"Multi-purpose Cubesat at the ISS”

Executive Summary Report

Prepared by

Tyvak International
A Terran Orbital Corporation

POLITECNICO DI TORINO

OHB

Distribution List

Name	Organization	Copies
Authors	Tyvak International Politecnico di Torino, OHB	pdf
Jessica Grenouilleau	ESA	pdf
Antonella Sgambati	OHB System AG	pdf
Sabrina Corpino	Politecnico di Torino	pdf

Document Change Record

Issue	Rev.	Date	Modified pages and description/reason
0	1	16-11-2016	First draft

Table of Contents

List of Tables

List of Figures

Abbreviations And Acronyms

Abbreviation	Meaning
ESA	European Space Agency
EVA	Extra Vehicular Activity
GSP	General Studies Programme
IR	infrared
ISS	International Space Station
KOS	Keep-Out-Sphere
OBDH	On Board Data Handling
OC	Operational Capability
ORD	Optical Resolved Distance
PSD	Pixel Sampling Distance
TA	Technology Area
TRL	Technology Readiness Level
VIS	Visible
VV	Visiting Vehicle

Table 1 - Abbreviations & Acronyms

1 Introduction

1.1 Scope of the Document

The present document describes the findings of the “Multipurpose Cubesat at ISS Contract”, providing a brief overview of the whole program, major findings, conclusions and further study areas.

1.2 Background

The CubISSat study investigates the feasibility of operating a multi-purpose small satellite in the International Space Station (ISS) environment whose aim is to provide the ground and flight crew with effective tools to cope with a variety of situations, potentially avoiding to rely on complex robotics and extravehicular activities as currently conceived. The project has been promoted by the General Studies Programme (GSP) with the purpose to provide European Space Agency (ESA) and its member states with the necessary information on which to base their decisions about the implementation of new programmes and the future direction of space activities.

The study, kicked-off on March 2016, is executed by a team composed of three partners: Tyvak International SRL, Politecnico di Torino University and OHB System AG. Tyvak acts as the main technical and managerial responsible for the study, including iterations with the partners and with ESA and for all the deliverables and coordination activities.

2 Aim of the study

In the short term, ESA aims at flying a demonstrator for human-tended operations at the ISS. The long-term goal is to achieve a useful space asset for human exploration beyond ISS (e.g. support to cis-lunar habitat, moon exploration). The present study is aimed at exploring the following mission concepts:

1. External inspection / surveillance of the ISS with (semi)autonomous free-flying; this is also where support to astronauts Extra Vehicular Activities (EVAs) could be analysed;
2. Scientific Payload Free-Flyer;
3. Retrieval of an ESA science/experiment payload in the vicinity of the ISS, e.g. retrieving a Cubesat;
4. Deployment as part of a human cis-lunar habitat in Near-Rectilinear Orbit (75000 km above Lunar Surface).

It was discussed and agreed that, while the mission requirements to support these missions were analysed, the demonstrator mission requirements should be established so as to confirm technical feasibility of a demonstrator platform based on CubeSat technologies that can be serviced in the ISS environment. It was agreed that the mission concept for a free-flyer in internal environment is completely different in terms of objectives, technical requirements and constraints, safety aspects, among other factors.

3 Findings

The external environment of the ISS was identified as primary interest, so among the given four mission scenarios and related s/c required capabilities, the inspection mission at ISS has been selected as reference mission. In fact, current surveillance and inspection operations at ISS rely on EVAs, complex robotics TV ops, external TV technologies and imagery from internal astronauts. However, several blind areas still remain without coverage. Having a set of small specialized drones readily available, reusable and capable to:

- support the ISS crew in inspection and surveillance for long duration missions (e.g. providing surveillance of EVAs complementing current capabilities),
- operate autonomously, limiting or avoiding EVAs and robotic operations dedicated to inspection;
- host multi-purpose sensing instruments providing alternative measurements (e.g. radiation, thermal environment),
- communicate with ISS and/or ground,

might help to overcome some of the issues mentioned above. Therefore, the focus of the study has been an ISS inspector demonstrator, by developing a nanosatellite s/c based on CubeSat technologies capable to operate safely in proximity of the ISS, providing imagery of the ISS exterior, data about the ISS environment and engaging the general public with unprecedented imagery of the ISS. The inspector, moreover, shall be able to provide demonstration of autonomous navigation, rendezvous, berthing, docking, communication operations, refurbishment capabilities, and payload re-configurability capabilities.

The mission takes into account the CubeSat technology readiness in the European framework and eventual technology roadmap to be implemented for a reference implementation in 2 years with an overall budget of 5M euro. First driver for mission development is the safety of the ISS as well as prove key operation concepts.

The main stakeholders involved on the demonstrator mission have been identified in the Scientific and Research Community driven by ESA, and in particular the Human Spaceflight and Robotic Exploration directorate (HRE), Robotics and Future Projects office (HRE-IDR), Development and Future Projects Division (HRE-ID), Biology and Environmental Monitoring Unit (HRE-UB), and the Directorate of Technical and Quality management (TEC), Automation and Robotics Section (TEC-MMA). Astronauts and ISS operators will benefit from the demonstrator mission as direct users of the system. NASA is also a relevant stakeholder, and will provide input requirements for EVAs free-flyer concept and to cooperate on many aspects of the study (mission, command and control, wireless communications, software, safety). General public will be involved for outreach purposes but not playing active role on the mission.

3.1 Mission statement

According to what has just been listed above, the mission statement for such an inspection and surveillance mission has been defined as follows: *to provide inspection and surveillance capabilities of the external framework of the ISS, deploying and retrieving a multipurpose, (semi)autonomous or remotely-controlled vehicle based on CubeSat technologies capable to support ISS crew and operators, complementing or substituting current surveillance capabilities (EVAs, complex robotics TV operations, external TV technologies, crew imagery from internal module windows) in view of future long-duration human exploration missions. Furthermore, to engage the general public, this vehicle could provide unprecedented imagery of the ISS for outreach purposes*.

3.2 Mission objectives and high-level functions

The following high level mission objectives have been identified:

1. To provide inspection and surveillance of the external framework of the International Space Station;
2. To provide mission data (images/videos/other sensor data) to ISS crew and operators;
3. To provide imagery/media to the general public.

Starting from these, some of the required capabilities which the spacecraft needs to sustain in order to fulfil the mission purpose have been derived. They are shown in Figure 1 where it is possible to distinguish 4 different functional competences:

- operations to transfer and deploy the spacecraft (later called DEMO#1) by means of external platform, which shall be installed on ISS and/or on a Visiting Vehicle (VV), in red. In first analysis, the deployment of the spacecraft from an astronaut EVA has not been excluded a priori; however, given that one of the study drivers relates to the possibility to avoid or limit EVA operations as currently conceived, this option will not be taken in to account in the trade-offs;
- navigation operations in blue;
- communication operations in yellow;
- retrieval operations in green (note, they have been planned to be performed by means of a docking platform, called DS1.0, and robotic arms already installed on the ISS).

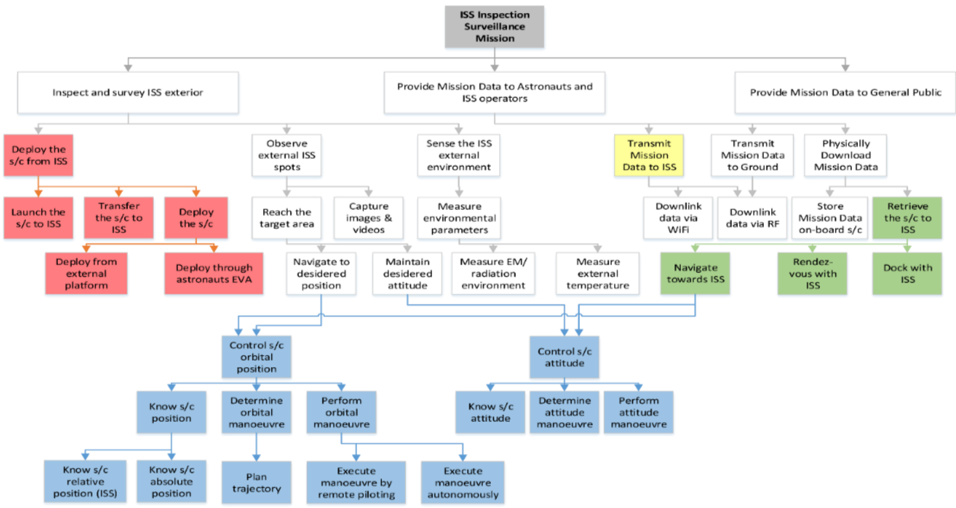


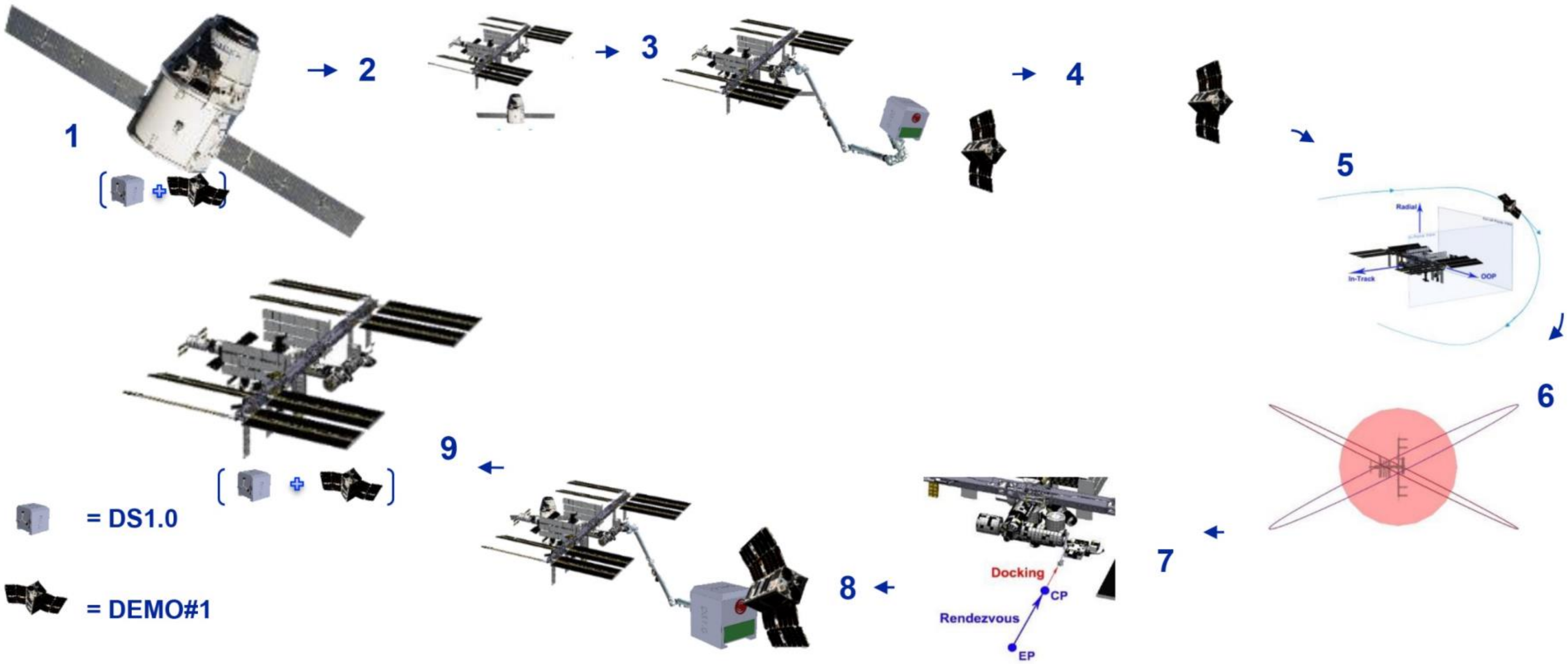
Figure 1 - Functional Analysis for the Inspection/Surveillance Mission

3.3 Demonstrator Concept of Operations

For the consolidated ConOps, two main deployment strategies have been investigated:

a) s/c separation from a VV before docking with ISS;
b) s/c released directly from ISS.

Both approaches have been compared and trajectories simulated to maximise the safety of the ISS. A brief overview of the demonstrator concept of operations is shown in Figure 2 in case the approach b) is selected. It highlights the deployment of s/c DEMO#1 from a VV, the installation of docking platform DS1.0 on the robotic arm, the inspection mission outside the Keep-Out-Sphere (KOS) (see Figure 3), the rendezvous and berthing of DEMO#1 with DS1.0, the un-berthing, the inspection mission inside the KOS (see Figure 4), and the final berthing of DEMO#1 with DS1.0.



1 – DS1.0 including satellite and deployment system is delivered as cargo to ISS on board a VV.	2 - VV is berthed to ISS. DS1.0 is moved to KIBO.		3 - DS 1.0 is mounted to the sliding table of module and grappled by JEM SS-RMS. The arm is held in position. CubISSat is then deployed.	4 – Satellite activation. Commissioning Phase at few km away from the ISS. First propelled manoeuvre outside the KOS.
5 – Semi-autonomous Step-by-Step approach to ISS. RGPS navigation	6 – Start inspection orbits. RGPS and Visual-based navigation	7 – Rendez-vous manoeuvres and docking with same DS1.0	8 – CubISSat is returned inside ISS after docking with DS1.0.	9 - DEMO#1, DS1.0 and payload are stowed inside the KIBO module where Crew performs post-mission detailed inspection.

Figure 2 - Concept of operation for the Demonstrator Mission in case the deployment of the s/c from VV is selected

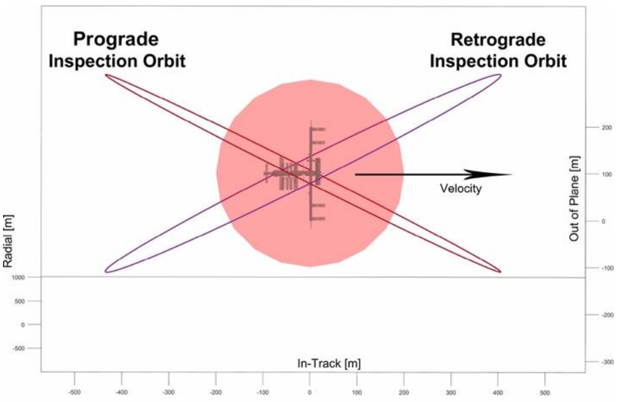


Figure 3 - Inspection mission outside the KOS

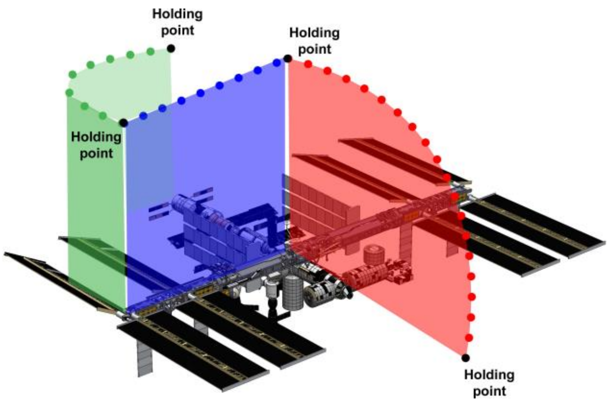


Figure 4 - Inspection mission inside the KOS

3.4 Technology Assessment

As part of the study, a technology database was created. The activity's outcome is a technology assessment, evaluating the available European and on-going technology developments and COTS products for flight qualification. Non-EU technology has been also considered for completeness and comparison. Finally, selected technologies have been prioritized and candidate for further analyses to select final platform technology and to assess potential modification requirements to meet technology needs.

The technology shortlist definition was based on an iterative process and is shown in Figure 5. In the first iteration(s), to maintain a more general view of the problem, the mission scenarios, even the reference one, were neglected and all the functions connected to hypothetical missions of a multipurpose CubeSat were considered. To this purpose, the full Operational Capabilities (OCs) list was obtained performing a high-level functional analysis.

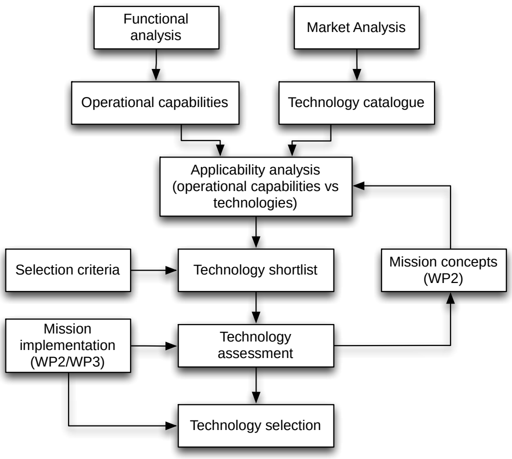


Figure 5 - Iterative process for the technology assessment and shortlist definition

As a result, a list of generic Technology Areas (TAs) has been developed. For each TA, the set of equipment/items (called building blocks - BBs) available or under development in Europe and outside Europe is identified via a thorough analysis of industrial and R&D capabilities. The outcome of this activity is a complete catalogue of potential technologies to be used in the context of a multi-purpose CubeSat-based platform.

The catalogue takes into account 9 TAs, further expanded in several categories where needed. The TAs are: *Deployment systems*, *Structures and Mechanisms*, *On Board Data Handling* (OBDH), *Power solutions*, *Attitude Determination and Control* (ADCS), *Communications*, *Propulsion*, *Navigation*, *Docking systems*, and *Cameras and spectrometers*.

For all TAs, common properties have been included, such as physical (i.e. mass, dimensions, material), thermal (i.e. operative and survival temperature range, thermal coefficients), design lifetime, electrical (i.e. input/output voltage, power), technology readiness, cost and developer (i.e. company, country). Some additional properties specific to each TA have been also identified.

A total of more than 200 building blocks have been identified within the TAs, and are included into the technology database. The database structure makes it suitable to be embedded in an automatic (future) design software.

To obtain the final technology shortlist, the following selection criteria were defined:

- Technology Readiness Level (TRL) and the heritage from previous missions
- Compatibility with ISS, that is whether the technology has been already used in conjunction with ISS operations or not
- Inherent Safety, that is the technology affects or not the safety of the ISS due to its inherent characteristics

and additional ones were defined for future implementations, such as modularity index (i.e. the ability of the technology to be included in a multi-purpose platform can be accounted in terms of commonality of interfaces, plug and play features), programmatic index (i.e. an index to take into account the efforts in terms of cost and time, and strategies to increase TRL, where needed), and cis-lunar compatibility.

A subsequent iteration on the technology catalogue was performed, by assessing and selecting a limited group of technologies which meets the system requirements, as summarised in Figure 6.

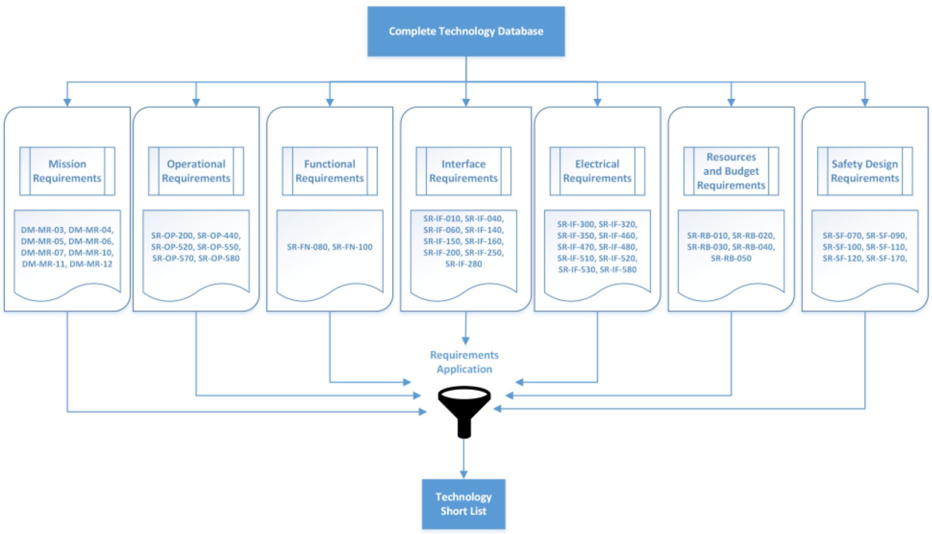


Figure 6 - Technology Shortlist Definition Process

3.5 Spacecraft Physical Descriptions

The spacecraft, shown in Figure 7 in its unfolded configuration, is defined as a Multipurpose CubeSat capable of accommodating specific ISS payloads. The spacecraft is a 6U picosatellite with dimensions and features shown in Figure 8. As generic constraint, the mass of the 6U CubeSat shall not exceed 12.00kg.

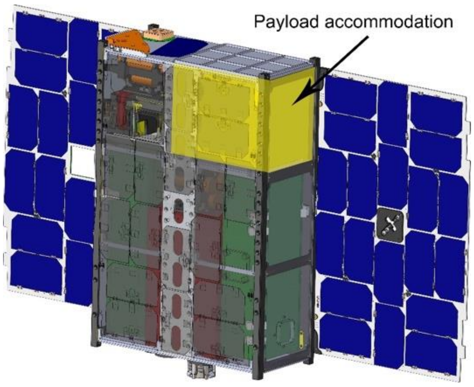


Figure 7 - Demonstrator Platform

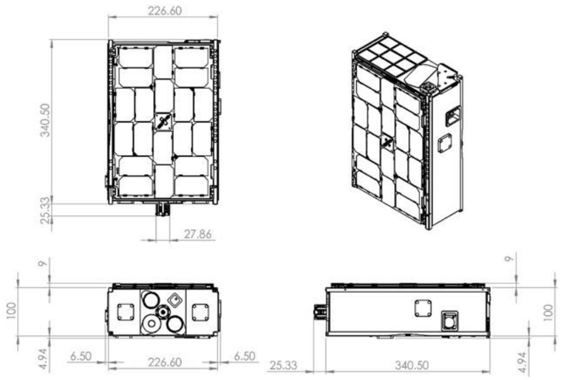


Figure 8 - Demonstrator general dimensions

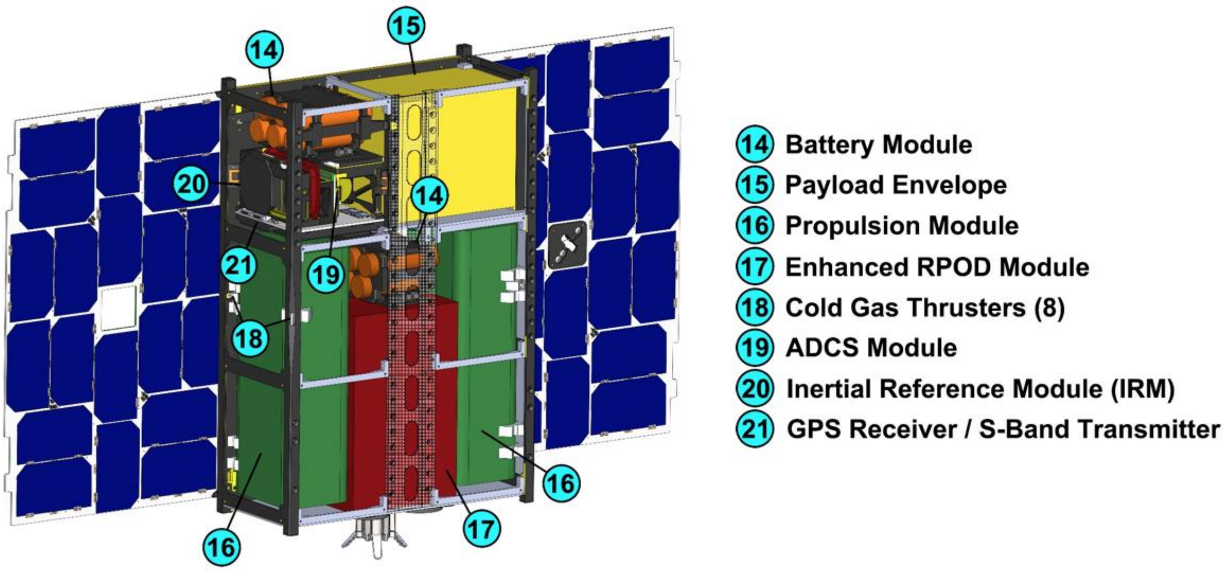


Figure 9: Possible internal configuration

4 Conclusions

A feasibility assessment has been performed as required, in terms of feasibility of the ISS multipurpose Cubesat objectives, and identification of major limitations of the potential applications. The major conclusions are:

- Many developments are ongoing in the CubeSat technology area at European level. For most part of the TAs, European technologies are at the highest level of development. No need to seek for non-EU developments is envisaged.
- Many developments still need to be proven in an operational environment, especially considering the level of reliability and safety required for a mission in the vicinity of the ISS (to be confirmed by safety assessment).
- Some criticalities have been identified in some TAs, in particular, a lack of dedicated/integrated/ready COTS solutions for relative navigation with respect to the ISS and a lack of dedicated 6U platform deployment system at the ISS has been found. It has been then recommended to assess the feasibility of the qualification of a “new” CubeSat deployment system from the ISS, which can also be used for the retrieval of the CubeSat, i.e. for docking/berthing (mating) and hosting a dedicated relative navigation element. A deployment strategies involving a Visiting Vehicle has been recommended for the first demo mission, which can leverage on existing space qualified 6U orbital deployers.
- Propulsion is the TA for which TRL and heritage are lower, although many efforts are currently being spent to develop propulsion system for CubeSats. This result is in line with the fact that most CubeSat missions to date have been accomplished with no propulsion on board. CubISSat would likely need a custom design and development of propulsion system element.
- Current ISS External Television Camera Group (ETVCG) camera capabilities, in terms of detectable resolution at max zoom are approximately:
    - 0.25 inch (6.35 mm) @ 25 feet (7.6 m)
    - 0.5 inch (12.7 mm) @ 50 feet (15 m).

  However, considering the above elements, it has been defined feasible to focus precise inspection activities of the demonstrator to those external features whose size is bigger or equal than 1 cm. Spatial resolution of 0.6cm can be considered as a reasonable target value for optical visible imaging from a distance of 200m (with goal of better performances for reference recurrent missions or from closer distance). The current Tyvak technology (CPOD heritage) characteristics have been used as reference for achievable resolution from 200m distance (outside KOS). The technology is space qualified and ready for flight in early 2017.
    - VIS imager: PSD = 1.1 cm; ORD = 2.1 cm
    - IR imager: PSD = 8.5 cm.

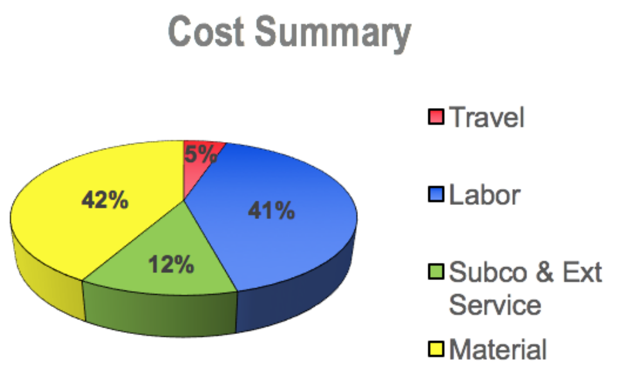
  Even better resolution performance can be achieved through a better lens focal ratio. With small modification, it would be possible to use a f/# 2.8 lens getting **0.53 cm** optical resolution for the instrument. Another possibility is to modify current imagers by using higher resolution sensor from the same manufacturer, with longer focal length (~150 mm). In this case, the following resolution performance can be achieved:
    - VIS imager: PSD = 0.18 cm; ORD = 0.25 cm
    - IR imager: PSD = 3.4 cm.

  For the abovementioned reasons the currently available technology is considered mature for implementation in CubISSat mission.
- A deployment from VV is feasible outside the KOS with an ejection velocity off about 0.5 m/s (achievable with existing 6U deployment system technology) in order to put the satellite

in a lower free drift safe orbit wrt ISS. A V-bar approach is can be performed from the safety hold ellipse to ISS proximity where a series of scan ellipses are performed in order to observe the target from different point of views.

- Final calculations on Total Delta-V and Propellant Usage (i.e. a reference cold-gas system has been assumed) show results compatible with implementation of a 6U platform satellite and cold-gas propulsion system.
- Considering the concept of operations envisaged, the approach to the analysis of safety requirements would suggest an iteration with ESA/NASA safety panel in order to revise the scenario approach and receive feedback on the applicability of requirements (or need of tailoring). The general approach in this case would be to try to avoid the spacecraft to be considered as a pure VV, at least for the standard deployment procedures and manoeuvres outside the KOS, leaving room for discussion on the applicability of SSP 50808 (or applicable tailoring) for the Rendez-Vous and Docking approach.
- Feasibility of the proposed CubISSat Program has been investigated at the end of the study and an estimate of effort and budget for the implementation of CubISSat project has been provided. The result of the assessment shows that the implementation is feasible within a timeframe of two years, including relevant margin for reviews and iterations. The ROM budget estimated for the performance of the activity amounts to ~6 M Euro. This is developed from a combination of direct labor estimates, materials, services and travel costs. Included in this budget amount is the development of the Dispenser/Docking platform, which counts for about ~1M EURO alone (including material, labor and testing). It is to be noted that a 20% margin has been used for direct labor cost calculation, therefore an optimization of the costing exercise is considered feasible, in order to meet the original objective of 5MEuro.

		duration (months)		ROM COST
1.0	PROJECT MANAGEMENT			
1.1	Program Oversight	24	€	30.643,20
1.2	Team Coordination	24	€	30.643,20
1.3	Program Reviews (10x)	3	€	22.024,80
1.4	Safety Reviews	1	€	7.341,60
2.0	SYSTEMS ENGINEERING			
2.1	Trade Studies and Analyses	12	€	57.456,00
2.2	System Requirements consolidation	5	€	23.940,00
2.3	Vehicle Modeling and Simulation	18	€	34.473,60
2.4	Mission Modeling and Simulation	20	€	38.304,00
3.0	PAYLOAD			
3.1	Payload coordination	18	€	22.982,40
3.2	Payload imaging sensors (VIS, IR)	11	€	84.268,80
3.3	Reconfigurable Payload Unit	11	€	63.201,60
3.4	RPU software for P/L plug&play	17	€	113.954,40
4.0	SPACECRAFT Design and development			
4.1	Bus development	7	€	73.735,20
4.2	ems dev (CDH, EPS, ADCS, space2ground)	12	€	126.403,20
4.3	space2space Comsys	17	€	65.116,80
4.4	Propulsion	17	€	179.071,20
4.5	Docking System	19	€	236.527,20
4.6	RPO software	18	€	120.657,60
4.7	Image recognition software	18	€	86.184,00
4.8	Vehicle flight software	18	€	120.657,60
5.0	DOCKING/DISPENSER PLATFORM			
5.1	System Design and Development	11	€	115.869,60
5.2	Subsystem Design and Development	11	€	115.869,60
5.3	Docking Platform Software	18	€	86.184,00
6.0	INTEGRATION AND TEST			
6.1	Mission Assurance (HITL & Flatsat)	14	€	111.720,00
6.2	Bus Subsystems AI&T	5	€	52.668,00
6.3	Bus System AI&T	4	€	34.473,60
6.4	Vehicle AI&T	7	€	60.328,80
6.5	Docking Platform AI&T	6	€	51.710,40
6.6	Docking Platform Integrated Testing	7	€	46.922,40
7.0	MISSION OPERATIONS			
7.1	MO plan	12	€	15.321,60
7.2	MCC development	17	€	65.116,80
7.3	Ground Network Coordination	9	€	34.473,60
7.4	UHF Ground Systems	9	€	34.473,60
7.5	S/X band Ground Systems	9	€	34.473,60
8.0	LAUNCH VEHICLE SERVICES			
8.1	Launch procurement and coordination	12	€	15.321,60
8.2	Deployer Procurem[illegible]	[illegible]	[illegible]	[illegible]
		Labor	€	2.443.156,80
		Material	€	2.504.922,00
		Subco & Ext Service	€	727.776,00
		Travel	€	257.115,60
		TOTAL	€	5.932.970,40



Category	Value
Labor	€ 2.443.156,80
Material	€ 2.504.922,00
Subco & Ext Service	€ 727.776,00
Travel	€ 257.115,60
TOTAL	**€ 5.932.970,40**

N.B. € 1.042.716,00 is entirely dedicated to the development of the DS1.0 Docking Platform

Figure 10: Development plan - cost summary

End of Document