Interplanetary CubeSats for asteroid exploration: Mission analysis and design

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Interplanetary CubeSats for Asteroid Exploration: Mission Analysis and Design

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Abstract: Recent advances in CubeSats technology are leading the transition from purely education tools to actual scientific missions. The small volumes and masses, the versatile purpose, as well as the fast development time associated with a potential high return-to-cost ratio are at the origin of the increasing number of new mission architectures, also beyond low Earth orbit (LEO). The purpose of this study is to assess the CubeSats ability to complement an interplanetary scientific mission. The proposed AIDA (Asteroid Impact and Deflection Assessment) mission, an ESA/NASA joint effort with the purpose to demonstrate the kinetic impact technique to change the motion of an asteroid in space, has been selected as case study, having a mission context particularly suitable in showing CubeSats supporting capabilities. The feasibility study of a mission involving the use of CubeSats as secondaries for technology demonstration and science purposes was performed. Mission objectives and requirements was defined, followed by the development of concepts of operations and mission architectures proposals. Eventually, multiple trade-off tools were adopted to define the proposed mission baseline, which involves the deployment of two 3U CubeSats performing a detachment to achieve the final configuration of one 2U and four 1U CubeSats. The scientific campaign conducted by the CubeSats includes gravitational and magnetic field mapping, on-surface chemical-physical measurements via multiple wide chip-size-sensor nets deployed from orbit, on-surface seismic measurements via landing of the 2U CubeSat, direct observation of the impact from multiple viewpoints and evaluation of the asteroid's orbit deflection due to the impact. The mission proposed involves also some important technological demonstrators. The S-iEPS (Scalable-ion Electrospray Propulsion System) has been considered as propulsion system, while a potential landing system has been proposed to achieve the soft touchdown of the 2U CubeSat. Finally, an inter-satellite communication link via laser has been included as main communication system. The proposed mission baseline has shown that CubeSats can be successfully integrated as multi-platform systems to provide useful support to interplanetary missions. This solution may enable the capability to acquire more detailed information with the possibility to combine them to obtain better results with respect to single-platform systems. The proposed mission concept represents a valuable low-cost piggyback solution adaptable to several mission contexts, with a potential high return and a remarkable attitude for the implementation and testing of new technologies and operations. In this context, this study provides a useful framework for the design and development of interplanetary CubeSats missions.

Keywords: CubeSat, Interplanetary mission, Asteroid exploration

Acronyms/Abbreviations

AHP	Analytical Hierarchy Process
AIDA	Asteroid Impact and Deflection Assessment
MarCO	Mars Cube One
MP	Mission Phase

AIM	Asteroid Impact Mission	MS	Mission Scenario
ConOps	Concept of Operations	NASA	National Aeronautics and Space Administration
CER	Cost Estimating Relationship	NEA	Near-Earth Asteroid
COTS	Commercial Off The Shelf	QFD	Quality Function Deployment
DART	Double Asteroid Redirection Test	S/C	Spacecraft
EDL	Entry Descent Landing	SHA	Stakeholder Analysis
ESA	European Space Agency	S-iEPS	Scalable-ion Electrospray Propulsion System
FFBD	Functional Flow Block Diagram		
FoM	Figure of Merit	SMA	Semi-major axis
FY	Fiscal Year	SRP	Solar Radiation Pressure
GNC	Guidance, Navigation and Control	STM	Science Traceability Matrix
IMU	Inertial Measurement Unit	STK	Systems Tool Kit
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport	TRL	Technology Readiness Level
INSPIRE	Interplanetary NanoSpacecraft Pathfinder In Relevant Environment	USD	United States Dollars
IR	Infrared	1U	One unit CubeSat
ISRU	In-Situ Resource Utilization	2U	Two units CubeSat
LEO	Low Earth Orbit	3U	Three units CubeSat

1. Introduction

CubeSats were originally conceived as education tools, as well as low cost technology demonstration platforms with a fast development time. However, recent CubeSat technology advances are leading the transition to actual scientific mission, promising small volumes and masses, versatile purposes and potential high return-to-cost ratios [1]. The idea of a CubeSat-based multi-platform system comes with the possibility to decompose the capabilities of a single large satellite into a cluster of smaller, single-purpose satellites (i.e. CubeSats). This strategy may enable the acquisition of more detailed information and the possibility to combine them to obtain better results with respect to single-platform systems [2]. The reduction of development cost and time introduced by the CubeSat platform standard, together with the use of Commercial-Off-The-Shelf (COTS) components and miniaturized technologies are leading to several potential new mission architectures, also beyond low Earth orbit (LEO) [3].

Several CubeSat missions beyond LEO have been proposed, from space weather evaluation at Earth-Sun libration point L1 [4] to dust and radiation studies at Jupiter's moon Europa [5], very low frequencies radio astronomy at the lunar lagrangian point L1 [6] and many others. CubeSats missions proposed cover three main classes of applications: technology demonstration, mission operations, science. This shows the increasing relevance of the role the CubeSats are going to play in the future space exploration missions. As originally conceived, *technology demonstration* class missions regard the use of CubeSats for technology validation and testing in a relevant environment. *Operations* class missions regard, for example, the use of CubeSats as telecommunication relay during critical mission phases, to support manned missions or to facilitate teleoperations. *Science* class missions regard the use of CubeSats to conduct secondary or even primary science or reconnaissance [7]. Examples of proposed CubeSats missions beyond LEO include NASA's INSPIRE (Interplanetary NanoSpacecraft Pathfinder In Relevant Environment), a proposed *technology demonstration* class mission involving a small satellite platform for navigation demonstration beyond the Moon [8]. On the other hand, the MarCO (Mars Cube One) twin CubeSats represent the first *operations* class mission attempting to use small satellite platforms for interplanetary telecommunication relay during the critical EDL (Entry, Descent, Landing) phase of the NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission [9]. Finally, the NEAScout (Near-Earth Asteroid Scout) mission has been proposed as a *science* class precursor expedition to perform reconnaissance duties before committing a crewed mission to visit a NEA [10].

This study focuses on a proposed asteroid exploration mission involving the use of CubeSats as secondaries for technology demonstration and science purposes. The reference mission is ESA's AIM (Asteroid Impact Mission) which is part, along with NASA's DART (Double Asteroid Redirection Test), of the joint mission AIDA (Asteroid Impact and Deflection Assessment) which has the purpose to demonstrate the kinetic impact technique to change the motion of an asteroid in space [11]. In 2016, AIM failed to get the financial support it needed, bringing to the cancellation of the mission proposal [12]. Despite this, the objective of this paper is to assess the CubeSats ability to complement an interplanetary scientific mission. AIM has been selected only as a case study, having a mission context particularly suitable in showing CubeSats supporting capabilities.

This paper summarizes the proposed mission, highlighting the CubeSats capabilities in support of an interplanetary mission for asteroid exploration, and describes the mission analysis and design process used to determine the mission baseline. Section 2 reports the preparatory activities needed to structure the mission, as the definition of mission objectives and requirements. The Section 3 describes the mission implementation and analysis, including the definition of the concept of operations and the mission architecture, and the trade-off tools used. The Section 4 summarizes the mission design results, presenting the description of the mission baseline. The last section provides also an overview on future developments.

2. Mission Definition

This section introduces an overview of the preparatory activities to structure the mission. Firstly, the main purposes of the mission are analyzed. The process of identification of mission purposes is closely linked to fill scientific and technology gaps, outlined among three different levels: increase the knowledge of asteroids in terms of dynamics and composition, test deep space technologies and operations, understand the effectiveness of the impact risk mitigation technique implemented. Secondly, the main actors involved in the mission are identified, performing an accurate understanding of mission stakeholders, identifying objectives, goals, needs and values for each one of them, the so-called stakeholder analysis. Then, once the problem and involved actors have been identified, it is possible to define the mission statement, in terms of identification and characterization of mission needs, expected performance, dependability and goals, and, finally, the high-level mission objectives of the proposed CubeSat mission.

2.1 Mission Context

The preliminary step was to understand the overall mission context and the operational environment. This study will be the input for the identification of mission requirements.

65803 Didymos is a binary Apollo class asteroid. The secondary body, called Didymoon, orbits the primary on its equatorial plane. A virtual representation of the binary system is shown in Fig. 1.

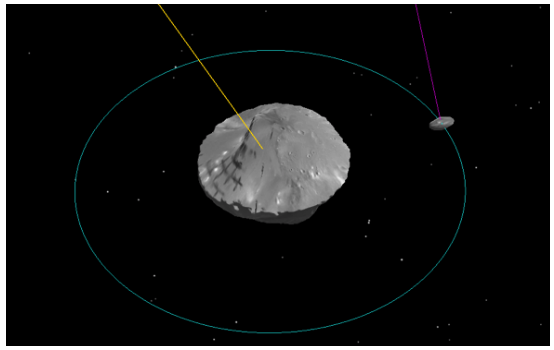

Fig. 1. Virtual representation of the binary asteroid system.

Didymos is classified as an S-type asteroid, and ground-based observations revealed that the system is composed mostly by silicates (Nickel and Iron) [13]. Unfortunately, radar observations could not provide useful data about the secondary body. The proposed mission, exploiting CubeSats for interplanetary mission, is part of a huge international project, AIDA, carried out by a partnership between ESA and NASA. DART (Double Asteroid Redirection Test), the NASA's probe, is expected to impact Didymoon at high speed. The European's counterpart, AIM, will remain in orbit around Didymos for several months before and after the impact, characterizing the target body and monitoring the impact event. The proposed mission must support and boost AIM's main mission. AIM mother ship will carry the CubeSats in proximity of Didymoon, where they will be released. The major objectives of AIM's mission are to collect high-resolution images, to perform thermal and radar mapping, to produce a detailed map of the surface, as well as to provide information on the effects of DART's impact. Once at destination, AIM will start the asteroid study, determining characteristics and surface properties, bulk and dynamic state. Before moving back at the safe distance of 100 km, which should be held during DART crash, AIM will release the CubeSats. After the impact, AIM will approach again the asteroid, performing a second campaign of observations in conclusion of the mission [14]. CubeSats can be defined as a discrete but scalable 1 kg, 100x100x100 mm, cuboid spacecraft unit (dimensions referred to one unit, 1U), adopting standard design specifications [15]. AIM was expected to accommodate up to six CubeSat units divided into two 3U deployers.

Unfortunately, at the end of 2016, AIM did not receive enough funds from ESA and the mission proposal was cancelled. However, NASA will continue with DART mission and the effect of the impact will be monitored by ground telescopes [16].

2.2 Mission Objectives

The process of identification of mission purposes is closely linked to filling the gaps with knowledge and technological targets, which can be outlined over three different levels:

- Increase in the limited knowledge of the asteroids (orbits, chemical composition, morphology, resources etc.): a thorough understanding of these bodies is strongly requested by the scientific community. Asteroids characteristics resemble those of primordial planet, and an accurate analysis may shed light on how our Solar System originated and evolved over time.
- Technological advancement: this deep space mission would constitute an excellent opportunity to test new technologies that might be useful in future interplanetary explorations, even outside the Solar System (e.g. improvement of communication technologies, such as laser communication).
- Risk mitigation: studying the possibility of diverting orbit of extra-terrestrial bodies would constitute a first step in a risk mitigation plan that for the first time includes an active intervention towards the prospective threat.

To fully capture the mission purposes essence and translate it into accurate mission objectives, it is necessary to perform a thorough analysis of needs, values, and influences for every mission stakeholder. The term *stakeholders* specifically refer to those actors (e.g. public organisations, academia, private commercial initiatives, NGO, etc.) who either manifest a direct or indirect effect on the mission or receive direct or indirect benefits from the mission activities. The stakeholders' analysis was carried out in three steps.

The first step involves the identification of the stakeholders by using a set of key questions framed to reveal all cause-effect relationships and to not neglect any aspect related to the realization of the mission: Who pays? Who is going to use the information? Who is involved? [17]. This analysis led to the identification of numerous stakeholders, of which the most significant are shown in Tab. 1.

Once stakeholders and their respective roles are outlined, a rigorous analysis involves an appreciation of the ultimate objectives of each stakeholder, as well as an in-depth understanding of what are the needs and values that move them. Tab. 1 summarizes stakeholders needs and values, that will deserve for mission objective development.

Tab. 1. Mission Stakeholders' values.

Stakeholder	Needs	Values
Space agencies	Successful scientific mission, test new technologies, find funds	Successful, not expensive, simply operations, easily realizable, not risky, scientific knowledge return, technological test, external support, visibility, respect of standards and laws
Scientific community	Investigate asteroid features and origins	Successful, scientific knowledge return, technological test
Governments	Political advantage on the mission, plans and reports of demonstrated progress	Successful, not expensive, approval and visibility, respect of laws and standards
General Public	Improvement of technologies, new information	Usefulness, successful, not expensive, technological improvement

The *space agencies* are entities that provide the means with which to expand human knowledge of Earth and space. They are responsible for program organization, management, data acquisition, and providers of products and services derived from the accomplishment of the mission. For these reasons, the Space Agencies express the needs of the development of a successful scientific mission, intended as a mission that has the capabilities to achieve, in the most effective way, every mission objective to have the required scientific-return-to-cost ratios. As already mentioned, being relatively low-cost, this mission represents for the Space Agencies a good opportunity to test new technologies to be used in future mission. Many of these agencies are governmental entities, that have the need to get funds and resources from other actors (e.g. governments or NGOs) to develop the mission.

The *scientific community* represents the totality of scientist, engineers and theorists, and their relationship and interactions, involved in the scientific research process. Obviously, the main needs deriving from the success of the mission involved the acquisition of data useful to investigate asteroid features and origins, but also the development of new technologies represent important values of a huge part of this community.

The *governments* are the organizations that take over the political and economic responsibilities of every State. Governments could take political advantages on the mission because their economic and political grant is the primary contribution to the development of the mission.

In the *general public* eye (intended as the whole population generally not interested in the mission aim), the governments are the makers of the mission.

To better understand the relationship that need to be established among the various stakeholders, it is useful to create a network model to highlight the values flow, as shown in Fig. 2. In this figure, also the minor stakeholders involved are present.

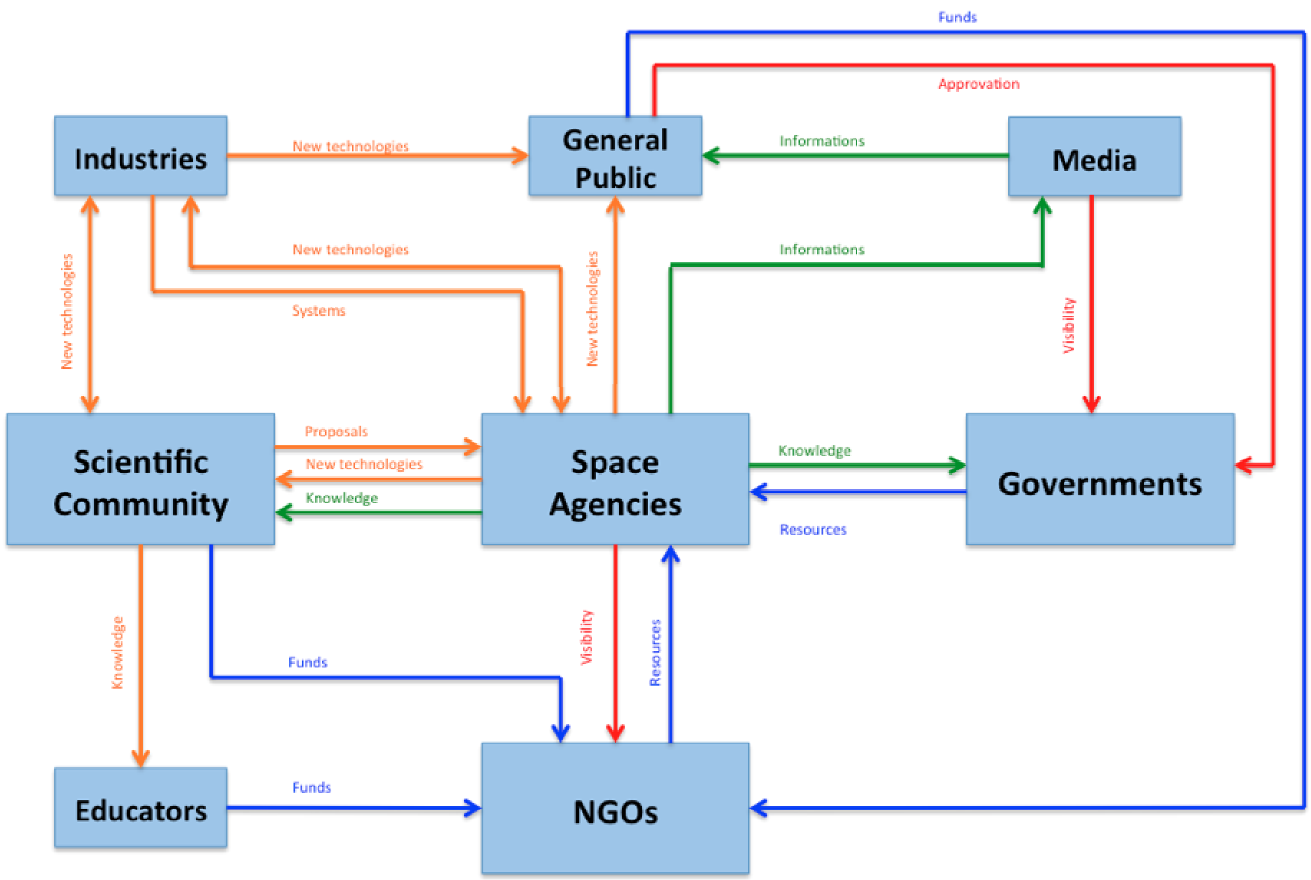

Fig. 2. Stakeholders interactions.

Once the values of each stakeholder are outlined, a mathematical tool was used to rank them to prioritize the objectives of the mission that must be achieved. This tool is a QFD (Quality Function Deployment) analysis and helps identify which are the more important needs to be satisfied and, eventually, any area of conflict among the values of each stakeholder that participate in the mission development [18]. From this analysis two main conclusions have been achieved.

- Among the most important values, the successful accomplishment of the mission is placed, along with the necessity to maintain limited costs and the need to assure a useful scientific knowledge return.
- The need to keep costs low collides with most of values involving a technological advance and return of knowledge, as well as with the probability of success of the mission. It is important to take care of this aspect because it could undermine the relations between founders and developers.

Starting from the outcomes deriving from the mission purposes study and the stakeholder's analysis, the mission statement was then produced and reported below.

The proposed CubeSats mission aims to address three main topics concerning science, support to the primary mission and technology demonstration. Regarding science, the CubeSats mission aims **to increase the scientific knowledge** about asteroids to answer the many open questions about the origin of the Solar System. On the other hand, the deployment of CubeSats devices aims **to support the AIDA mission**, **providing technical know-how** about trajectory deflection with the goal to prevent the possibility of an impact with an extra-terrestrial body.

Finally, the implementation of technology demonstrators aims to test, in a relevant environment, **new advanced technologies** that could be leveraged for future missions in deep space and terrestrial application.

As highlighted in the mission statement above, the primary role of the CubeSats lies in the support of AIM in the study of asteroid characteristics, as well as in the assessment of trajectory deflection capabilities. CubeSats limited size and autonomy impose specific constraints on their capability to entirely fulfil all mission objectives. For this reason, CubeSats intervention shall avoid any duplication in AIM capability, by leveraging those objectives and technologies that might help fill the gap and maximize complementarity with AIM mission. The high-level objectives of the mission, and the scientific objectives, are summarized in Tab. 2**.**

The main scientific objective is to photograph and to study the DART's impact with Didymoon. At that precise moment, in fact, the CubeSats are the only ones with a good sight of the phenomenon, since AIM is far 100 km. It is important analyse the sequence of the formation of the crater, the ejected dust composition and concentration and the physical properties of minerals through the measure of the surface temperature and thermal inertia. Moreover, the CubeSats support AIM to calculate the orbit deflection, one of the most important objectives of the AIDA mission, by evaluating the variation of the eclipse period. The objectives derived from the Didymoon's physical properties study are categorised as secondary scientific objectives. The results can reveal the key answer to the first materials that have formed the Solar System and could give us the possibility to understand its origin and formation. In addition, the study of the magnetic and gravity field is performed to learn more about the asteroid's properties with the aim to help defining better techniques to modify the trajectory for planetary defence. Finally, a CubeSat landing on Didymoon would help probing its internal structure with on-board seismic instruments. This solution would also be a new technological achievement, since CubeSats never have landed on an asteroid before.

Tab. 2. High-level and Scientific Objectives.

Mission Goals	High-level objectives	Scientific objectives
To increase scientific knowledge	To study the DART's impact and its effects	To measure the crater formation
		To study the produced dust
		To measure the crater temperature
	To study Didymoon's physical properties	To measure magnetic field
		To measure gravity field
		To acquire shape and dimension
		To study superficial composition
		To measure superficial temperature
		To measure seismic properties
To provide technical know how about trajectory deflection	To study Didymoon's deflection	To measure variation of ecliptic period
To support AIDA mission	To pursue complementary objectives with AIM's mission	
	To help AIM in obtaining accurate data by using a different methodology	
To use advanced technologies	To study CubeSat capability to landing	
	To test CubeSat propulsion system	
	To use inter-satellite communication	

2.3 Mission Requirements

As result of the preliminary analysis carried out so far, it is possible to identify the high-level Mission Requirements. The word 'requirement' refers to a sentence written in the form of 'shall' statement that defines what is needed, in terms of restrictions or targets, to fulfil the mission. Their purpose is to switch from a qualitative to a quantitative and technical language. The requirements definition process has been carried out following the standard method suggested by ESA [19].

First of all, mission statement and mission objectives form the basis for the generation of the top-level requirements. Therefore, it is necessary that such requirements do not arise solely from the stakeholders' requests. Indeed, they are subjected to an iterative and recursive redefinition process. Their definition is conducted through the entire initial phase of the project to verify that the elaborated solutions, that come from Concept of Operations, Simulations and Mission Architectures and Cost Analysis, can satisfy stakeholder requests. Other main actors in the mission requirements definition process are environmental constraints that the system meet in the entire mission and operational conditions. In fact, the different environments that the product is expected to encounter during lifetime impose limits to be respected. Additional inputs are constraints and restrictions to be compliant with standards, such as the technical documents by ESA and the CubeSats Design Specification document [15].

The process of generating the requirements is extremely delicate since it requires great attention in respecting contents but also the form and the methods, as well as being compliant with a specific lexis. These aspects to be followed are explicated in the NASA Engineering Handbook [17]. Once the requirements have been identified, it has been considered useful to divide them into two wide sections. *Design & Product Constraints* contains requirements related to limit conditions and high-level analysis, *Function Expectations* includes lower level requirements, among which also system requirements. Among *Design & Product Constraints* are included Design Requirements, Interface Requirements, Environmental Requirements, etc. Among *Function Expectations* are included Functional Requirements, Operational Requirements, Mission Requirements, etc. All Mission Requirements have been categorised according to the classification suggested by ESA [19].

2.3.1 Scientific Requirements

A dedicated section in the Mission Requirements concerns Scientific Requirements, derived by the requests of the scientific community and the related Objectives.

The mission context and the high-level objectives, as well as the prior knowledge about the target body, together constitute the input to scientific requirements specification. By means of a Science Traceability Matrix (STM), it is possible to explicit the logical flow from high-level objectives down to measurement objectives, measurement requirements and instrument requirements. Once the measurement requirements have been established, it is possible to trade off instruments required to achieve the specified measurement targets. The STM contains all high-level information needed to understand why a given proposal is relevant, what is its scientific purpose, how it intends to accomplish the required goals, and what expected products and knowledge would result from its success. Thus, the STM is an input to Concepts of Operations, Functional analysis, Simulations and Mission Architectures. Other indications about STM content may come out from the studies reported in the following paragraphs. These indications could change or complete STM content. Once the STM is complete, requirements could be written.

3. Mission Implementation and Analysis

After outlining mission context and objectives, as well as specifying mission requirements, next step is to focus on mission development and implementation. The objective of this phase is to define different concepts of operations and mission architectures. The purpose of these analysis is to produce a set of possible mission concepts capable to fulfil the mission objectives, respecting all the requirement. This set of ConOps and Architectures will be examined by a trade-off analysis to choose the most appropriate mission concept. As every project activity, it cannot be concluded with a single-shot procedure. It must be carried on with a circular and iterative process allowing the project team to develop the best mission configuration, consistent in all its parts with performance studies, including requirements and mission objectives.

3.1 Concepts of Operations

A Concept of Operations is a well-defined set of phases, scenarios and operations required to meet stakeholders' expectations and mission objectives. The first task is the definition of Mission Phases, to provide a logic organization of the operations, seen from a static perspective. Each Mission Phase can be divided into multiple Mission Scenarios, a dynamic perspective used to describe in a simple sentence what is the operation that should be fulfilled and, when necessary, how it is done. Tab. 3 shows how the mission has been divided in three main Mission Phases; a further division of the second phase in two Mission Subphases has been performed in order to focus on two different aspects of the same main phase, and it is shown in the second column; the third column shows Mission Scenarios in which the Mission Phases and Mission Subphases have been divided.

Tab. 3. Mission Phases, Subphases, and Scenarios.

<table>
<tr><th>Mission Phase</th><th>Mission Subphase</th><th>Mission Scenario</th></tr>
<tr><td colspan="2" rowspan="4">Deployment & Commissioning</td><td>Deployment</td></tr>
<tr><td>Primary systems checkout</td></tr>
<tr><td>In-orbit insertion</td></tr>
<tr><td>Payloads' checkout</td></tr>
<tr><td rowspan="12">Science & Technology demonstration</td><td rowspan="9">On-orbit operations</td><td>Before impact maneuver-free mapping</td></tr>
<tr><td>Impact observation</td></tr>
<tr><td>Impact consequences evaluation</td></tr>
<tr><td>After impact maneuver-free mapping</td></tr>
<tr><td>Propulsion system activation and tests</td></tr>
<tr><td>Maneuvers tests</td></tr>
<tr><td>Before impact maneuver-assisted mapping</td></tr>
<tr><td>After impact maneuver-assisted mapping</td></tr>
<tr><td>Chip-size-sensor nets deployment</td></tr>
<tr><td rowspan="3">Landing & On-surface operations</td><td>Descent</td></tr>
<tr><td>Touchdown</td></tr>
<tr><td>On-surface science</td></tr>
<tr><td colspan="2" rowspan="3">Disposal</td><td>On-orbit disposal</td></tr>
<tr><td>Propelled disposal</td></tr>
<tr><td>On-land disposal</td></tr>
</table>

Tab. 3 suggests that a single phase/subphase usually contains more than a single scenario, which represents a set of information. In addition to the operation itself, it contains also the operative modes that can be used in performing the operation, the environment that can be encountered and other characteristics of the operations to perform, namely duration, constraints and potential off-nominal events. Notice that in Tab. 3 the full set of MS is reported, but not every ConOps developed contains all of them. In fact, some of them must be chosen in a aut-aut way (e.g. mapping can be done both using maneuvers or without them, and two different scenarios describe the modalities separately).

Different operative modes (set of functions defining an operational status for the spacecraft) have been designed to complete each MP/MS, since different operations need different operative modes (e.g. a scientific mode prioritizes observations and measurements, so it should be used for observations, while a maneuver mode prioritizes the propulsion system and it should not be used for observations, but for maneuvers only), and those are reported in Tab. 4, with two additional columns, describing their main usages and phases/scenarios in which the operative mode could be used, respectively.

Tab. 4. Operative modes.

Mode	Main usages	Phases/Scenarios
Checkout Mode	Activation of the system, systems checkout	Deployment and commissioning phase
Basic Mode	Simple anomalies resolution, stationary state	All
Mapping Mode	To map vector fields on-orbit	Mapping scenarios
Science Mode 1	On-orbit scientific operations	On-orbit operations subphase
Science Mode 2	On-surface scientific operations	On-surface science scenario
Landing Mode	To perform landing operations	Descent and touchdown scenarios
Disposal Mode	Shutdown of the system	Disposal phase
Safe Mode	Deep recovery of the system	If anomalies occur

The duration of scenarios may vary between a few minutes to several weeks, depending on the scenario itself. In particular, it depends on factors such as the number of low-level operations and the duration of every operation. Some of the constraints found with the MP/MS subdivision method became requirements in the iterative mission development process.

Different combinations of phases and scenarios allowed the development of six different ConOps, summarized in Tab. 5. A brief description is needed to understand the summary. Each ConOps is similar to the previous one, the modifications are minimal and performed incrementally to take in consideration different accomplishment levels.

- ConOps 1 represents the first approach in developing a set of operations to be performed to complete the mission, and the main characteristic is that it is composed just by a minimum set of operations. In particular, it is a maneuver-free ConOps, in which the observations are performed without a propulsion system helping in the tasks.
- ConOps 2 is similar to ConOps 1: the main difference is that a propulsion system is added as a testing payload. Bearing this in mind, ConOps 2 is still maneuver-free, since the propulsion system should not be seen as a subsystem of the probe.
- ConOps 3 uses the propulsion system as a subsystem. Maneuvers are now possible, so mappings can be done with more freedom.
- In ConOps 4 a landing is performed as a technology demonstration, before the disposal of the satellite.
- In ConOps 5 the landing introduced in ConOps 4 is performed and, in addition, scientific objectives are achieved, namely the study of the surface and some post-impact seismic properties.
- In ConOps 6 the landing is performed before DART's impact, to study it also from a seismic perspective.

Tab. 5. ConOps Characteristics.

ConOps	Characteristics	Science Objective Achieved	Technology Objectives Achieved
1	Minimum set of operations: deploy, on-orbit science operations, disposal	Maneuver-free vector fields mapping, impact observation, deflection determination, surface morphology analysis	Inter-satellite link
2	Propulsion testing (no maneuvers' design, orbits propagate without a control system)	Same as ConOps 1	Inter-satellite link, propulsion system testing
3	Maneuvers are possible and the orbits' design is used to assist the mapping	Same as ConOps 1 + maneuver-assisted mapping of vector fields	Inter-satellite link, propulsion system testing, orbit control
4	Cubesat(s) landing after DART's impact	Same as ConOps 3	Inter-satellite link, propulsion system testing, orbit control, Didymoon landing
5	Cubesat(s) landing after DART's impact and surface's properties study	Same as ConOps 3 + surface properties study	Same as ConOps 4
6	Cubesat(s) landing before DART's impact	Same as ConOps 5 + impact seismography study	Same as ConOps 4

An accurate trade-off of ConOps must be carried out to choose the most appropriate one. The ConOps evaluated in the trade-off were initially six. The iterative process involving also mission simulations made clear that two ConOps were not compatible from a functional viewpoint. In particular, ConOps 1 and ConOps 2 have been rejected. Such ConOps were proposed as maneuver-free designs, but simulations eventually confirmed that the propulsion system, considered as a functional system, not as a testing payload, is mandatory.

3.2 Functional Analysis and Mission Simulations

The main objectives of this analysis are the development of a functional architecture which might help in the selection of the best ConOps to implement, the exploration of all possible related incongruences that might occur in a mission concept, and the construction of high level evaluation strategy helping architecture definition and mission debugging. The following tools have been used.

- Functional tree, that allows to break down a system into its low-level components and gives the possibility to take a functional perspective.
- FFBD (Functional Flow Block Diagram), that indicate the sequential relationship of all functions that must be accomplished by a system.
- N2 diagram, that relates the systems functions highlighting the mutual influences [20].

The steps followed to perform the analysis are presented in Fig. 3. The whole process is iterative. Starting from the mission requirements, mission architectures, simulations and ConOps drafts, the functional trees for each combination of them is developed, then the FFBDs and at last the N2 diagrams. At the end of each step the new outputs are reinserted in the cycle starting from the beginning, influencing requirements, mission architectures, simulations and ConOps since a functional architecture is developed. This is the main output for Mission Architectures where, from the Functional Trees, the Functions-Systems matrices are developed.

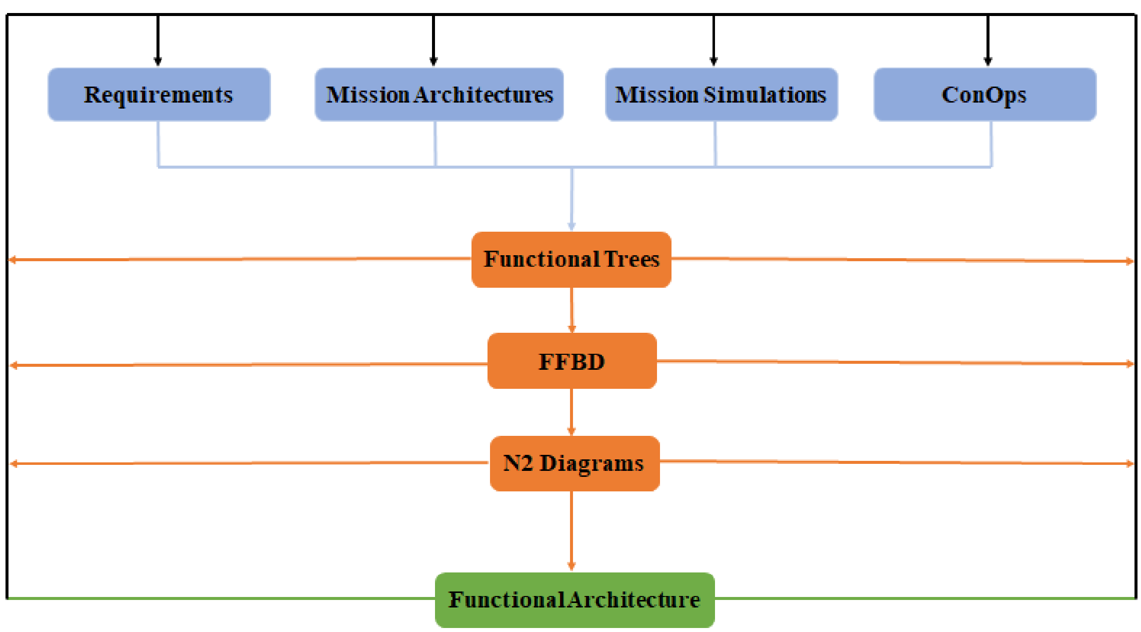

Fig. 3. Functional Analysis methodology.

The mission simulations were then carried out to validate the considerations and assumptions made so far and to approach more consciously further stages of the study. The effects of multi-body dynamics and perturbations were introduced to make the simulations as realistic as possible, even though initial input data were already affected by uncertainties. Firstly, after the CubeSats are released by AIM mothership in heliocentric orbit, they must enter the sphere of influence of Didymoon. In this phase, it was considered a double targeting (green trajectory in Fig. 4) and capture (blue trajectory) maneuver to be caught in Didymoon's orbit. This result confirmed the need to implement a propulsion system.

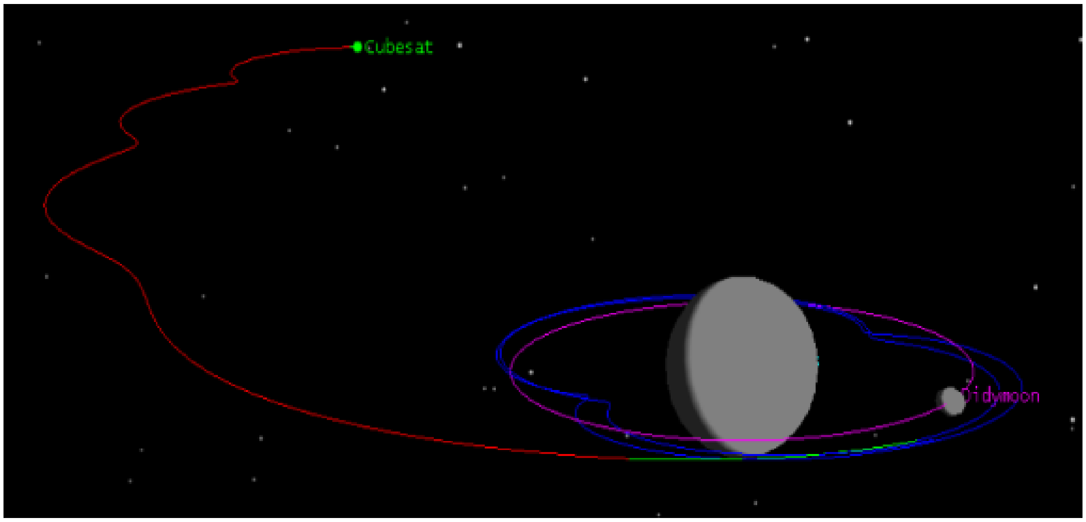

Fig. 4. Double targeting and capture manoeuvres to be caught in Didymoon's orbit.

Secondly, instead of constantly mitigating perturbations, it was decided to take advantage from such phenomena to achieve mission objectives and to reduce the use of the propulsion system. By choosing the right orbital parameters, it would be possible to map a broad equatorial area at no station-keeping cost. Once this task is completed, a polar orbit can be reached to cover the areas not mapped yet. In this case, the use of the propulsion system is needed for a shorter period to mitigate perturbations. A ΔV estimation for such maneuvers is shown below in Tab. 6.

Tab. 6. ΔV Budgets.

Manoeuvre	V(x) [m/s]	N(y) [m/s]	C(z) [m/s]	Total [m/s]
Didymoon targeting	-0.0092760	0	0	0.009276
Didymoon capture	-0.0450695	0.00217532	-0.0155599	0.047730
			Total	0.057006

Two different configurations are identified to achieve 95% mapping (Fig. 5). The first one considers a single CubeSat which moves from equatorial to polar orbit to complete mapping campaign.

The other considers a 4-CubeSats constellation which requires less time to achieves the same result.

Finally, the possibility to land one CubeSat on Didymoon surface before the impact of DART was introduced in the simulations to enable the seismic analysis of DART's impact. Below, in Tab. 7, are presented the maneuvers and the ΔV needed to achieve a soft landing, independently of the inclination of the departing orbit.

Tab. 7. Estimated CubeSat landing ΔV cost.

Event	Description	ΔV [m/s]
Retroburn	Periapsis lowered to 0.085 km	0.20061
Stabilization	V(x) and N(y) velocities killed	0.00512
Vertical landing	Kill horizontal speed	0.19231
Soft landing	Kill vertical speed	0.31305
	Grand total	0.71109

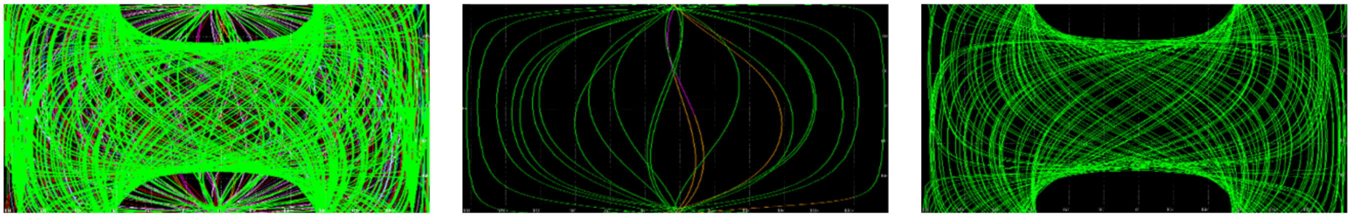

Fig. 5. Mapping configurations able to cover about 95% of Didymoon's surface. Equatorial configuration on the right, polar in the centre, combined on the left.

Moreover, the possible CubeSats orbital configurations for DART's impact observation have been studied. Three or more remaining CubeSats after one has landed are desirable, to have at least two of them in direct line-of-sight of the impact site and at least another one slightly above the local horizon. This configuration would allow the observation of the dust produced by the impact, as of its dispersion and raising from the ground. An enhanced configuration could have the Sun placed behind the camera, illuminating the dust and allowing an augmented imaging quality.

Below, in Tab. 8, the orbital parameters for potential mapping configurations are provided.

Tab. 8. Orbital parameters.

CubeSat type	Orbit type	Mapping area	SMA [km]	Eccentricity	Inclination [deg]
1x2U and 2x1U	Inclined prograde	± 49.1° of latitude	0.198	0.01	49.1
4x1U or 2x1U	Polar prograde	Polar areas	0.198	0.01	90
4x1U	Equatorial prograde	Equatorial area	0.198	1e-4	0

It is noteworthy, indeed, that every CubeSat in the equatorial configuration, both during the mapping and during the impact observation, should be spaced apart from the neighbours by at least 3° in true anomaly to maximize the impact observation coverage and to ensure reliable redundant measurements.

For completeness, the verification of the orbital stability is given by an ad hoc propagator that implements a high-precision orbit propagator for 15+ days, with Didymos and Sun's gravitational fields as third-bodies perturbations, spherical SRP (Solar Radiation Pressure) and second-order differential equations for the bodies' oblateness as additional perturbations, and Runge-Kutta-Fehlberg 9th order method as numerical integrator. Fig. 6 below shows the resulting perturbed orbit, passively stable without the use of a propulsion system, while Tab. 9 shows the summary of perturbations, to be specifically considered for polar orbits. Indeed, while the CubeSats may be stable on an equatorial orbit, they do need a propulsion system for the scientific mapping and observation campaigns.

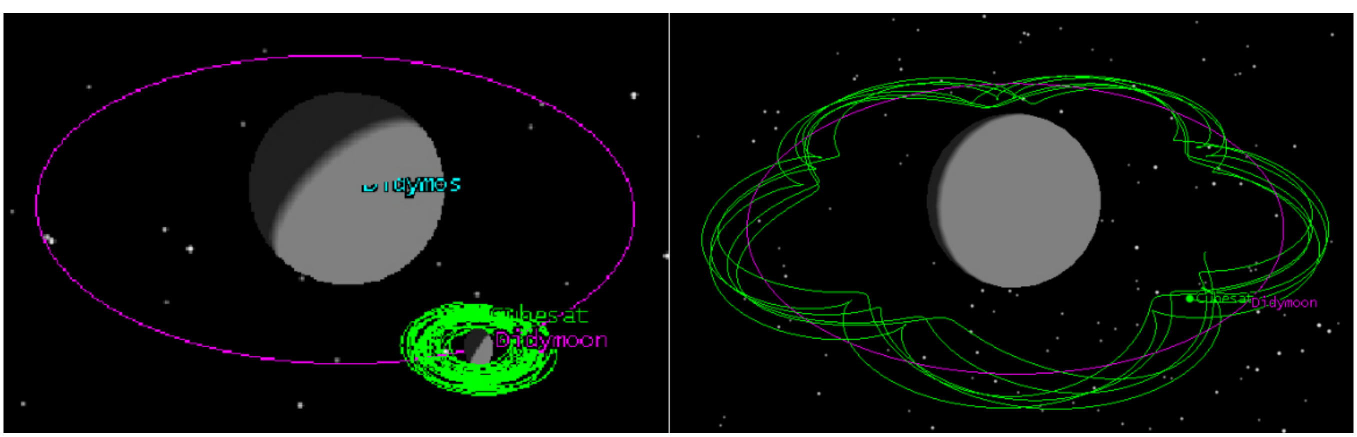

Fig. 6. CubeSats stable orbits for 15+ days with provided data and propagator.

Tab. 9. Summary of the perturbations.

Type	Didymos	Didymoon	SRP	Total	Units
Precession of the line of nodes	7.221e-6	5.0817e-8	8.9912 ± 1e-5	9.7183 ± 0.5e-5	deg/sec
Precession of the line of nodes	2.9835e-6	2.6051e-8	7.4798 ± 1e-5	7.7807 ± 0.5e-5	deg/sec
Grand total precession				1.7499 ± 1e-4	deg/sec

With specific reference to the event times that may arise in a mapping and impact observation campaign, it is noted that the mapping campaign lasts 12.5 days, value obtained from simulations as the minimum time span to have a 95% area coverage with 90+% certainty with a 5-CubeSat constellation in a combined inclined equatorial and polar orbit configuration. The typical times to change planes between orbits, for CubeSat swapping and station-keeping reasons, is always less than 4 hours. Impact observation times are variable; simulations show that a constellation of 4 CubeSats spaced on an equatorial orbit guarantees a minimum of at least 4.5 hours per day of direct observation.

3.3 Mission Architectures

The primary objective of this study is to derive the physical architecture of the mission. It directly stems from ConOps definition and functional analysis and produces as output the Mission Architecture, which in turn enables the implementation of ConOps and functions-systems matrices according to functional trees. An important aspect to highlight is the close connection between Mission Architectures and Simulations, since an iterative process is required to produce the mission architectures associated with each ConOps, while validating them with Simulations. Finally, processes and results from this section are considered inputs to mission requirements, trade-off analysis, baseline description and, finally, costs. The first step is the examination of mission concepts and mission elements, by using the Tradable Elements Matrix, shown in Tab. 10 below [21]. The matrix will be unique since elements' tradability is constant across multiple concepts.

Tab. 10. Tradable Elements Matrix.

Element	Tradable	Reason
Subjects	NO	They are defined in the mission ConOps
Payloads	YES	They can be chosen between different alternatives according with STM
Spacecraft Bus	YES	It can be arranged in different configurations
Launch & Transfer Vehicle	NO	It is AIM and its deployers
Orbit Geometry	YES	It can be defined according to scientific requirements and S/C configurations
Ground Segment	NO	It is imposed by AIDA main mission
Communication Architecture	YES	It can be defined according with S/C configurations and orbital geometry

The main options for each tradable element are identified and the selection narrowed down to those elements directly influenced by ConOps, Mission Statement, Mission and Science Requirements, and Simulations. The next step is to design the Trade Trees, considering all possible combinations of chosen mission elements. The spectrum of possibilities will be trimmed further by keeping only feasible combinations obtaining the possible space segment architectures.

The preliminary evaluation of CubeSats' payloads and buses has been performed. At this stage, it is crucial to understand whether payloads and buses fit inside the CubeSat structure. For this purpose, a preliminary budget for ΔV, power, mass and volume were performed. In terms of space segment architectures, only the combinations 1x1U + 1x2U + 1x3U, 2x1U + 2x2U, 4x1U + 1x2U, achieved by disengaging the magnetic docking systems holding together the smaller units that compose the 3U CubeSats, comply with mass and volume constraints [15]. Considering a set of six ConOps (two of them rejected), it is clear that it is not possible to describe here all the possible mission architectures able to implement each ConOps, since all potential combinations include three possible space segment architecture, a set of different orbit geometries and tradability of payloads, spacecraft buses and communication architectures. For this reason, a snap of mass, volume, power consumption and ΔV budgets relative to ConOps 6 are shown in Tab. 11, 12, 13 and 14, considering the space segment architecture of 4x 1U + 1x 2U CubeSats. It must be noted that in this particular space segment architecture, there are two pairs of 1U CubeSats which are totally identical and perform the same operations. In fact, the only difference between them is that one pair is equipped with a IR camera while, the other, with a visible one. So, only the budgets for three CubeSats (named 1Ua, 1Ub and 2U) are provided. Furthermore, in the following budgets are included also the thrusters, which derive from the ΔV budget. In terms of size and mass, the constraints from the CubeSats Design Specification [15] have been used as the "available" amount of such parameters to obtain a margin from the ratio between the total and available mass and size. The available power is the power delivered from the solar panels while the battery pack power is the power consumed by the battery's electronics.

Tab. 11. CubeSat 1Ua Size, mass and power budgets [22][23][24][25][26].

Quantity	Component	Size [mm³]	Mass [g]	Power [W]
3	Sun Sensors (Bi-Axis)	28*14*6	4	0.01
4	Reaction Wheels	23*31*26	5	0.18
1	IMU	12*12*4	66	0.044
9	Thrusters	30*70*12	30	0.3
1	IR Camera	45*40*20	35	1.1
1	Optical Spectrometer	45*50*80	200	1.1
1	Communication System	48*53*7	37.5	1.5
1	On Board Computer	38*33*8	20	0.45
1	Battery Pack	32*26*10	100	0.25
Total	-	516924	880.5	9.47
2	Solar Panels	8.5*10*2.5	120	7.2
Available	-	1000000	1330	14.4
Margin	-	**48.24%**	**33.8%**	**34.2%**

Tab. 12. CubeSat 1Ub Size, mass and power budgets [22][23][24][25][26].

Quantity	Component	Size [mm³]	Mass [g]	Power [W]
3	Sun Sensors (Bi-Axis)	28*14*6	4	0.01
4	Reaction Wheels	23*31*26	5	0.18
1	IMU	12*12*4	66	0.044
9	Thrusters	30*70*12	30	0.3
1	Visible Camera	45*25*45	45	0.24
1	Optical Spectrometer	45*50*80	200	1.1

1	Communication System	48*53*7	37.5	1.5
1	On Board Computer	38*33*8	20	0.45
Total	-	537399	890.5	8.44
2	Solar Panels	8.5*10*2.5	120	7.2
Available	-	1000000	1330	14.4
Margin	-	**46.2%**	**33.1%**	**41.4%**

Tab. 13. CubeSat 2U Size, mass and power budgets [22][23][24][25][26].

Quantity	Component	Size [mm³]	Mass [g]	Power [W]
3	Sun Sensors (Bi-Axis)	28*14*6	4	0.01
4	Reaction Wheels	23*31*26	5	0.18
1	IMU	12*12*4	66	0.044
9	Thrusters	30*70*12	30	0.3
1	Net + Net Deployer	70*50 (diameter, length)	350	0.2
1	Seismometer	30*20*20	50	0.03
1	Anchorage System	150*7*7	500	0.75
1	Laser Altimeter	45*53*52	180	0.5
1	Battery Pack	57*45*15	150	0.25
1	Communication System	53*47*10	63	1.5
1	On Board Computer	57*53*10	45	0.45
Total	-	705812	1946	8.61
2	Solar Panels	8.5*10*2.5	120	7.2
Available	-	2000000	2660	14.4
Margin	-	**64.68%**	**26.8%**	**40.2%**

Tab. 14. ΔV required for each CubeSat during the mission.

Maneuver	2U CubeSat [m/s]	1Ua CubeSat [m/s]	1Ub CubeSat [m/s]	Total [m/s]
Capture	0.0564	2x 0.0564	2x 0.0564	0.282
1st Plane change 0° - 49.1°	0	2x 0.207	2x 0	0.414
Plane change 0° - 90°	0.335	2x 0	2x 0.335	1.005
1st Station keeping	3.75	2x 0	2x 3.75	11.25
Plane change 90° - 49.1°	0.173	2x 0	2x 0.173	0.519
Plane change 49.1° - 90°	0	2x 0.173	2x 0	0.346
2nd Station keeping 2	0	2x 3.75	2x 0	7.5
Plane change 90° - 0°	0	2x 0.335	2x 0	0.67
Plane change 49.1° - 0°	0.173	2x 0	2x 0.173	0.519
Landing	0.372	2x 0	2x 0	0.372
2nd Plane change 0° - 49.1°	0	2x 0	2x 0.173	0.346
2nd Plane change 0° - 90°	0	2x 0.335	2x 0	0.67
3rd Station keeping	0	2x 3.75	2x 0	7.5
2nd Plane change 90° - 49.1°	0	2x 0.173	2x 0	0.346
2nd Plane change 49.1° - 90°	0	2x 0	2x 0.173	0.346
4th Station keeping	0	2x 0	2x 3.75	7.5
Total	**4.86**	**2x 8.78**	**2x 8.58**	**39.58**

Moreover, one per each simulation result, the orbit geometry was selected by searching a good compromise between the required ΔV and the scientific campaign quality.

Finally, in terms of Communications Architecture, the inputs to the analysis were provided by simulations. It was noticed that CubeSats will experience non-visibility conditions with respect to AIM, therefore it has been decided to adopt a Store & Forward Architecture via a laser Inter-Satellite Link Communication. A sample of Inter-Satellite Link Communication between two CubeSats is shown in Fig. 7 below, while a sample for the visibility conditions with respect to AIM is shown in Fig. 8 below. Both are computed in the case study start date in April 2022.

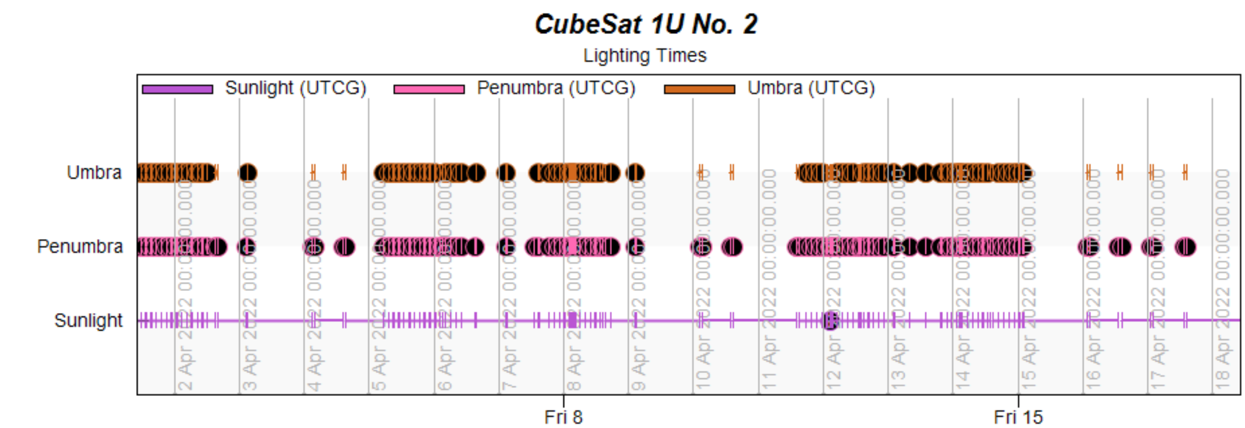

Fig. 7. CubeSat no. 2 visibility with respect to AIM and Sun. Sample visibility times.

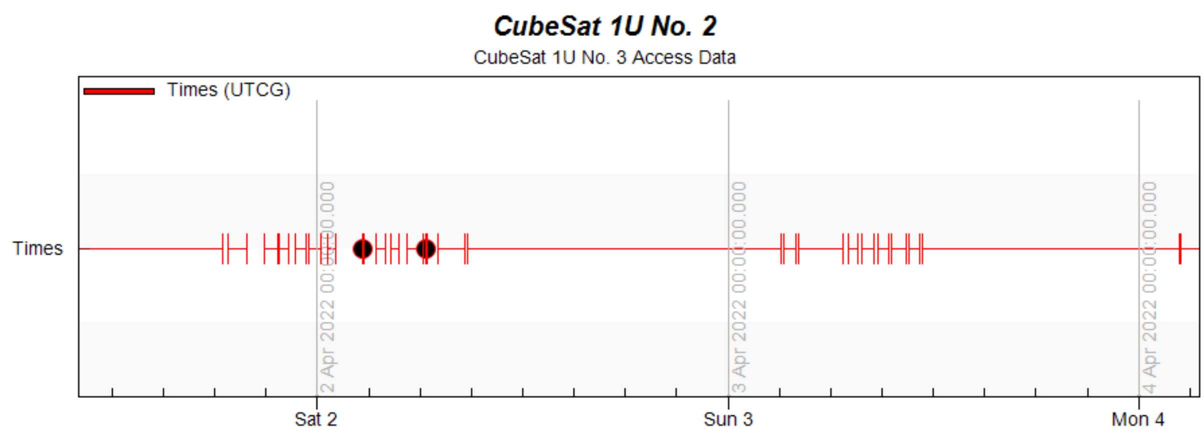

Fig. 8. CubeSats 2 and 3 Inter-Satellite Link Communication. Sample access times.

3.4 Trade-off Analysis

A trade-off analysis is necessary to choose the ConOps and the Mission Architecture that best fit with the mission expectations. It will be possible then to describe the mission, in terms of baseline and timeline, as with relative costs and risks analysis. Decision-making analysis offers techniques for mathematical decision modelling necessary to find an objective optimal solution. Moreover, the Figures-of-Merit (FoMs) approach, used for the ConOps trade-off, represents an effective methodology to objectively conduct a quantitative analysis of design configurations. FoMs are criteria chosen to be representative of the mission, and that can be successfully used to compare different ConOps or Mission Architectures [27]. The FoMs selected for this study, considering the high level of the work, are.

1. Targets: secondary scientific and technological objectives accomplished by the different ConOps.

2. Technology Readiness Level (TRL): esteem of the maturity level of the scientific equipment and the technological demonstrators considered in each ConOps.
3. Operations: the number of main operations to be performed. In this work, the main differences among ConOps regard orbital manoeuvres, considering the minimum score as the optimal.
4. Complexity: the number of equipment considered in each ConOps.
5. Costs: the output of the cost analysis performed within this study.
6. Autonomy: capability of the system to perform operations autonomously, considering Go/no-Go checks.

These are mathematically expressed to range from a minimum value of zero to a maximum of one, for the optimal solution. The Analytical Hierarchy Process (AHP) is used to weight the selection criteria [28]. The FoM relative importance is defined through a prioritisation matrix, establishing the FoMs weight. Finally, the ConOps trade-off is concluded by multiplying the obtained scores by the relative FoM weight (Tab. 15). Scores and weight factors are normalised to 1. The ConOps 1 and ConOps 2 are excluded because of functional incompatibility, as reported in Paragraphs 3.1 and 3.2.

Tab. 15. ConOps trade-off matrix.

		ConOps 3	ConOps 4	ConOps 5	ConOps 6
Targets	26,3%	0,30	0,50	0,70	1,00
TRL	21,1%	0,68	0,67	0,56	0,56
Operations	10,5%	1,00	0,75	0,75	0,75
Complexity	15,8%	1,00	0,89	0,73	0,73
Cost	15,8%	1,00	0,98	0,96	0,96
Autonomy	10,5%	1,00	0,80	0,67	0,67
Trade-Off	100,0%	0,748	0,732	0,717	0,796

The ConOps 6 has the highest score, so it is the one that best fits with respect to the mission objectives and the requirements.

Likewise, an analogous approach was used to find the best mission architecture for the ConOps 6. The key criteria considered for the architecture trade-off are the values obtained during the Stakeholder Analysis (SHA), to offer an alternative approach to the trade-off analysis. The values, output of the SHA, considered in this analysis are the mission success, the complexity of operations, costs, and the complexity of manufacturing. Such values are normalised to 1 [29].

Common parameters to compare the different alternatives, mission architectures, were identified and weighted. These are the total mission ΔV, the number of orbital manoeuvres, the number of CubeSats, and the total mass. The identified architecture parameters are normalised to 1.

To integrate the SHA values with the architectural parameters, an influence level was defined. The overall score for each space segment architecture is obtained through the sum of the products between the weighted architecture components (parameters) and the normalized SHA values (criteria) and presented in Tab. 16.

Tab. 16. Mission Architectures trade-off matrix.

Space Segment Architecture	Mission Success	Complexity of Operations	Cost	Complexity of Manufacturing	Risk	∑
2x2U, 2x1U	0,12	0,07	0,40	0,09	0,18	0,85
1x1U, 1x2U, 1x3U	0,15	0,09	0,52	0,12	0,17	1,05
1x2U, 4x1U	0,33	0,20	0,32	0,07	0,17	1,09

The space segment architectures considered are the ones implementing landing capabilities, according with ConOps 6. The result shows that the more compliant space segment architecture is the 1x 2U + 4x 1U.

Moreover, the result also agrees with the ideal orbital configuration previously shown in Tab. 7.

3.5 Cost Analysis

The mission cost estimation ensures a balance between effectiveness and cost of the S/C systems and payload. Thus, a mission cost analysis is required to find a good compromise between these two constraints and to evaluate the economic feasibility of the mission.

The steps followed to perform this analysis are: development of the Cost Breakdown Structure (Fig. 9) to identify all element costs, computation of CubeSat Space Segment cost, computation of payload costs, computation of CubeSat subsystems cost, computation of project level costs, computation of inflation effects and management reserve, computation of overall cost.

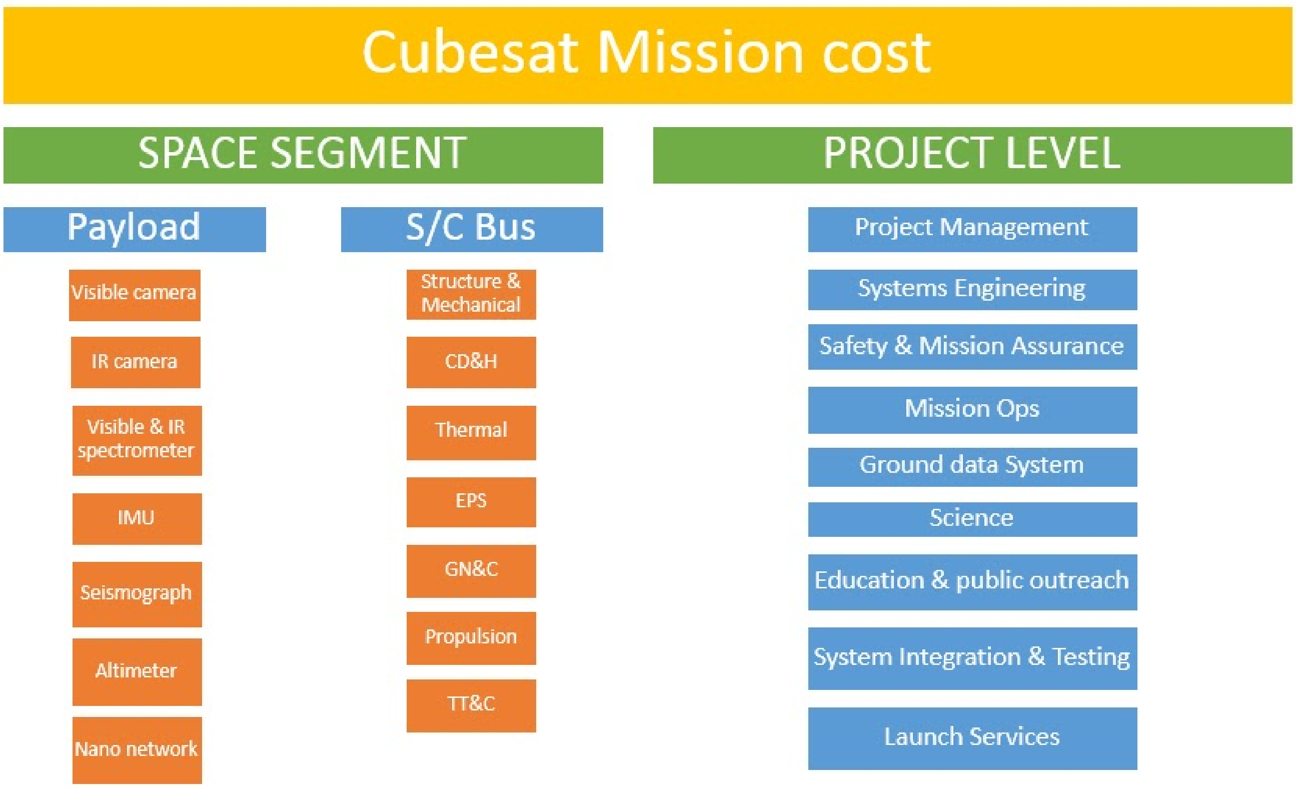

Fig. 9. Cost Breakdown Structure.

A parametric methodology has been considered for the mission cost estimation. This top-down approach uses a series of mathematical relationships to relate cost to physical, technical, and performance parameters. To complete this procedure, only system requirements and top-level design specifications are required.

Cost estimations have been previously evaluated for 1U CubeSat and subsequently extended for all considered CubeSat configuration (Tab. 17).

It must be noted that the classical existing CER (Cost Estimating Relationship) models for satellites [30] [31] cannot be properly used for the cost estimation of very small satellites (< 10 kg). Thus, cost methodologies properly developed for very small satellites have been considered for the mission cost analysis [32] [33].

Space segment overall cost has been estimated by using the A-PICOMO cost model S/C mass-related equation [32].

$$Space\ Segment\ Cost = 282.93 * m_{sat} + 155.8\ \ [Thousand\ USD]$$

Tab. 17. CubeSats Space segment cost.

CubeSat configuration (Mass [kg])	Space Segment estimated cost [FY2016 Million USD]
1U (1,33)	0,532
2x 2U (2x 2.66), 2x 1U (2x 1.33)	2,881
1x 1U (1.33), 1x 2U (2.66), 1x 3U (3.99)	2,725
1x 2U (2,66), 4x 1U (4x 1,33)	3,036

Regarding the cost estimation for the scientific payload, various online data and technical reports have been used [34], given the availability *off the shelf* of almost all components (Tab. 18). Furthermore, by considering the TRL grade of the payload components, corrective factors have been applied. In particular, a multiplicative coefficient $K_{LOW\ TRL} = 2.0$ has been applied for not-*off the shelf*, low-TRL cost components in order to taking into account to RDT&E further cost. Even for the available *off the shelf*, high TRL cost items, a multiplicative coefficient $K_{HIGH\ TRL} = 1.05$ has been introduced to consider possible minimal component modifications.

Tab. 18. Mission CubeSats Payload cost

Payload Component	Estimated cost [FY2016 Thousand USD]	Estimated cost [FY2016 Thousand USD]	Estimated cost [FY2016 Thousand USD]	Estimated cost [FY2016 Thousand USD]
	1U configuration	2x2U, 2x1U configuration	1x1U, 1x2U, 1x3U configuration	1x2U, 4x1U configuration
IMU	3,796	15,187	11,390	18,984
Visible Camera	13,645	81,868	68,223	81,868
Visible and IR Spectrometer	32,391	129,565	97.174	161,957
IR Camera	53,445	213,780	160,335	267,225
Seismograph	4,2	16,800	12,600	21
Altimeter	2,1	4,2	2,1	8,4
Nano-network	21	84	63	105
TOTAL PAYLOAD	130,578	545,401	414.823	664,434

S/C subsystems (Tab. 19) and Project Level (Tab. 20) cost estimations have been performed by using the cost fractions proposed by NASA AMES Cost model for Micro/Nanosatellites [33].

Tab. 19. Mission CubeSats S/C Bus cost.

S/C Subsystem (*fees*)	% of total S/C Bus cost	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]
		1U configuration	2x2U, 2x1U configuration	1x1U, 1x2U, 1x3U configuration	1x2U, 4x1U configuration
Guidance, Navigation & Control	14 %	0,056	0,327	0,323	0,332
Command & Data-handling	18%	0,072	0,420	0,416	0,427
Telemetry, Telecomm. & Control	11%	0,044	0,257	0,254	0,261
Propulsion	5%	0,02	0,117	0,115	0,119
Electrical Power Subsystem	21%	0,084	0,490	0,485	0,498
Structure and Mechanical	10%	0,04	0,233	0,231	0,237
Thermal	4%	0,016	0,0934	0,092	0,095
Contract fees	17%	0,068	0,397	0,393	0,403
TOTAL BUS	100%	0,402	2,335	2,310	2,372

Tab. 20. CubeSats Project Level cost.

Project Level Costs	% of total S/C Bus cost	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]
		1U configuration	2x2U, 2x1U configuration	1x1U, 1x2U, 1x3U configuration	1x2U, 4x1U configuration

Project Management	73,26%	0,294	1,711	1,692	1,738
Systems Engineer	76,36%	0,307	1,783	1,764	1,812
Safety & Mission Assurance	78,37%	0,315	1,830	1,810	1,859
Mission Ops	65,13%	0,261	1,512	1,504	1,545
Science	72,25%	0,29	1,687	1,669	1,714
Launch Services	78,37%	0,315	1,830	1,810	1,859
Ground Data System	73,26%	0,294	1,711	1,692	1,738
System Integration & Testing	73,26%	0,294	1,711	1,692	1,738
Education & Public Outreach	7,54%	0,03	0,176	0,174	0,179
TOTAL PROJECT LEVEL	532,67%	2,139	13,962	13,811	14,182

A management reserve factor of 25% has been considered for the cost risk analysis and cost risk spreading [33]. The overall mission cost (Tab. 21) has been evaluated in FY2016 USD and an inflation factor of 1.103 was considered to evaluate the cost in FY2020 USD [35] (Tab. 22). The overall mission cost results being evaluated 23.738 FY2020 Million USD, the 11.33% of the forecasted AIM's mission cost [36].

The overall mission cost has been found to be in line with typical mission cost and mission cost percentages proposed by NASA JPL for Interplanetary CubeSat missions [4].

Tab. 21. Mission overall cost (FY2016 USD).

Costs	% of total mission proposed cost	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]	Estimated cost [FY2016 Million USD]
		1U configuration	2x2U, 2x1U configuration	1x1U, 1x2U, 1x3U	1x2U, 4x1U configuration

				configuration	
Space Segment (BUS + PAYLOAD)	19%	0,532	2,881	2,725	3,036
Project Level	81%	2,139	13,962	13,811	14,182
TOTAL	100%	2,671	16,843	16,536	17,218
Reserve	25%	0,668	4,211	4,134	4,304
TOTAL WITH RESERVE	125%	3,339	21,054	20,670	21,522

Tab. 22: Mission overall cost (FY2020 USD).

Costs	% of total mission proposed cost	Estimated cost [FY2020 Million USD]	Estimated cost [FY2020 Million USD]	Estimated cost [FY2020 Million USD]	Estimated cost [FY2020 Million USD]
		1U configuration	2x2U, 2x1U configuration	1x1U, 1x2U, 1x3U configuration	1x2U, 4x1U configuration
Space Segment (BUS + PAYLOAD)	19%	0,587	3,177	3,005	3,348
Project Level	81%	2,359	15,400	15,233	15,642
TOTAL	100%	2,947	18,577	18,239	18,991
Reserve	25%	0,737	4,644	4,559	4,747
TOTAL WITH RESERVE	125%	3,683	23,222	22,799	23,738

4. Results

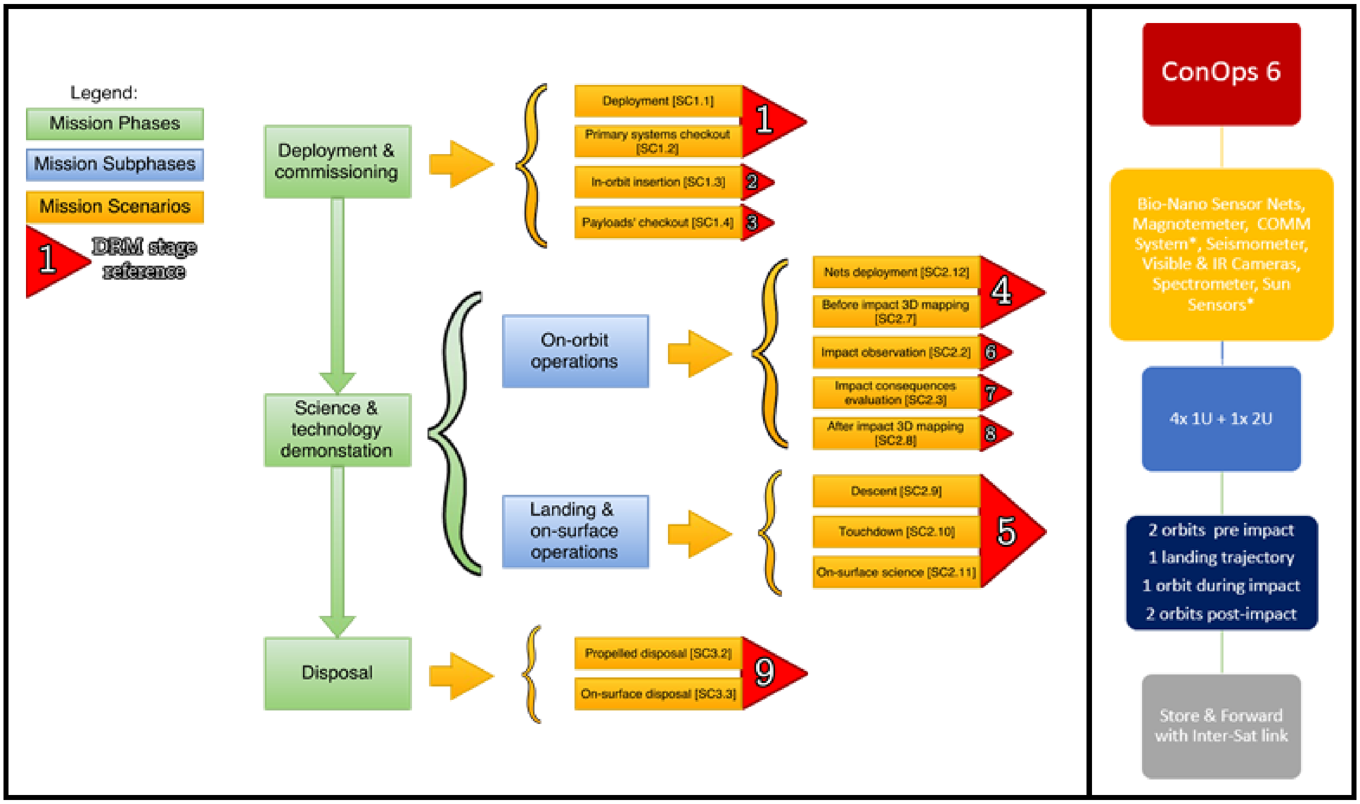

Fig. 10. The ConOps selected for the mission on the left (ConOps 6). The mission architecture selected on the right.

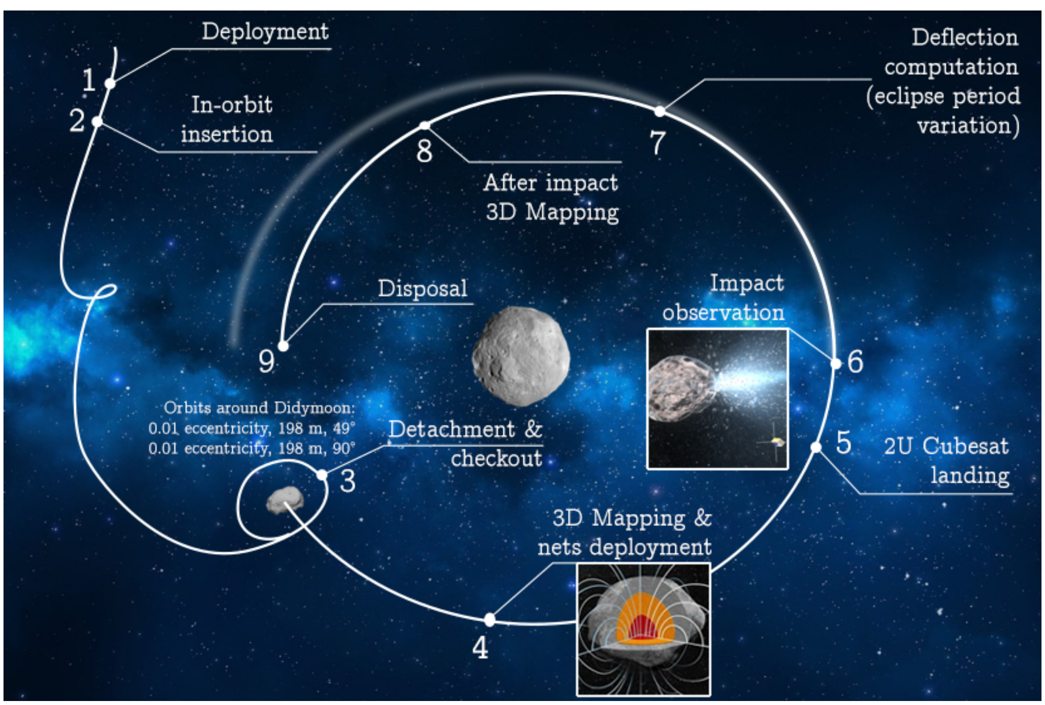

Fig. 11. Mission Design Reference.

Fig. 10 represents the ConOps selected for the proposed CubeSats mission (the ConOps 6) representing all its phases, subphases and scenarios. The figure reports also the mission architecture selected and associated with the ConOps 6. The main features of the mission architecture are reported in terms of CubeSats configuration selected, along with the payload, the orbital configurations and the communication architecture chosen.

Fig. 11 shows the Mission Design Reference, which represents the mission sequence according with the numeration adopted in Fig. 10 to list the mission scenarios. The mission starts with the deployment of two 3U CubeSats from the mothership and followed by the orbit insertion about the asteroid. Once orbit insertion is achieved, the mission baseline configuration of one 2U and four 1U CubeSats is achieved by disengaging the magnetic docking systems holding together the smaller units that compose the 3U CubeSats. Two orbital configurations, as shown in Fig. 11 and previously anticipated in Tab. 8, are planned to carry out the pre-impact scientific campaign, which includes gravitational and magnetic field mapping. Gravitational field mapping is achieved by using the Communication System, adopting a strategy that places two or more CubeSats into the same orbit around Didymoon and measuring changes in their relative position and velocity (Gravity Ranging System). Magnetic field mapping is realized by using the magnetometer provided with the Inertial Measurement Unit (IMU). In this phase, the 2U CubeSat deploys from orbit multiple wide chip-size-sensor nets on Didymoon surface. These nets interact with the outside environment where they were spread opened. The purpose is to enable in-situ measurements of chemical-physical surface properties. This allows the collection of a high amount of scientific data concerning a wide surface area, with the use of a lightweight and compact system that can be stored inside a CubeSat. Furthermore, before DART's impact the 2U CubeSat lands on a spot diametrically opposite with respect to the impact site, to record the seismic waves passing through the asteroid's core. This allows the analysis of the asteroid's internal structure through a seismometer placed on board. The orbiting CubeSats will then move into a near equatorial orbit to perform the analysis of DART's impact. Afterwards, the CubeSats will continue the gravitational and magnetic field mapping by returning to the previous orbit configuration until disposal. Orbiting CubeSats are designed to use Sun sensors to measure the variation of the asteroid orbital period caused by DART's impact. This is achieved by measuring the variation of the eclipse time before and after the impact, giving a different source of data to evaluate the effects about asteroid's trajectory deflection. The mission involves also some important technological demonstrators. The S-iEPS (Scalable-ion Electrospray Propulsion System) has been considered as propulsion system. This thruster concept is based on electrostatic extraction and acceleration of charged particles from room temperature molten salts, using porous emitter arrays with emitter densities of 480 emitters per square centimetre. Each module presents themselves as building blocks for scalable propulsion systems, leading to easy integration and high redundancy [37]. Landing challenge will be conducted by a laser altimeter, working concurrently with the propulsion system, to gather terrain distance at any given time as to regulate the Guidance Navigation and Control (GNC) system. Once on the surface, a novel anchorage system will ensure the system stability especially for the seismic measurements. This system involves telescopic legs ending with "ice screws" skewering into the asteroid surface by using micro electric actuators. All systems are self-contained in the CubeSat volume. In conclusion, the Inter-Satellite Communications Link via laser will be used during the entire mission. Store & Forward will be used to permit blinded CubeSats to communicate with AIM using other CubeSats as relays. Tab. 23 reports the key features of the mission concept proposed. Eventually, the virtual models of the CubeSats 1U and 2U are shown in Fig. 12.

Table 23. Key features of the mission concept proposed.

Mission architecture	4x 1U + 1x 2U CubeSats
Mission ΔV	39.58 m/s
Minimum mission duration	~ 1 month

Scientific objectives	• Asteroid's gravitational field mapping • Asteroid's magnetic field mapping • Asteroid's chemical-physical surface properties mapping • Impact observation • Asteroid's internal structure mapping • Assessment of asteroid's trajectory deflection
Scientific campaign	• Pre-impact mapping ○ 3x 1U CubeSats in a 49.1° inclined orbit ○ 1x 1U + 1x 2U CubeSat in a polar orbit • Impact observation ○ 4x 1U CubeSats in an equatorial orbit ○ 1x 2U CubeSat on surface • Post-impact mapping ○ 2x 1U CubeSats in a 49.1° inclined orbit ○ 2x 1U CubeSats in a polar orbit ○ 1x 2U CubeSat on surface
Percentage of asteroid's surface mapping	95%
Technology demonstrators	• Propulsion system • Chip-size-sensor nets • 2U CubeSat landing system • Seismometer • Laser Inter-Satellite Communications Link
Mission Cost	23.738 Million USD (FY2020)

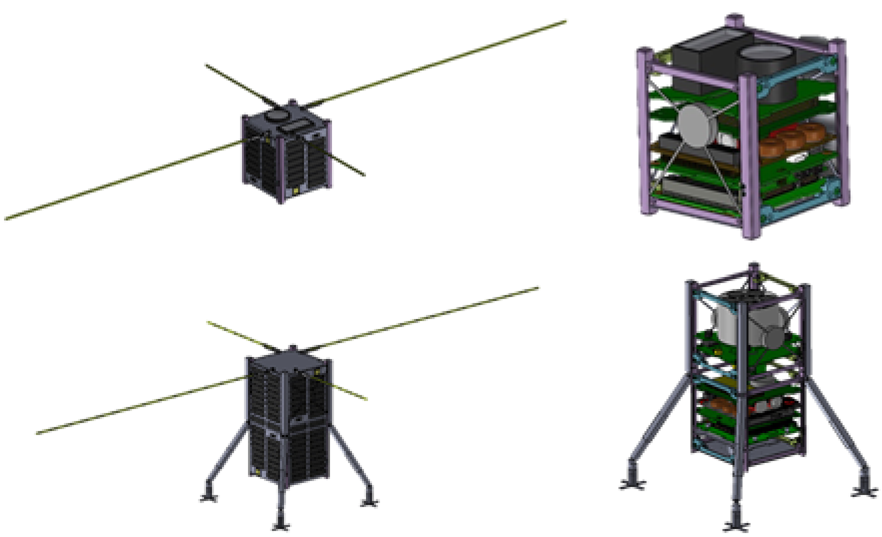

Fig. 12. CubeSats architecture, 1U (top) and 2U (bottom).

5. Conclusions

This case study has shown that CubeSats can be successfully integrated to provide relevant support to interplanetary missions.

The CubeSat standard provides very useful modularity and scalability features, making possible the realization of potentially every type of science, operations and technology demonstration mission. In particular, it has been shown that several different architectures are possible by combining the base units in different ways, according to needs. In this context, the possibility to create multi-platform architectures has several advantages with respect to classic single-platform satellites. From the science point of view, this solution can provide the capability to acquire more detailed information with the possibility to combine them to obtain better results with respect to single-platform systems. From the operations point of view, multi-platform systems can provide better coverage, higher redundancy and accuracy. Moreover, multi-platform systems can be easily re-configured to comply with different needs arising during the mission, as well as to overcome potential issues. The analysis conducted have shown also the high flexibility of CubeSats on integrating several types of payloads to support science, operations and technology demonstration missions. From an economic perspective, those features combined with the increasing availability of COTS components, have a direct impact on costs reduction across several levels: mission design, development, integration, verification, tests, mission operations. Relevant benefits come also about development time, which is highly reduced.

All features listed above make the concept proposed a valuable low-cost piggyback solution with high return, adaptable to several mission contexts.

The concept shown in this study represents the first step to exploit CubeSats in support of interplanetary missions. Further ideas regard the use of CubeSats for asteroid and planetary prospection with the aim to prepare future ISRU (In-Situ Resource Utilization) missions. Moreover, CubeSats constellations may help obtaining high resolution imaging for Earth observation and monitoring, as well as for astrophysics and planetary research. Swarms of precursor CubeSats may be also placed on the Interplanetary Transport Network, jumping from target to target through the Solar System, exploring different celestial objects and producing an incredible amount of scientific data. Each of those potential missions can be performed by CubeSats, thanks to their unique features.

This study has shown how such features can be concurrently exploited to achieve mission goals, providing a useful framework to design and develop an interplanetary CubeSat mission.

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8. Vitae

Gianluca Benedetti is a junior Aerospace Engineer, graduated in November 2016 at Politecnico di Torino (Italy). He is currently working for Thales Alenia Space Italia (Turin, Italy) as Space Debris Analyst. He is involved in the development of a 6-DoF software for the re-entry analysis of satellites and in several space environmental test campaigns on satellite hardware components of Exomars 2020, Euclid and Orion MPCV. Furthermore, he has already been involved in several engineering projects with different student teams in different international contexts. He is looking for the opportunity to prove his skills and to further expand his engineering knowledge.

Nicoletta Bloise studied Aerospace Engineering at Politecnico di Torino, where she graduated in July 2017. In the same year she starts a research activity at Mechanical and Aerospace Engineering Department of Politecnico di Torino, focusing on guidance and control algorithms for obstacle avoidance for orbital manoeuvres. In 2015 she participated to the Erasmus Extra-UE program at Universidad Nacional de Córdoba, Argentina. This experience represented for her a great opportunity to grow up both professionally and personally.

Davide Boi received the MSc. in Aerospace Engineering in April 2017 with a dissertation on hypersonic aircraft for civil passengers' transportation. He presented his work at EASN congress that took place in Warsaw in September 2017. His dissertation has been accepted by JAERO (Journal of Aerospace Engineering). His field of expertise is the system designing and more specifically the aircraft design. I am currently employed at Microdrone GmbH in Siegen, Germany where I have the position of CAD design engineer.

Francesco Caruso was born on November 30, 1991 in Ischia, and received the scientific high school diploma in 2010. In 2014 he graduated in Aerospace Engineering at Politecnico di Torino, where he is pursuing the MSc. in Aerospace Engineering. He is currently working on his Master's thesis on the optimization of the heat treatment of the superalloy Hastelloy-X for aerospace applications. He is a sport enthusiast and plays basketball since the age of 7 years old.

Andrea Civita was born in Naples on June 23rd 1993. He is an aerospace engineer student at Politecnico di Torino, master degree course in aerodynamics. In 2016 He achieved a bachelor degree at Politecnico di Torino in Aerospace with a thesis on "Structural analysis of multifunctional elements". He had an internship in Aeroteam di Paolo Cavalla and he worked as sale assistant. He studied at Liceo scientifico Farnesina in Rome and he graduated in 2012. Rugby is his passion and he is playing for 14 years. Currently he is playing for a Serie A rugby championship team.

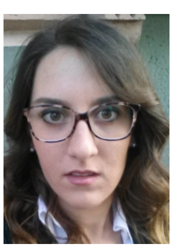
Sabrina Corpino is Professore aggregato and Confirmed Assistant professor of Aerospace Systems at Politecnico di Torino. Since 2000, she takes part in the AeroSpace Systems Engineering Team (ASSET) of Politecnico di Torino. The team works in the area of aerospace system engineering, and in particular focuses on methods for the design of systems and missions taking into account all design variables and their interactions in the global architecture. She is author of several scientific publications in the field, and reviewer for several international journals.

Erik Garofalo received the MSc. in Aerospace Engineering from Politecnico di Torino. Currently, he works on the CERES (Colloidal EneRgEtic Systems) Project at the Italian Institute of Technology in Turin. During his Master he spent six months in California, conducting the research project "N2O two-phase flow analysis for hybrid rocket nozzle cooling" at CalPoly, while his bachelor dissertation was related to 3D printing for space application. During his academic experience he was member of the DIANA. Team involved in space robotics and FATO Mars and ARACNE. teams working on space mission analysis and design, within a multicultural and multidisciplinary environment.

Giuseppe Governale is taking part at the 2nd level specializing master programme in "Space Exploration and Development Systems", supported by ESA, ASI and more. The master is focused on the human and robotic exploration of space and on the related missions, systems, and technologies. He has a B.S. and a M.S. in Aerospace Engineering for Space Exploration at the Politecnico di Torino, Italy. He worked at JPL for a phase II NASA Innovative Advanced Concept addressing the energy problem for lunar and extreme environment applications, through terrain modelling and thermal analysis. He also has a theater academy diploma.

Luigi Mascolo is graduating in the MSc. in Aerospace and Astronautical Engineering at the Politecnico di Torino (Italy). He worked on his Master's thesis at NASA Jet Propulsion Laboratory (JPL), focusing on the feasibility study and design of an electromagnetic lunar mass driver for non-chemical delivery of lunar resources. His other interests concern astrodynamics, space mission analysis and design, and permanent planetary human bases. He began researching in the Politecnico mathematical methods for the analysis of EM Lagrangian points, in the perspective of the PhD.

Gianluca Mazzella is a student in the process of graduating in Aerospace Engineering and will present his thesis on the Optimal Robust Design of Hybrid Rocket Motor at Polytechnic of Turin. He graduated after exhibiting his thesis on Analysis of Refrigeration in Rocket Motor and Study of the Heat Transfer Coefficient from Polytechnic of Turin in Italy, in October 2014, and has remained at this university to complete his Masters of Science degree in Aerospace Engineering. During the course of his studies, he has devoted himself to volunteering and he has practiced a lot of sports activities.



Mariangela Quarata graduated in Aerospace Engineering at Politecnico di Torino, and received a Master in Space Flight. Her Master's thesis concerned Legislation for Suborbital Flight. She worked in collaboration with ALTEC and Enac to evaluate the suitability of FAA Legislation about suborbital reusable launch vehicles to the Italian case. She estimated the public risk level thanks to some parameters as the expected casualty and distance requirements for storage of propellants. She also worked as editor for a web site about engineering. She is member of a team of engineers, that write scientific articles and interview relevant figures of the field.

Dario Riccobono received the M.S. in Aerospace and Astronautic Engineering from Politecnico di Torino, where he is currently pursuing a Ph.D. in Mechanical Engineering, emphasis in Space Robotics. He worked on his Master's thesis at NASA Jet Propulsion Laboratory (JPL), focusing on the development of a full-scale/mass, air-levitated spacecraft emulator for a potential Comet Surface Sample Return mission. His main field of study concerns robotic manipulation and sampling for space applications. He is currently collaborating with JPL on the development of sampling technologies for potential sampling missions to Enceladus and Ceres. Other interests involve space mission analysis and design.

Giulia Sacchiero was born in Italy in 1993. She holds a MSc Degree in Aerospace Engineering from the Politecnico di Torino in 2017. She is currently working in Argotec s.r.l (Turin) as a System Engineer on ArgoMoon project, a 6U cubesat that will be part of the maiden launch of the next NASA vector (SLS) with the major objective to document the separation of Orion and secondary payloads from the ICPS stage. Previously, she worked as Thermal Control System engineer for the Space Rider mission (future reusable European vehicle), as part of an internship in Thales Alenia Space.

Domenico Teodonio obtained his B.Sc. in Aerospace Engineering at Politecnico di Torino in 2016 and is now enrolled in a Master Program in Aerospace Engineering at Politecnico di Torino, with a specialization in space systems. He is currently a Visiting Research Scholar in the Department of Aerospace Engineering in University of Illinois at Urbana-Champaign, working on his Master Thesis on artificial intelligence used to increase space probes' autonomy, under advisement of professors Koki Ho and Sabrina Corpino. He is interested in space operations' control, trajectory definition and control laws' implementation. Other interests include web innovation development and HPC.

Pietro Maria Vernicari is pursuing a 2nd level Specializing Master in Space Exploration and Development Systems at Politecnico di Torino. His research activity represents the continuation of my Master of Science Degree and includes the creation of an innovative Cost Model for high-mass, high-power spacecraft, and, in particular, the application of this model for the Lunar Space Tug scenario: a new transportation system, developed in collaboration with the European Space Agency, that might be able to support the assembly and resupply of the future Deep Space Getaway.