deep space missions gives to this study a paramount innovation value.

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