RODiO: a cluster of 16U Cubesats for in-orbit technological demonstration of distributed radar imaging and hybrid propulsion

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RODiO is an innovative mission concept which has successfully concluded phase A study in the framework of the ALCOR program, funded and coordinated by the Italian Space Agency. The main objectives of the mission are i) in-orbit technological demonstration of Distributed Synthetic Aperture Radar (DSAR) concept; ii) in-orbit-demonstration of a novel hybrid rocket propulsion system for formation reconfiguration and iii) the validation of new SAR measures and products suitable for a commercial/scientific downstream. To reach these objectives, the mission relies on a cluster of 4 CubeSats. All the Cubesats embark a receiving-only X-band SAR instrument able to collect bistatic echoes exploiting PLATiNO-1 (PLT-1) SAR satellite as an opportunity illuminator, and one of the CubeSats hosts a novel hybrid rocket propulsion unit that enables orbit reconfiguration. As conceived, the mission foresees that all the Cubesats flies both in formation with PLT-1, at a safe distance of tens of km, but also formation-flying techniques are used to keep all the CubeSats in the cluster within an overall envelope of a few hundred meters, until the orbit reconfiguration maneuvers occurs, in which one Cubesat flyes far away in across track direction. The paper shows an overview of the mission with specific focus on space segment.

1 MISSION OVERVIEW

RODiO is an innovative mission concept which has currently concluded phase A study in the framework of the ALCOR program [1]. As represented in Figure 1, the mission relies on a cluster of 4 CubeSats flying in formation with PLATiNO-1 (PLT-1) SAR mission. The CubeSat cluster flies at a safe distance of tens of km from PLT-1, and formation-flying techniques are used to keep all the CubeSats in the cluster within an overall envelope of a few hundred meters. Each CubeSat embarks a receiving-only X-band SAR instrument able to collect bistatic echoes exploiting PLT-1 as an opportunity illuminator. The passive radar, including a very compact receiving unit and the proper

deployment mechanisms for the antenna, is conceived to comply with a 16 U CubeSat. In addition, one of the CubeSats embarks a novel hybrid rocket propulsion unit that enables orbit reconfiguration. The main objectives of the mission are i) in-orbit technological demonstration of DSAR concept (multi-platform image synthesis); ii) in-orbit-demonstration of a novel hybrid rocket propulsion system for formation reconfiguration and iii) the validation of new SAR measures and products suitable for a commercial/scientific downstream.
In the framework of the first objective, RODiO is expected to achieve high imaging performance through a series of very compact, low weight, platforms. Receivers can be assumed as self-sufficient from the point of view of their payload, that is each receiving unit, as an isolated entity, generates a bistatic SAR image. However, owing to the low SWAP (Size Weight And Power) characteristics of the receiving platforms, the achieved performance by these bistatic images is not complaint with operational applications. Nonetheless, applying DSAR techniques [2]-[3] to the raw data collected by each receiver, RODiO, as a cluster of CubeSats, is able to generate a high-quality bistatic SAR image. Indeed, when multiple close receiving platforms are available, DSAR theory guarantees a power gain factor equal to the number of receivers and an improvement of image quality (e.g. ambiguity suppression) through the application of multi-platform image synthesis techniques.

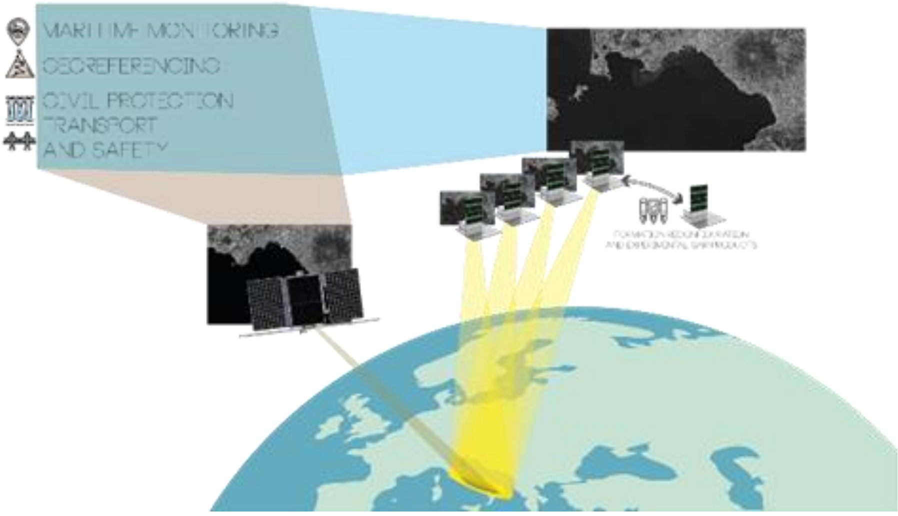

Figure 1. RODiO mission concept

The approach proposed for RODiO image synthesis is based on the principle that the imaging properties of all the available receivers, when analysed as isolated items, are very similar. However, since receivers work from different locations, the phases of the bistatic images are different and can be used to synthesize a further array called spatial diversity array. This is the physical array realized by the relative positions among the receivers in the cluster. Hence, DSAR array pattern is the product of two main contributions [3]:

- The common array pattern, which measures the contribution of a single receiver in the formation as an isolated item.
- The spatial diversity array pattern, depending on the baselines among the receivers. It characterizes the added value of the DSAR in which more than a single receiver is available.

According to basic array theory, the radiation pattern of a generic array is defined as the coherent weighted sum of the signals collected by each element of the array. Suitable weighting functions are adopted to provide the array with some desired features, such as pointing the array towards an assigned direction and filtering out noise or unwanted signal from specific directions. Hence, the combination of the common and the spatial diversity arrays by suitable beamforming techniques leads to the resulting high-quality DSAR image, i.e. multi-platform image synthesis.

In RODiO case, the goal is to generate SAR images with similar performance with respect to PLT-1 ones. For this purpose, the expected performance improvements with respect to the single-channel bistatic SAR image include:

- Signal to Noise Ratio (SNR) improvement [3]-[4]. Working with N receivers, as an effect of the coherent combination of the raw bistatic signals the SNR achieved by a DSAR is the sum of the SNR of each bistatic receiver. Moreover, if short baselines are established, range variations among the receivers can be neglected, thus the SNR is the same for all receivers. So, SNR can be improved up to a factor given by the number of adopted receivers.
- Ambiguity level enhancement [2],[5],[6]. Null-steering techniques can be applied to suppress the desired ambiguous contributions. Specifically, the short receiving antenna of the receivers implies that a large Doppler Bandwidth is established. The latter can remain under sampled by the PRF of the transmitter, so that azimuth ambiguities arise in the SAR image. DSAR instead is able to synthesize an increased PRF up to a factor given by the number of available receivers, thus reducing azimuth ambiguity signal level.

The second objective is reached thanks embarking on one of the CubeSat platforms a flight demonstrator of an innovative hybrid rocket propulsion unit.This propulsion system has been conceived to answer the needs of future formation-flying missions requiring the orbital reconfiguration of the formation. The subsystem is miniaturized following CubeSat standards, occupying a volume of 1-1.5U, and weighing less than 2 kg.
At the end of the mission, the CubeSat embarking this propulsion unit will fly far from other platforms in the cross-track direction. This phase has been planned: i) to demonstrate in-orbit a high-thrust propulsion system capable of performing reconfiguration; ii) to enable novel multistatic SAR data collections at different observation geometry. Indeed, the data gathered in the final reconfigured positions represent a triplet of acquisitions over the same area at three different observation angles.
Therefore, this subsystem has a twofold outcome. The design, development, and testing of the hybrid rocket propulsion system, specifically tailored for CubeSats, and its flight demonstration allows for validating a key enabling technology. Moreover, SAR acquisitions performed by the manoeuvring CubeSat can be exploited to demonstrate new SAR products based on the simultaneous availability of three different images collected over the same area with different observation geometry.

Finally, RODiO's aim is also to demonstrate new SAR products taking advantage of the strong synergy and cooperation with the pre-existing PLT-1 mission. The idea is that the high quality bistatic SAR images generated by RODiO can be processed together with the corresponding monostatic PLT-1 ones collected over the same area, so that the products resulting from this combination can benefit from the increase of qualitative and quantitative measurements above the observed scene. These products are expected to widen PLT-1 application fields, so they are expected to be complementary and synergic to those planned in the framework of the PLT-1 mission. Moreover, due to the nature of the mission, the added value will be in the novelty of the products rather than in their amount.
The individuated products derive from the bistatic geometry of the system. Depending on the involved baseline, the cluster observes the same scene as that of the transmitter but from different perspective (bistatic angle) and a different time instant (owing to different bistatic range history). Hence, comparing at the amplitude level the monostatic image to the bistatic one resulting from multi-platform image synthesis, original applications can be realized which are impossible or limited in accuracy for monolithic systems.
This principle is exploited for the generation of the products relevant to a wide range of application domains through different techniques. The Sub-Pixel Offset Tracking (SPOT) is used to process SAR images with subpixel accuracy extracting surface displacements based on monostatic-bistatic pixel offset [7]. Thanks to this technique, land deformation and flood risk can be measured, and infrastructures can be monitored, thus aiding civil protection and safety tasks. Moreover, Digital Elevation Models (DEM) can be generated applying suitable radargrammetric techniques. As an

example, through the solution of the so-called bistatic rigorous SAR stereo problem [8], a pair of monostatic-bistatic images can be processed so to measure the elevation of targets on the observed scene. The same method can be applied on a triplet of images rather than just a couple of them, in such a way to improve DEM accuracy. This may be possible by exploiting the manoeuvring capabilities of the RODiO CubeSat embarking the hybrid propulsion unit. Indeed, after its orbit reconfigurations, this receiver can collect an additional image over the same area from a different line of sight that can be used together with the other images generated by the rest of RODiO cluster and by PLT-1. The aforementioned radargrammetric techniques can be applied to estimate ship velocity as well. In particular, the azimuth component of this velocity can be measured due to the bistatic geometry of the system characterized by a long along-track baseline. For the same reason, RODiO also shows different imaging properties with respect to PLT-1 that can be used for different purposes. As an example, ambiguities in RODiO images are expected to be displaced with respect to the ones in PLT-1 images. This property can be exploited in ship detection algorithms, improving their rejection capabilities of false alarms caused by azimuth ambiguities. Last but not least, wake analysis can also take advantage of the additional bistatic information provided by RODiO. Owing to the long baseline between PLT-1 and RODiO cluster, different wake features are expected to be imaged, thus improving the overall detectability and analysis of the wake.

2 SPACE SEGMENT

Four satellites will be developed in the frame of RODiO mission, to be launched into a formation flying configuration to implement a Distributed Synthetic Aperture Radar (DSAR) architecture with PLT-1 satellite as the illuminator. In this section, an overview of platform design is shown focusing on the one equipped with hybrid propulsion system.

RODiO satellites platform is based on a 16U CubeSat category with shape and envelope allowing for the deployment by a standard 16U CubeSat deployer. The selected CubeSat class is the result of an in-depth trade-off analysis, that has been performed during the first phase of the project. This preliminary assessment has been conducted to damp, from the very beginning, the high risk of selecting a platform category not compliant with RODiO mission and payload needs.

To enable the accomplishment of mission objectives, each CubeSats is designed to:

- receive bistatic SAR echoes and to download bistatic raw data to the ground;
- fly in formation with the other elements of the cluster and with PLT-1;
- guarantee routine satellite operations and tasks.

The common design driver is the miniaturization. COTS components with flight heritage, or with flight heritage expected in a timeframe compatible with the project, have been selected though trade-offs processes and efforts will be put to identify available solutions/technologies.

Moreover, the structure of the CubeSats, together with the deployment mechanisms, are designed to accommodate the payloads minimizing the total envelope of the satellite and to guarantee the deployment of the SAR antenna. The proposed layout allows for the maximization of volume available for the payload, ensuring at the same time robust power properties and thermal control.

The identified satellite solution is designed to have a nominal operational lifetime of 1 year, in order to be compliant with RODiO mission timeframe, and must be compatible with LEO environment.

A high-level description of the platform most demanding subsystems is reported in Figure 2, focusing mainly on their performances and functionalities. The selection and the dimensioning of these subsystems has been performed according to mission assumptions, platform analysis and payload requirements. The latter refers both to SAR antenna and Hybrid propulsion system (HPS).

The best antenna architecture for RODiO mission has been designed by a trade-off analysis. Parameters taken into account are RF performance, available envelope and mass. The last two aspects are particularly critical because of available platform sizes. On the other hand, to meet RF requirements for SAR applications a large radiating aperture is needed, leading to selection of deployable low-profile antennas. Two different solutions have been investigated for the SAR antenna architecture: a Direct Radiating Array (DRA) and a Reflect-Array (RA). Both solutions are based on flat panels that have to be deployed after launch forming the whole antenna aperture. Finally, the proposed baseline obtained from the outcomes of this trade-off is an Antenna based on Reflect-array solution.

The innovative hybrid rocket propulsion unit is miniaturized in accordance with CubeSat standards, occupying a volume of 1.5U, and weighing less than 2.5 kg. The propulsion unit is activated at the end of the main DSAR mission in order to reconfigure the CubeSat formation. Thanks to this approach, there will be the possibility to demonstrate an additional technology by the same mission without putting at risk the success of the DSAR demonstration. The propulsion system, allowing to carry out the orbital manoeuvres considered in this mission with thrust on the order of 10 N, will use low-cost and easily procurable polymeric fuels (such as ABS or HDPE) and, as a liquid oxidizer, hydrogen peroxide, which is a non-cryogenic propellant, environmentally-clean, with reduced toxicity, low storage and handling costs, and which allows a simplified design of the thruster, besides a rich heritage of safe, industrial use. The exothermic catalytic decomposition of hydrogen peroxide, achieved by means of a catalytic bed, favours its application in hybrid propellant rockets thanks to heat release, which allows the fuel to self-ignite, overcoming the need for a separate ignition system, thus favouring compliance with the stringent volumetric constraints imposed by the CubeSat standards. In addition, the fact that hybrid peroxide systems tend to achieve optimal performance at high mixture ratios provides an advantage in reducing the size of the combustion chamber, besides decreasing the sensitivity of these thruster to instability in fuel consumption, which constitutes only a limited fraction of the total propellant mass.

The platform design is defined considering the most critical configuration including the Hybrid Propulsion Unit on-board. The platform design is studied in order to satisfy the payload requirements and accommodate properly the other subsystems on-board. In particular, the position of the subsystems' components is defined in order to grant the correct functionalities of the payload and maximize the performance of the satellite. Specifically, the main drivers for the definition of the configuration are:

- The deployment and accommodation of the radar SAR;
- The accommodation of the SAR electronics;
- The misalignment between the Center of Mass (CoM) of the satellite and the electric propulsion system;
- The misalignment between the Center of Mass (CoM) of the satellite and the hybrid propulsion system;
- The operative temperature ranges of the components;
- The electromagnetic compatibility among the system components;
- The presence of deployable appendages;
- The Field of View (FoV) of the AOCS sensors;
- The maximization of the power generation.

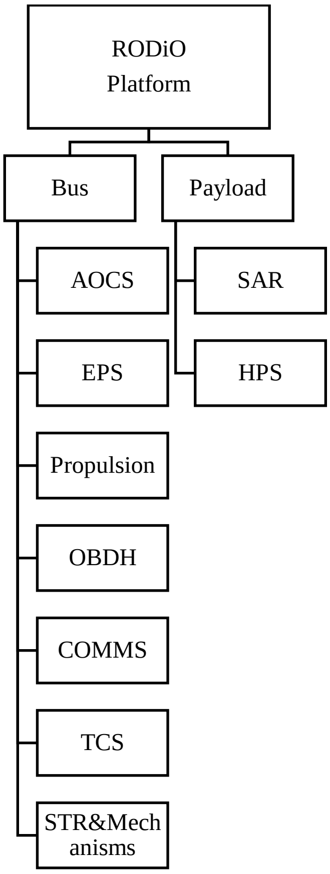

Figure 2. Block Diagram of RODiO platform

The following picture show the 16U proposed satellite in stowed and deployed configurations including the Hybrid Propulsion System, that is required to be embarked as a second P/L in only one of the four RODiO satellites. Moreover, a graphical representation of the body reference frame adopted for the description of the platform is provided by Figure 3.

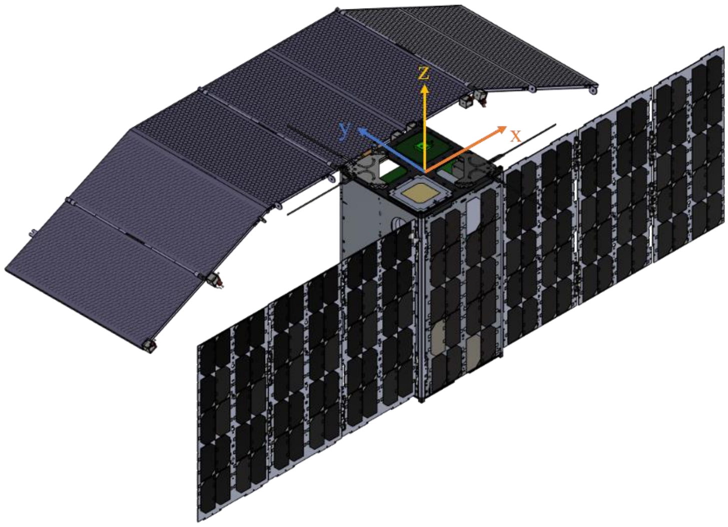

Figure 3. Graphical representation of the CubeSat body reference frame

The platform design is based on a modular approach implementing the following elements:

- Attitude and Orbit Control Subsystem (AOCS)
- Electrical Power Subsystem (EPS)
- Propulsion Subsystem (PRP)
- On-Board Data Handling (OBDH)
- Communication Subsystem (COMMS)
  - Based on X-band transmitter for downloading of bistatic raw SAR data recorded onboard
  - TT&C functions (S-band transponder and antennas)
  - Inter-satellite link capability using the MPCU Subsystem (double transceiver module at UHF and VHF frequencies)
- Thermal Control Subsystem (TCS)
- Structure (STR) and Mechanisms

Attitude and Orbit Control Subsystem (AOCS)

RODiO Avionics Subsystems integrates the Attitude and Orbit Control functions. Specifically, the AOCS is in charge of guaranteeing stable and precise 3-axis pointing of the spacecraft, as well as attitude maneuvering and control capability during the whole mission lifetime. In order to be compliant with the S/C pointing requirements specified by the mission analysis for the SAR image synthesis, the AOCS shall be able to guarantee a pointing accuracy lower than 0.03°, which is around the 5% of the angular aperture of the TX main beam. This means that the AOCS shall be able to provide a pointing knowledge lower than 0.003° (the pointing knowledge shall be an order of magnitude lower than the pointing accuracy).

The selection of the attitude determination hardware is influenced directly by the sources available for attitude determination during all mission phases. The RODiO mission environment is characterized by a low altitude orbit, meaning that the measurements of the Earth magnetic field could be exploited to determine the satellite attitude together with the estimation of the Sun direction and the observation of the stars. In particular, the stringent requirement on the attitude determination

implies the need of a Star Tracker-based AOCS on-board the RODiO platforms. Furthermore, to guarantee a robust and reliable attitude determination, several Sun sensors must be included inside the RODiO platform together with the magnetometers and a high-performance GNSS system.
To satisfy all the requirements on the attitude determination and control, the Attitude Control System XACT100, developed by Blue Canyon Technologies, is proposed as baseline for the AOCS subsystem of the RODiO satellites. Its design is compatible with a wide range of satellite configurations and includes an accurate stellar-based attitude solution. Moreover, it is able to host four reaction wheel RWp0100 and provides a powerful processing core enabling a precise attitude knowledge and control for cost-efficient miniaturized spacecraft. In addition, the proposed Attitude Control System has already been flight proven (TRL 9) and is characterized by a compact packaging.

Electrical Power Subsystem (EPS)

The EPS has been designed performing a parametric analysis using as baseline flight-proven components the ISIS Lithium-Ion battery packs and Endurosat 8U deployable Solar Panels and considering CubeSats volume and mass constraints. Within the parametric tool, the battery pack sizing has been conducted by considering a worst-case scenario with a 24-minute eclipse duration, a Sun Aspect Angle of 31.4°, the peak power requirements associated with formation maintenance maneuvers and a maximum Depth of Discharge (DoD) set to 80%. The proposed solar arrays configuration is capable of generating a maximum power more than 150W in daylight and a minimum power larger than 100W in worst-case scenario. Hence, it is possible to highlight that the designed EPS is able to satisfy the power demand of the RODiO system and to charge completely the Lithium-Ion batteries during the SAR Acquisition Mode.

Propulsion Subsystem (PRP)

The Electrical Propulsion System selected for this mission is REGULUS-50-I2, which is a miniaturized, robust, versatile and cost-effective low-thrust PRP system. REGULUS-50-I2 enables new mission scenarios and efficiently makes in-track maneuvers possible, compensates drag in VLEO\LEO and performs end-of-life operations
More specifically, REGULUS-50-I2 is composed by the following elements:

- The thruster sub-system, based on MEPT technology
- A thermal radiator
- A tank with iodine propellant mass
- Electronic boards for controlling and conditioning
- Propulsion Power Unit (PPU).

On-Board Data Handling (OBDH)

A preliminary definition of the OBDH design has been carried out for the most critical aspects, as the electrical and mechanical interfaces, main parts specifications, budgets, processing and storage capabilities, communication protocols, etc. A remarkable aspect is that they have been considered in a single unit, both the typical tasks of a satellite OBDH and of a payload data system dedicated to the high level general management of the SAR payload and data acquisition and storage.
The OBDH digital electronics baseline is based on a Polarfire Flash FPGA by Microchip implementing all the processing functionalities and interface protocols. Indeed, the PolarFire FPGA appears a good candidate; it is not volatile and available in different quality grade: MIL, Space, but also the industrial (with same silicon die) which exhibits tolerance to radiation and might be a good choice for a low cost Cubesat.
Moreover, this FPGA permits the implementation of an embedded system-on-chip (SoC) whose main components will be:

- a soft-IP processor belonging to the RISC-V family running the OBDH Software
- processor bus structure, system memory controller and standard peripherals

- third part VHDL IP core (e.g. CAN bus, SpaceWire, etc.)
- all other front-end functionalities requiring deterministic timings for the I/F with HW components, implemented by specialized lower level logic blocks custom developed in synthesizable VHDL (e.g. flash devices, different types of memories and I/F chips, Multi-Gbit link, etc.)

Communication Subsystem (COMMS)
The communication system of RODiO is based on several units used to support all required services:

- an X-Band transmitter to download the bistatic raw SAR data recorded onboard. The possibility to use SAR antenna for data download shall be investigated to reduce weight and complexity.
- an S-Band full duplex transceiver for the satellite's TT&C transfer. The possibility to use this link as an inter-satellite ranging and TLC system shall be assessed to support both formation flying and P/L operations.
- a Multi-Purpose Communication Unit (MPCU) to transfer raw GNSS navigation data among the satellites for RTK relative positioning in a time division multiple access scheme. This unit is also able to establish automatic low bit rate radio link and to transmit selected critical telemetry data to the ground. It includes:
    - Double Transceiver module at UHF and VHF frequencies for communication link with the ground Station and inter-satellite link;
    - Navigation Board for the geo-localization data management, completed with data and power interfaces with the satellite platform;
    - two dipole (deployable) antennas.

Structure (STR) and Mechanisms
The CubeSat Structure module provides the structural backbone of the satellite, playing a vital role in the overall system. Despite its relative simplicity, it fulfills a crucial function by accommodating other modules within it, such as the Electric Power System (EPS), On-board Computer (OBC), and payloads, while also allowing for the attachment of additional components like solar panels and antennae on its sides. The structure module shall also withstand launch loads and resist to the harsh orbital environment.
For RODiO satellites the Endurosat 16U Cubesat Structure is considered as baseline. EnduroSat's 16U CubeSat Structure adheres completely to the CubeSat standard and is compatible with a wide range of third-party CubeSat subsystem manufacturers' products. It is made by the space-grade 6082 aluminum alloy, ensuring both lightweight properties and robustness. The structure is 226.3 × 226.3 × 454 mm and is treated with hard anodization. A full campaign of tests at qualification level has already been performed on the the Endurosat structure following the European Space Agency (ESA) standard ECSS-E-ST-10-03C.

3 CONCLUSIONS

RODiO mission has two main phases. The first one in which it aims to achieve high imaging performance through a series of very compact, low weight, platforms. Receivers can be assumed as self-sufficient from the point of view of their payload, that is each receiving unit, as an isolated entity, generates a bistatic SAR image. However, owing to the low SWAP (Size Weight And Power) characteristics of the receiving platforms, the achieved performance by these bistatic images is not complaint with operational applications. Nonetheless, applying DSAR techniques to the raw data collected by each receiver, RODiO, as a cluster of CubeSats, aims to generate a high-quality bi-static SAR image, through the application of multi-platform image synthesis techniques. The second one

focuses on the innovative hybrid rocket propulsion unit. It has been conceived to answer the needs of future formation-flying missions requiring the orbital reconfiguration of the formation in terms of sizing and utilization. Indeed, the subsystem is miniaturized following CubeSat standards, occupying a volume of 1-1.5U, and weighing less than 2 kg. But, also, it allows to demonstrate in-orbit a high-thrust propulsion system capable of performing reconfiguration and to enable novel multistatic SAR data collections at different observation geometry. Indeed, the data gathered in the final reconfigured positions represent a triplet of acquisitions over the same area at three different observation angles. Therefore, this subsystem has a twofold outcome. The design, development, and testing of the hybrid rocket propulsion system, specifically tailored for CubeSats, and its flight demonstration allows for validating a key enabling technology. Moreover, SAR acquisitions performed by the maneuvering CubeSat can be exploited to demonstrate new SAR products based on the simultaneous availability of three different images collected over the same area with different observation geometry.
With specific reference to space segment, a 16U standard Cubesat can be considered the reference platform for RODiO and its design has been carried out with the common design driver of miniaturization, with particular reference to: (i) the passive radar, including a very compact receiving unit and the proper deployment mechanisms for the antenna; (ii) the hybrid propulsion system; (iii) the electrical propulsion system, as the only propulsion system to enable the formation flying with the other elements of the cluster and with PLT-1.
COTS components with flight heritage, or with flight heritage expected in a timeframe compatible with the project, have been selected though trade-offs processes. The structure of the CubeSats, together with the deployment mechanisms, are designed to accommodate the payloads minimizing the total envelope of the satellite and to guarantee the deployment of the SAR antenna. The proposed layout allows for the maximization of volume available for the payload, ensuring at the same time robust power properties and thermal control. The identified satellite solution is designed to have a nominal operational lifetime of 1 year, in order to be compliant with RODiO mission timeframe, and must be compatible with LEO environment.

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