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The 16U4SBSP Mission: a Swarm of CubeSats for Demonstrating Space-Based Solar Power in Earth Orbit

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Abstract

The 16U4SBSP mission concept is based on using a swarm of CubeSats to perform a scaled demonstration of Space-Based Solar Power (SBSP) from Earth orbit. In this demonstration mission, seven identical spacecraft of 16U format are used to provide wireless energy in the kW-scale using Radio-Frequency (RF) Wireless Power Transfer (WPT), and the spacecraft in the swarm are designed to be suitable to both space-to-ground or space-to-space WPT applications. The main objective of the mission is to validate the general concept of providing SBSP using a swarm of satellites instead of a monolithic configuration, as well as some of the involved miniaturized technologies, in view of full-scale missions which could serve users in remote areas with low power requirements or support emergency operations in blackout zones affected by unpredicted hazards (e.g. natural disasters). More in general, the mission would represent a low-cost precursor towards MW-GW scale SBSP to supply clean and affordable energy from space to large areas on the Earth surface. A pre-Phase A study of the mission, funded by the European Space Agency (ESA) through the Sysnova campaign "Innovative Missions Concepts enabled by Swarms of CubeSats", has led to encouraging results on the feasibility of the mission concept.

This paper summarizes the main results of the 16U4SBSP pre-Phase A study, including the mission design and the possible way forward to the following steps in mission implementation (Phase A and later). A summary of the spacecraft system design and mission analysis is presented, as well as a short description of the mission CONOPS (concept of operations). Particular focus is given to the available options and objectives of the SBSP demonstration, and to the proposed solutions for RF power beaming, formation flying maintenance and end-of-life operations for compliance to the new ESA regulations on space debris mitigation.

Keywords: 16U4SBSP, Swarms of CubeSats, Space Based Solar Power, Radio-Frequency Beaming, Wireless Power Transfer, ESA SysNova challenge

1. Introduction

16U4SBSP is a mission concept intended to perform a scaled in-orbit demonstration of Space-Based Solar Power (SBSP). In this demonstration mission, a swarm of 7 identical 16U CubeSats is intended to provide wireless energy at power levels in the kW-scale (total amount of received power on the Earth surface), using Radio-Frequency (RF) Wireless Power Transfer (WPT). Although the mission is mainly intended for space-to-ground demonstrations, the spacecraft in the swarm are designed in such a way to also be suitable to space-to-space WPT applications. The main objective of the mission is to validate the concept of providing SBSP by means of a swarm of satellites instead of a monolithic configuration. At the same time, however, the mission is also intended as an in-orbit demonstration for a number of miniaturized technologies. The ultimate objective is to pave the way to full-scale missions which could serve users in remote areas with low power requirements or support emergency operations in blackout zones affected by unpredicted hazards (natural or man-made). The mission therefore represents a low-cost precursor towards larger scale SBSP, where the actual transferred power would be in the MW-GW range, to supply clean and affordable energy to large areas on the Earth surface.

16U4SBSP was one of the proposals submitted to the European Space Agency (ESA) SysNova challenge "Innovative Missions Concepts enabled by Swarms of CubeSats", intended to generate new concepts for CubeSat swarm missions in Earth orbit and to quickly verify their usefulness and feasibility via short concurrent studies [1]. After the first phase of the challenge (open call for ideas), 16U4SBSP has been one of the seven proposals selected for performing a pre-Phase A analysis, funded by ESA.

This paper, after shortly introducing the mission requirements, analysis and phases, will provide a general overview of the beam forming strategy for wireless power transmission, the payload characteristics and the general 16U4SBSP spacecraft architecture, as well as the envisaged mission development and integration plan.

2. Mission requirements, scope and objectives

A comprehensive set of more than 400 requirements for the 16U4SBSP mission has been elaborated by the project team. Particularly relevant for the scope of this paper are the mission requirements, a selection of which is presented in Table 1 at the end of the paper. For a more detailed list of system and subsystem requirements, please refer to a companion paper presented at the same edition of the IAC conference [2].

As stated in these requirements, the scope of the 16U4SBSP mission is to *design, develop, commission and launch a commercial space-based solar power (SBSP) demonstrator based on CubeSats in a distributed swarm configuration*.

The primary mission objective is to *validate with a small-scale mission the beamforming power transmission model developed by the consortium and, in this way, confirm that it is feasible and convenient to provide SBSP by means of a larger constellation of spacecraft (larger both in terms of number, and size)*.

The mission is however also open to additional secondary objectives (e.g. technology demonstrations, complex formation flight concepts), defined as objectives for which their achievement is not functional to the success of the mission and to the achievement of the primary mission objective.

Other mission constraints specifically stated in the requirements are the use of RF waves for the WPT demonstration, the number of spacecraft in the swarm (not less than 7) and the total mission cost (not higher than EUR 100 million). Additionally, all spacecraft in the swarm shall be launched by the same rocket, with launch date not later than December 2029 as prescribed by the Sysnova challenge rules.

3. Mission analysis, Concept of Operations and phases

The envisaged concept of operations (CONOPS) for the 16U4SBSP mission can be summarized as follows:

- **Launch**, including transfer to the deployment orbit on-board the selected launch provider.
- **Deployment** from the launcher, directly in the target Sun-synchronous operational orbit.
- **Commissioning** of the spacecraft and all its sub-systems, which is assumed to take a maximum duration of 10 days after deployment.
- **Acquisition of initial formation** at 1000 m inter-satellite distance.
- **Testing and troubleshooting** of all sub-systems, formation flying and power beaming maneuvers in the initial formation configuration at 1000 m inter-satellite distance.
- **Acquisition of a "distant formation"** swarm configuration at 100 m inter-satellite distance.
- **Nominal operation** of the swarm in the "distant formation" swarm configuration, for a duration of 3-6 months, including formation maintenance maneuvers, with maximum achievable power beaming frequency of one power beaming every two orbits.
- **Acquisition of a "closer formation"** swarm configuration at 10 m inter-satellite distance.
- **Nominal operation** of the swarm in the "closer formation" swarm configuration, until the end of the mission, including formation maintenance maneuvers, with maximum power beaming frequency of one power beaming every two orbits.
- **End-of-life maneuvers** (if necessary), with a minimum possible mission lifetime of no less than 1.5 years, corresponding to the natural orbital decay time of the lowest Sun-synchronous orbit considered in the mission analysis presented in the following (500 km altitude).

Based on the above operations, four different mission phases are envisaged:

- **Deployment and Commissioning.** In this phase, after being released from the launcher, the spacecraft will perform an initial de-tumbling maneuver. Solar arrays will then be deployed and all subsystems commissioned. At the same time, all communication links will be established.
- **Formation Acquisition.** Each of the possible formation modes presented in the above CONOPS will be acquired by performing all required orbital and attitude correction maneuvers. Reaction wheels will be desaturated, and the power transmission payload will be commissioned (first formation acquisition) or re-configured (successive formation acquisitions).
- **Operative phase.** After acquiring the formation, all subsystems (including payload) will be calibrated. When in range with the target ground receiver, power transmission operations will be performed. Outside these power transmission windows, other operations will be performed, including: formation maintenance, orbital maneuvers, reaction wheels desaturation, communication to ground.
- **End-of-Life.** After decommissioning all subsystems, any necessary End-of-Life maneuvers will be performed.

Based on the above mission phases, a comprehensive mission analysis has been conducted, with the final goal of determining the most convenient orbit for the demonstration mission and, consequently, the required Delta-V budgets. For the deployment from the launcher, it has been assumed that the CubeSats are deployed every 30 seconds, with a velocity differential (with respect to the launcher) ranging from 1.6 to 2 m/s. All CubeSats are then distributed, through dedicated maneuvers, within a range of 1 km from a central reference point. In this configuration, an observation campaign is conducted for a maximum of 10 days, in order to acquire sufficient data to define the required Delta-V to acquire the formation. A first formation at inter-satellite distance of 1000 m is then acquired, in order to perform a general test and troubleshooting of all sub-systems at safer intersatellite distance. Figure 1 shows the required steps to go from the initial along-track distribution of the seven CubeSats in the swarm, to this 1000 m intermediate formation.

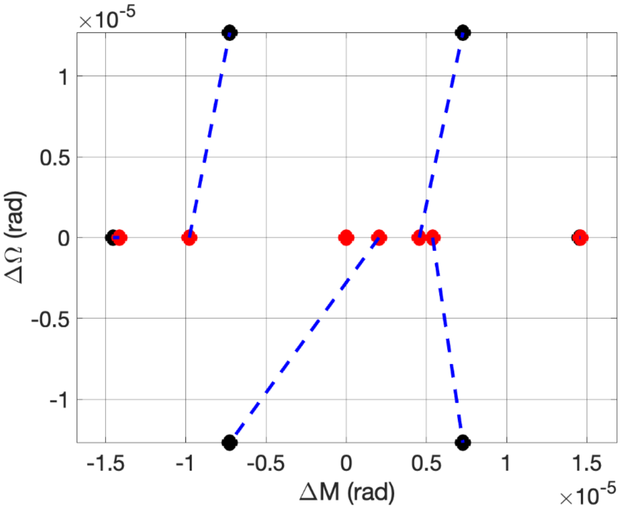

Fig. 1. Formation distribution from the along-track direction (in red) to the hexagonal formation (in black). The final and initial position in the *ΔM* - *ΔΩ* plane of each spacecraft is connected by a blue dashed line.

After this initial phase, the formation is then adjusted to decrease the inter-satellite distance to 100 meters, maintained for the first part of the mission (3-6 months). For the second part of the mission and until End-of-Life, the inter-satellite distance is then further reduced to 10 meters.

A comprehensive analysis, based on all possible perturbation sources (atmospheric drag, solar radiation, gravity gradient), was performed to define how frequently the formation needs to be controlled. For an attitude knowledge accuracy of 0.1 degrees, the results of this analysis show that the orbital position needs to be controlled every 7 days for 100 m inter-satellite distance, and every 2.5 days for 10 m inter-satellite distance.

Finally, for the End-of-Life phase, it is predicted that with an initial Sun-synchronous orbit at 500 km altitude, the CubeSats will re-enter the atmosphere within 1.5 years, thus staying compliant with the most recent ESA Space Debris Mitigation requirements. With higher Sun-synchronous orbits (600 km or 700 km altitude), an additional Delta-V from the main propulsion system would be required to allow for sufficiently fast End-of-Life maneuvers.

Table 2 presents the calculated worst-case Delta-V budgets for two possible Sun-synchronous orbits, at altitudes equal to 500 km and 600 km. Given the highly stochastic nature of these calculations, in order to determine the Delta-V budget and derive the main propulsion sub-system requirements, a 100% margin have been considered on all calculated Delta-V values, in compliance to the current ESA margin policies.

Table 2. Current worst-case Delta-V budget for 16U4SBSP, for two Sun-synchronous operational orbits.

Phase	***Δv* [m/s]** **500 km orbit**	***Δv* [m/s]** **600 km orbit**
Formation acquisition	75	68
Operative phase	130	90
End-of-Life	0	220
TOTAL	**205**	**378**

4. Beam forming and control

To maximize the amount of power transferred to ground, the 16U4SBSP mission aims to combining in a coherent way the beams of each individual spacecraft, by exploiting the capability to steer the beam using phased array antennas. However, this task is particularly challenging due to the uncertainties arising in the knowledge of the exact position of each platform during transmission and their exact attitude deviation with respect to the nominal pointing conditions. To overcome this issue, a strategy based on pilot signals from external sources is proposed for the mission. The pilots are signals emitted by cooperative ground stations and exploited by the distributed beam control software to estimate the actual position of the satellites with respect to a reference satellite. The estimated positions and electrical errors (phase and gain error) are then used to compute the exact complex valued weights to assign to each beam, ensuring the formation of a coherent composite beam pointing to the desired direction. This array calibration strategy is inspired by the approach presented in [3]. According to this reference, in order to calibrate the array, the pilot sources are not required to operate at the same time, which allows for significantly relaxing the ground segment design constraints. In the proposed design up to 4 calibration pilots are used, as three are required to remove the uncertainties related to location and electrical errors, while the fourth source is used to remove tapering uncertainties. However, the analysis performed for 16U4SBSP showed that tapering has a negligible effect, making it possible to use just 3 sources. Finally, it is also envisaged to use a circularly polarised transmitted signal, to avoid polarisation mismatch at receiver level.

The beamforming analysis, performed using the envisaged spacecraft antenna configuration as presented in the next Section and at the closest inter-satellite distance of 10 m, generated a gain distribution as function of the azimuth angle as shown in Figure 2. This analysis shows that the use of pilot calibration is an efficient strategy to compensate for uncertainties in position of the platform, allowing for a gain distribution close to the ideal one. Generally speaking, it was shown that in order to make the beamforming more efficient the number of spacecraft should be as large as possible, and the swarm shall operate at an inter-satellite distance as small as possible. The selected configuration for the 16U4SBSP mission, with seven CubeSats and an inter-satellite distance varying from 100 m in the first mission phase to 10 m in the second and final mission phase, was deemed to be the best compromise between beamforming efficiency, reduced collision risks and minimized mission costs.

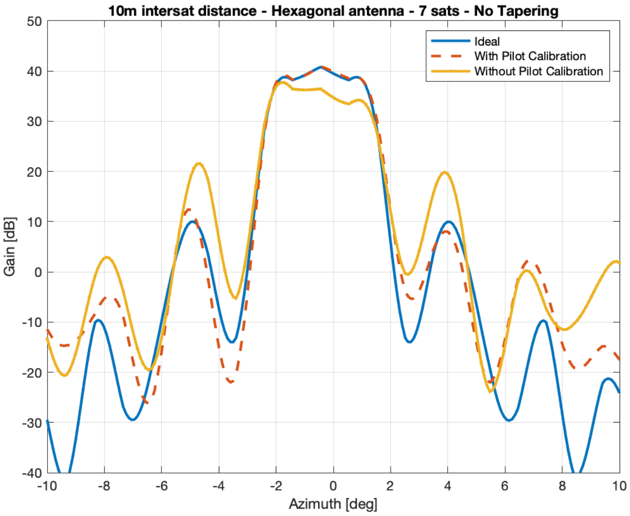

Fig. 2. Beam gain as a function of the azimuth angle, at 10 m intersatellite-distance for a swarm of seven 16U4SBSP CubeSats.

5. Payload design and integration

The power transmission antenna proposed for the 16U4SBSP mission is a deployable membrane hexagonal antenna, as shown in Figure 3 (fully deployed antenna). This configuration allows for a larger antenna size, improving the beamforming efficiency and the beam pattern. The concept, jointly investigated by Sirin Orbital Systems AG and its partner company Cosmobloom Inc, consists of a hold/release mechanism, a membrane film phased-array antenna, and electronics. Each triangular component has 240 antenna elements, and a full antenna consists of 6 triangular components. Microstrip lines are the preferential method for feeding the RF signal into the antenna components. Initial analyses performed by the project team showed that this deployable hexagonal configuration, compared to a non-deployable rectangular antenna body-mounted on the spacecraft, allows for improving the beam efficiency by a factor in the order of 10-12.

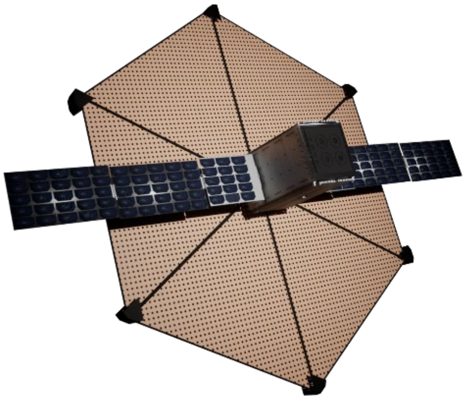

Fig. 3. Deployed hexagonal antenna on the 16U4SBSP spacecraft.

6. 16U4SBSP spacecraft architecture

The following Figures 4, 5 and 6 show renderings of the full 16U4SBSP spacecraft architecture, as derived from the pre-Phase A design. The total margined mass of the spacecraft, after taking into account all margins as prescribed by the ESA margin policies, is approximately 35.3 kg, which is compliant with the 36 kg maximum mass constraint set by the SysNova challenge rules. The volume of all subsystems fits with sufficient margin into the prescribed 16U CubeSat format.

The power budget for the operative phase shows that, even in a worst-case scenario in which power transmission to ground is performed every 2 orbits in eclipse (thus requiring multiple power receiving stations on ground), the available solar arrays power is sufficient to perform all operations, with a battery DoD equal to 34%. In a more realistic scenario with a single power receiving station on ground, the actual required power conditions will be less demanding. Given the very high amount of instantaneous power required in the operative phase, any possible power peaks in sunlight require less than the maximum available power from the solar arrays (144 W) and can therefore be sustained without using the batteries. In safe mode, all vital sub-systems require a power of less than 20 W, which can still be provided even with solar arrays orientation of 10° towards the Sun.

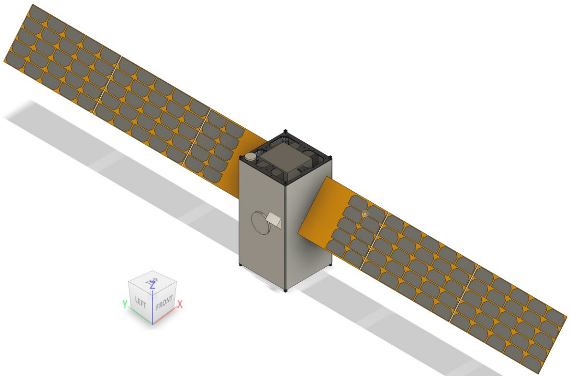

Fig. 4. Rendering of the 16U4SBSP spacecraft with cover panels, solar array wings deployed.

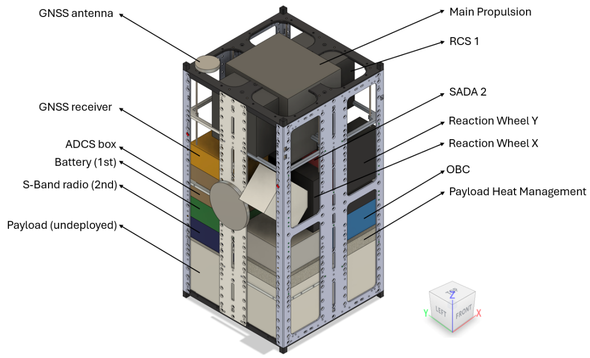

Fig. 5. X-/Y- view of the 16U4SBSP spacecraft without cover panels and solar array wings.

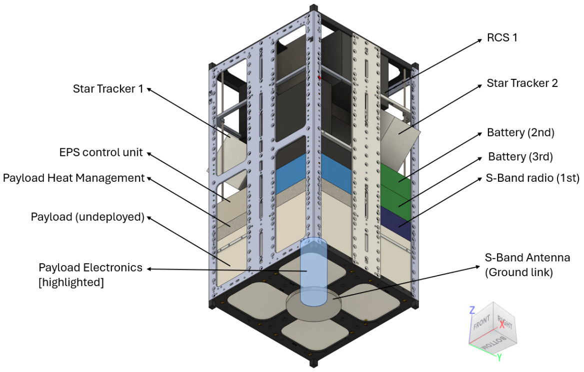

Fig. 6. Z- view of the 16U4SBSP spacecraft without cover panels and solar array wings.

For the main propulsion system, the Micro R^3 system produced by Enpulsion is selected, being the best one which matches all system and subsystem requirements (including a demanding total impulse requirement of 30000 Ns). Main task of this subsystem is to perform slow orbital control maneuvers for which no specific maximum maneuver duration is required. In the current spacecraft configuration, the presence of a RCS system is not strictly necessary, since not directly functional to the accomplishment of the mission needs: attitude control tasks can be fully accomplished by the reaction wheels, and wheels desaturation is performed by magnetic torquers. Nevertheless, a RCS system has been included in the spacecraft for additional 6DOF control authority, to support detumbling and reaction wheel desaturation if needed and as a higher-thrust system for emergency collision avoidance maneuvers. The IANUS 6DOF system (cold gas) designed by t4i for the Milani mission was selected, mainly due to its current maturity/development stage

For ADCS, the EnduroSat 16U system was selected, including an attitude control computer and three CW5000 reaction wheels. Since a star-tracker needs to be used to meet the required pointing accuracy under eclipse, the Sodern Auriga CP has been selected, given its capability of providing the required pointing accuracy at the expected spacecraft rotational rate. Navigation tasks are accomplished by a real-time GNSS receiver, the FUGRO SpaceStar.

The electrical power systems consists of a complete package from Kongsberg/NanoAvionics, including 4 stacked Li-ion battery units, power conditioning and power distribution units. The solar array wings are based on a fully customized design, built upon the 30% Triple Junction GaAs Solar Cell Assembly from AzurSpace and consisting of 2 separate wings, each with a total of 60 cells and, in one of the two wings, 25 cells on the back side. Given the challenging power generation requirements, the spacecraft is equipped with a solar array tracking mechanism, the µSADA system produced by the company IMT.

The communications subsystem consists of two identical sets of radio and antenna, one for inter-satellite link and one for ground communication. The selected S-band radio is the Syrlinks EWC31 model, while the selected antenna is the Anywaves S-Band TT&C antenna. For the structure, the 16U structure provided by EnduroSat is used, while the deployer is the EXOpod NOVA 16U S1 dispenser from ExoLaunch. The selected On-Board Computer is the Argotec FERMI OBC, mainly due to its superior data storage properties which might result useful in case particularly high data-demanding science goals are chosen as secondary mission objectives. Thermal control is mainly passive, with an external spacecraft coating combination consisting of 65% vapor-deposited Silver coating, 30% Silvered fused silica, 5% Aluminized aclar film. To deal with particularly demanding cold temperature extremes in eclipse, 5 active heaters are included in the spacecraft, each with 5 W heating power available, to be strategically placed close to the most critical sub-systems and components. Finally, in order to dissipate the estimated 132.4 W heat power losses during wireless power transmission, the 16U4SBSP spacecraft is equipped with a phase-change material box, used to store the dissipated energy in the form of latent heat while melting the phase-change material and then slowly releasing it back during the remaining part of the orbit in eclipse.

7. Development and Integration Plan

According to the ESA policies and guidelines for CubeSat missions, a preliminary Development and Integration Plan for the mission has been drafted, based on the following assumptions:

- Each spacecraft in the swarm will be considered a Protoflight Model (PFM), for which qualification and acceptance will be conducted jointly at the QAR milestone.
- An Engineering Model (EM) of the spacecraft will be developed and tested during mission Phase C. This EM will be based on a "FlatSat" philosophy, and will be used for testing all electronical, command and on-board data handling functionalities of the spacecraft.
- The payload will follow a parallel development, with its own PDR milestones: an initial PDR (for a reduced-scale triangular version of the deployable antenna), coincident with the PDR of the whole mission; and a second PDR (for the full-scale hexagonal antenna), several months later.
- All subsystems (including the payload with reduced-scale antenna configuration) will have reached TRL 6 at the PDR milestone of the mission.
- The official start of the mission Phase A is assumed to happen in January 2025.
- Two "contract negotiation" periods are assumed in the planning (both with 3 months duration), one for the negotiation of Phase B activities and one for the negotiation of Phases C/D.
- The duration and content of each mission phase is defined according to standard CubeSat programmatic approaches.
- A 3-months contingency period is assumed between the QAR milestone and the delivery of the CubeSats to the launch provider.
- The CubeSats are assumed to be at the launch provider premises 3 months in advance to the launch date.
- An in-orbit demonstration (IOD) mission is planned, as per the constraints posed by the Sysnova challenge, before the end of 2027. Scope of this IOD will be to demonstrate a reduced-scale swarm of 2-3 fully functional spacecraft, not focusing on demonstrating the full power level received on ground, but on demonstrating instead the most critical technology aspects to make the mission possible, namely: topology and characteristics of the received beam on ground; close formation flight concept including in-flight verification of all navigation, attitude determination and control functionalities; actual capability of the spacecraft in the reduced-scale swarm to beam power in a combined/concurrent way; in-flight qualification of the payload (including the transmitting antenna in a reduced-scale triangular configuration).

Based on all above assumptions and considerations, the preliminary Development and Integration Plan is shown in Figure 7. According to this plan, the mission would be launched in February-March 2029.

8. Conclusions

The 16U4SBSP mission, one of the selected concepts of the ESA SysNova challenge "Innovative Missions Concepts enabled by Swarms of CubeSats", has the primary objective to validate, with a small-scale mission, the Wireless Power Transfer (WPT) model developed by the mission consortium and, in this way, confirm that it is feasible and convenient to provide space-based solar power by means of a larger constellation of spacecraft. In order to achieve this ambitious objective, the mission aims at designing, developing, commissioning and launching a commercial space-based solar power (SBSP) demonstrator, based on a distributed swarm of 7 identical CubeSats.

The 16U4SBSP spacecraft is a 16U CubeSat equipped with a deployable hexagonal antenna constituted of triangular elements, for improved beamforming efficiency and beam pattern. To maximize the amount of power transferred to ground, the beams of each individual spacecraft are coherently combined, by steering the beam with phased arrays and employing a strategy based on pilot signals from cooperative ground stations, to estimate the actual position of the satellites with respect to a reference satellite. The mission implements a sophisticated formation flight strategy and is possible only if extremely good accuracy in terms of spacecraft attitude, pointing and orbital position knowledge is ensured. Nevertheless, in the current design, the 16U4SBSP spacecraft is mostly based on advanced COTS CubeSat technologies. In this way, the mission will also serve as a demonstrator for the use of viable, low-cost CubeSats platforms for ambitious swarm missions.

In this paper, the main characteristics, objectives and mission requirements of 16U4SBSP were presented. According to the currently envisaged development and integration plan, in case all necessary funding and support is secured, the mission could be launched as early as the first half of 2029.

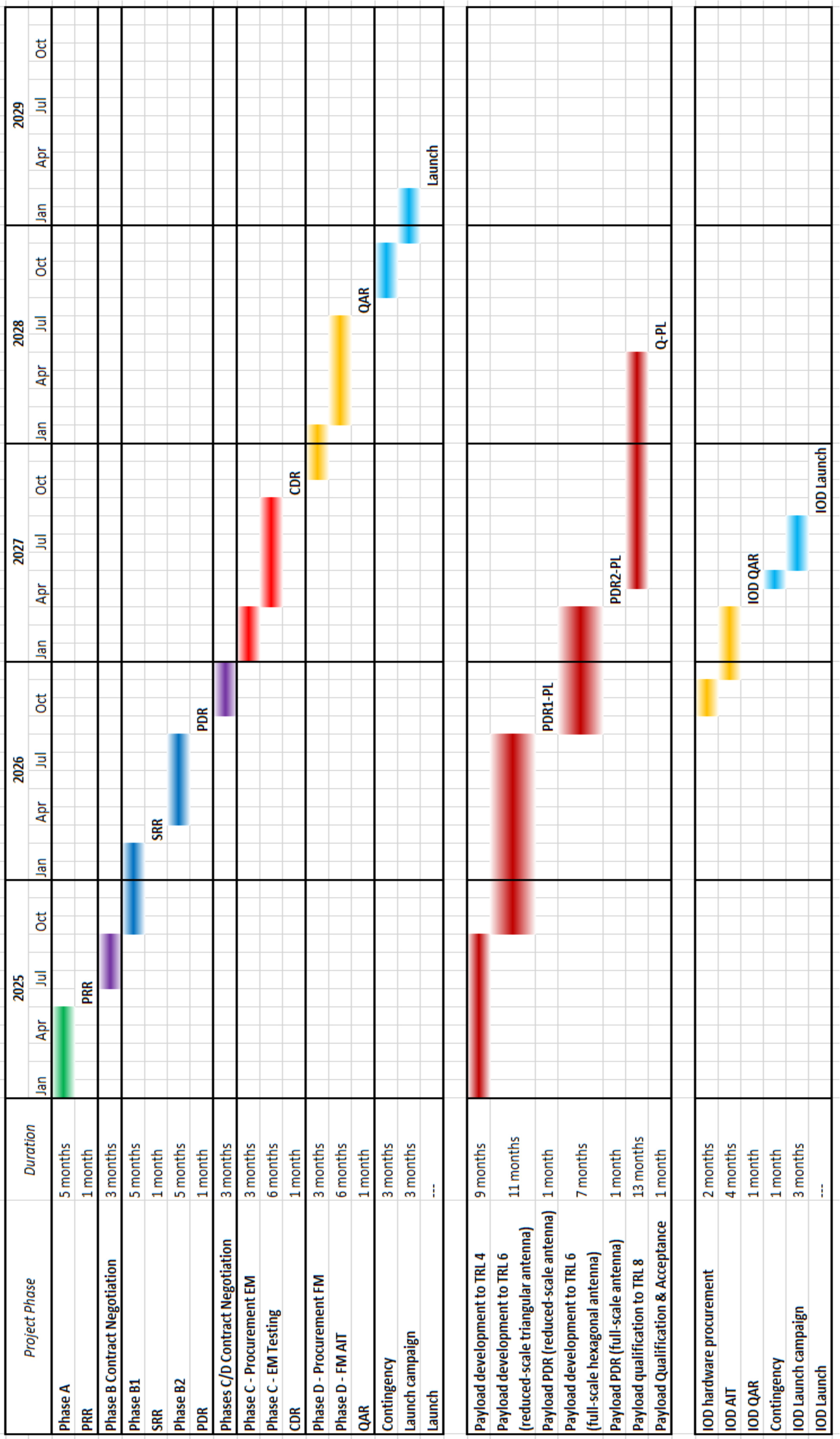

Fig. 7. Preliminary Development and Integration Plan for the 16U4SBSP mission.

Table 1. Selection of pre-Phase A mission requirements for the 16U4SBSP mission.

ID	Title	Requirement
MIS.010	Mission scope	The scope of the mission shall be to design, develop, commission and launch a commercial space-based solar power (SBSP) demonstrator based on CubeSats in a distributed swarm configuration.
MIS.011	Wireless transmission	The Wireless Power Transfer (WPT) demonstration shall be performed using RF waves.
MIS.012	Mission cost	The total cost for the whole mission shall be not higher than EUR 100 million.
MIS.013	Primary mission objective	The primary mission objective shall be to validate with a small-scale mission the beamforming power transmission model developed by the consortium and, in this way, confirm that it is feasible and convenient to provide SBSP by means of a larger constellation of spacecraft (larger both in terms of number, and size).
MIS.014	Secondary mission objectives	The mission shall include as many secondary mission objectives as possible (e.g. technology demonstrations, complex formation flight concepts), provided that they are not functional to the success of the mission and the achievement of the primary mission objective.
MIS.020	Mission segments	The mission shall include a space segment, a ground segment and a launch segment.
MIS.030	Space segment	The space segment shall consist of a swarm of no less than 7 CubeSats.
MIS.070	Launch segment	The spacecraft forming the swarm shall be launched within the same rocket, either as piggy back or dedicated payload.
MIS.090	Launch date	The mission shall be launched in the period from Jan 2028 (TBC) to Dec 2029 (TBC).
MIS.110	Initial orbit	The initial operational orbit of the swarm shall be a Sun-synchronous circular orbit at an altitude of 500 km (TBC).
MIS.114	Orbits of different spacecraft in the swarm	The spacecraft in the swarm shall stay in circular orbits with same altitude and same inclination, but different main anomaly and longitude of the ascending node (TBC).
MIS.150	Mission phases	The mission shall have the following phases: commissioning, initial formation acquisition, operation in initial orbit, closer formation acquisition, operation in closer formation, End-of-Life
DEMO.010	Uniqueness	The mission shall demonstrate RF Wireless Power Transfer (WPT) using a swarm of CubeSats as transmitting unit.
DEMO.020	Space-to-space demonstration	In case space-to-space demonstration is performed, the mission shall allow for wireless power beaming between the swarm of CubeSats and either (TBD): another CubeSat in the same swarm; or an already existing space asset, not part of the mission.
DEMO.030	Space-to-ground demonstration	In case space-to-ground demonstration is performed, the mission shall allow for wireless power beaming between the swarm of CubeSats and a (TBD) receiving station on Earth.
DEMO.040	Beam forming	The mission shall demonstrate beam forming methods for the signals generated by the phased-array transmitting antennas on each spacecraft of the swarm.
DEMO.050	DC-RF conversion	The mission shall include a demonstration of technologies for improved DC-RF conversion efficiency at the transmitter.

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