EXCITE - A 12U CUBESAT MISSION FOR IOD/IOV

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ABSTRACT

EXCITE (“EXtended Cubesat for Innovative Technology Experiments”) is a technology demonstration mission selected by ASI in 2021 in the frame of the "Future Cubesat Missions" call. Based on a custom-designed 12U CubeSat platform featuring a full-composite structure, EXCITE is aimed at in-orbit demonstration / in-orbit validation of a number of innovative small spacecraft technologies in the domains of chemical and electric onboard propulsion, thermal management of significant heat loads in limited volumes, COTS GPU computing for IoT applications, and steerable, integrated S-band antennas. In this paper we describe the EXCITE platform design, outline the mission profile and discuss the main expected technological innovations.

1. INTRODUCTION AND BACKGROUND

The EXCITE mission is jointly developed by a team including the University of Pisa as team leader. The mission proposal was prepared in late 2020 in response to ASI’s call for Future Cubesat Missions and was selected in 2021. Four SMEs based in the Tuscany region act as industrial partners: Aerospazio Tecnologie, a small company of the Siena/Livorno area with a strong background in space propulsion and testing; CRM Compositi, a structural workshop specialized in composite materials in Livorno; IngeniArs, a spin-off company of UniPi, dedicated to space electronics; and MBI, a telecom company located in Pisa, active in satellite telecommunications and networking. The consortium is a working example of a regional-scale initiative leveraging on Cubesat technology for local development.

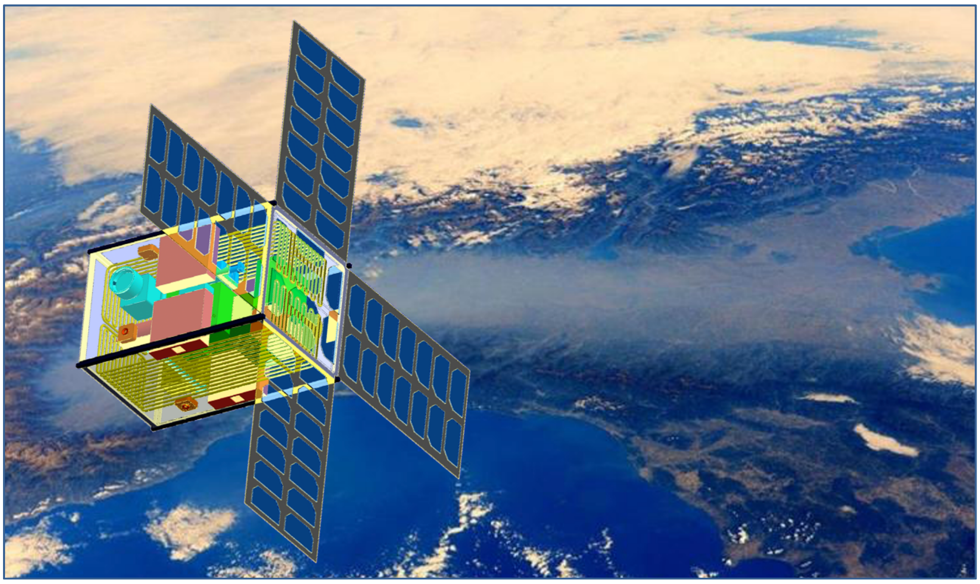


Figure 1. The EXCITE 12U Cubesat

The mission goal is to test several technologies in flight. As an additional result of successful completion of the IOD/IOV mission, the EXCITE extended functionality 12U CubeSat platform itself (Fig. 1) will be validated.

In addition to the primary IOD/IOV objectives, a few secondary goals have been identified for the mission:

- implement advanced bus technologies developed at UniPi (deployable solar panels, SMA actuators, etc.) in a high-performance 12 U Cubesat platform, providing invaluable experience in microsatellite development and operation;
- consolidate the existing space telecom activities at UniPi with the setting up of a microsatellite ground station located in Pisa;
- act as a hands-on educational laboratory across the engineering disciplines for graduate students at UniPi.

2. IOD/IOV PAYLOADS

The commonly accepted definition of In-Orbit Demonstration (IOD) and In-Orbit Validation (IOV) is as follows [1]: *"IOD refers to the spaceflight of a scaled version of a particular technology or critical technology subsystem, which would still need further steps to be ready for mission adoption. IOV would already serve as a qualification flight for future missions implementation. Such a successful validation flight of a particular technology would not require any additional space testing before it can be adopted for a specific mission."*

The primary mission goal of EXCITE is to validate in orbit several innovative technologies for small satellites. Within one microsatellite, EXCITE will test a varied set of technologies covering different domains of interest for future satellite platforms: onboard chemical and electric propulsion (H2O2 and PPT), management of heat flows in a limited volume (PHP), high-performance COTS Graphical Processing Unit onboard computing (IoT GPU), and compact, steerable microwave antennas (ReconfAnt). None of the technologies has ever been tested in space; they all need operation in the the space environment in order for a demonstration to be reliable and definitive.

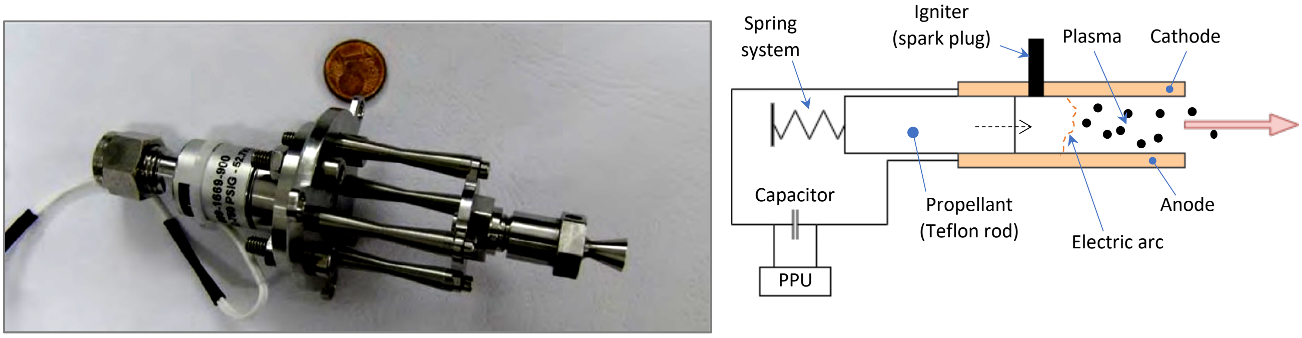


Figure 2. Left: UniPi's PulCheR 1 N monopropellant thruster;
right: schematic of a Pulsed Plasma Thruster

IOD/IOV payloads on EXCITE include five experiments:

1) a green monopropellant chemical thruster specifically developed for microsatellite applications (Fig. 2);
2) very low impulse bit pulsed plasma thrusters (Fig. 2), intended for microsatellite precision maneuvering in proximity operations;
3) pulsating heat pipes for management of substantial thermal loads in a limited volume (Fig. 3);
4) high-performance onboard computing algorithms for IoT signal processing on a COTS GPU board; and
5) reconfigurable, steerable microwave antennas integrated in the platform structural elements.

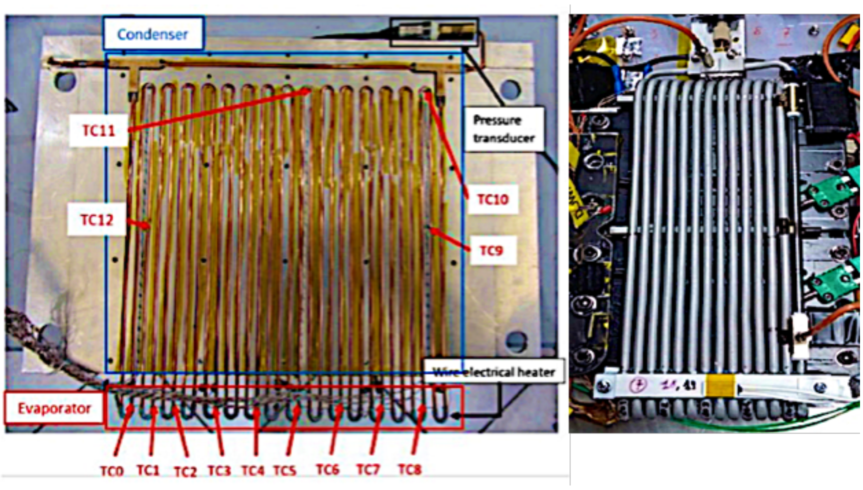


Figure 3. Left: UniPi's PHP tested on board two Parabolic Flight Campaigns; right: UniPi's PHP selected to be hosted on board of the International Space Station

Two of the experiments hosted on EXCITE belong to the IOV category (chemical and electric propulsion); the other three are extended scope IOD experiments (pulsating heat pipes, IoT GPU demodulator, reconfigurable integrated antenna). The main features of the experiments are shown in Table 1, along with the rationale for in-space demonstration / validation.

The H2O2 monopropellant thruster technology is under development under an ESA contract aimed at developing a monopropellant propulsion system specifically for CubeSats and will reach TRL 6 during EXCITE's Phase B. The Pulsed Heat Pipe experiment is in a similar situation, again in the frame of an ESA contract. PPT is already qualified (TRL 8), albeit never flown. The telecom experiments, IoT GPU and ReconfAnt, are at TRL 4.

EXCITE's mission philosophy is to provide affordable, effective in-orbit technology demonstrations by making use of a COTS-based approach to platform design, while maintaining adequate best practices in documentation, product/mission assurance [2], verification and testing [3], balancing the need for rigorous space project management with the limited resources of a Cubesat programme [4].

Table 1 - IOD/IOV Experiments on EXCITE

Experiment and Acronym	*Main features*	*Rationale of space IOD*
Hydrogen Peroxide Monopropellant Thruster **H2O2**	Green monopropellant thruster, alternative to toxic hydrazine. Microsatellite propulsion system for small to moderate delta-V maneuvers of micro- and small-satellites.	Ground testing, in atmosphere or in a vacuum facility, is not fully representative of the real space environment.
Pulsed Plasma Thrusters **PPT**	Miniaturized electric thrusters for high precision, very low impulse bit orbital maneuvers, proximity operations, microsatellite attitude control.	The very precise, ultra-low impulse bit performance of the PPT cannot demonstrated on the ground or in a vacuum chamber.
Pulsating Heat Pipes **PHP**	High throughput heat pipes based on unsteady fluid flow. Specially suited for compact, high heat flux space applications, such as high onboard power microsatellites.	PHP need microgravity to work. Tests in drop towers, parabolic flights or sounding rockets only allow for limited thermal conditions and very limited duration.
Internet-of-Things Graphical Processing Unit Demodulator **IoT GPU**	Demodulator for advanced Internet-of-Things waveforms based on a COTS Graphical Processing Unit. Low cost, high performance onboard computing.	The experiment must go to space to demonstrate the viability of operating a non-space, COTS GPU on a satellite.
Reconfigurable Integrated S-Band Antenna **ReconfAnt**	Integrated, electronically steerable antenna based on exciters distributed on suitable spacecraft surfaces. Allows for extreme compactness and low mass.	A proper demo of integrated antenna can only be done in space, with real ranges and real geometric constraints, and with the antenna mounted in the context of a real spacecraft, to assess the actual electromagnetic interactions.

3. SYSTEM ARCHITECTURE

The mission is based on a 12U CubeSat platform featuring a full-composite structure, deployable solar panels, 3-axes attitude control, and S-band telecommunications. Most of the subsystems will be procured on the commercial market as COTS, while some high performance, critical elements (power generation, thermal control, structure and deployables) will be entirely designed and manufactured by the EXCITE team.

A Sun-synchronous, 550 km Earth orbit is assumed as the baseline operational environment of EXCITE (Fig. 4). The mission can however easily be adapted to different LEO locations, should a convenient flight opportunity arise. This provides ample flexibility in the choice of launch opportunities. Considering the relatively low ballistic coefficient of the platform when solar panels are deployed, de-orbit will occur naturally form the chosen orbit within the 25 years term mandated by the international debris mitigation guidelines. It is additionally foreseen to perform the last chemical thruster burn in such a way as to lower the orbital attitude and further accelerate re-entry.

Space-qualified COTS will be used for the platform subsystems wherever possible. A large variety of CubeSat components are available today on the market and many more are predicted to become available in the immediate future. In a few cases, some non-space COTS may be considered as well (e.g., fluidic and/or mechanical components). While COTS are preferred for most subsystems, the EXCITE mission will also provide an opportunity to develop and use operationally a number of advanced microsatellite bus technologies that are already under development at UniPi and partners:

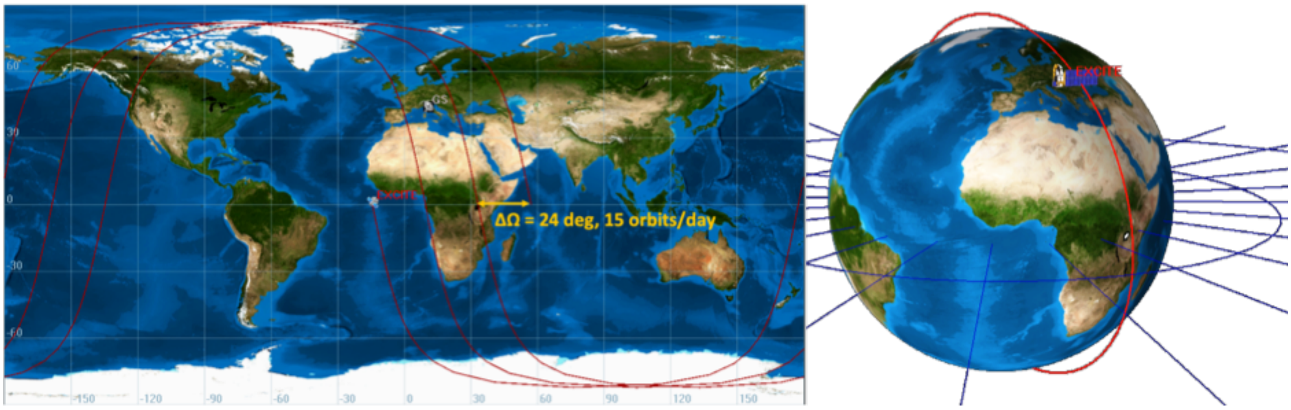


Figure 4. Nominal orbit

- the structure will be made of carbon composite materials. This will allow for mass reduction with respect to metallic frames and to the possibility to build custom layers into the composite structure, e.g. for the Reconfigurable Antenna experiment;
- deployable solar panels will be designed, manufactured and integrated using the same composite manufacturing techniques as for the spacecraft body, integrating Shape Memory Alloy actuators developed at UniPi;
- thermal control, a critical issue in such a high-power, small volume bus, will integrated with the PHP experiment.

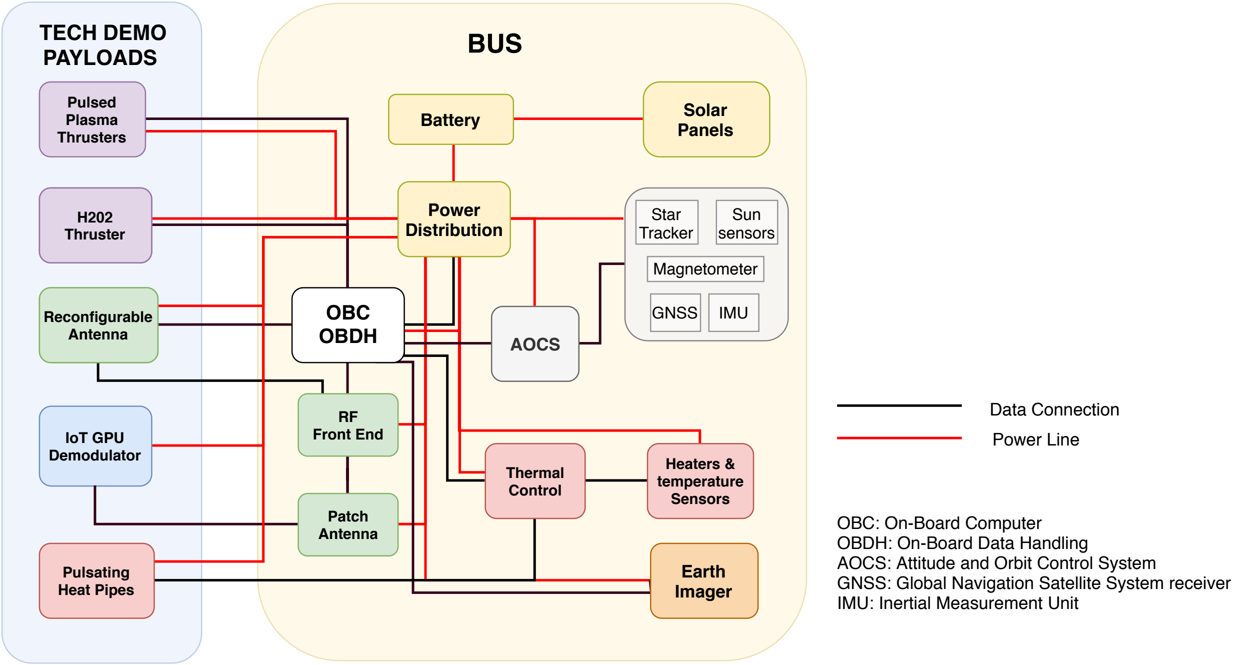


Figure 5. Functional Block Diagram

The spacecraft block diagram is shown in Fig. 5. The **OBDH** design is based on a distributed architecture, with a central computer in charge of coordinating and scheduling the actions of each functional block and providing routing to and from the telecommunication system. The power distribution system, the RF front end, the thermal control block, the Earth imager, and the five experiments, will all be equipped with their own individual processors/controllers.

Fig. 6 shows the arrangement of the spacecraft subsystems and experiments within the structure. The **power system** is based on custom-built deployable solar panels on a carbon composite substrate, equipped with state-of-the-art triple- or quadruple-junction solar cells (e.g., CESI CTJ-30-SCA). Deployment of the four identical solar panels (Fig. 7) is powered by a spring mechanism, initiated by Shape Memory Alloy actuators developed by UniPi. A fifth, smaller, fixed solar panel is placed on the $+z$ face. The panels are sized so to provide up 80 W continuous power in the nominal Sun-pointing attitude.

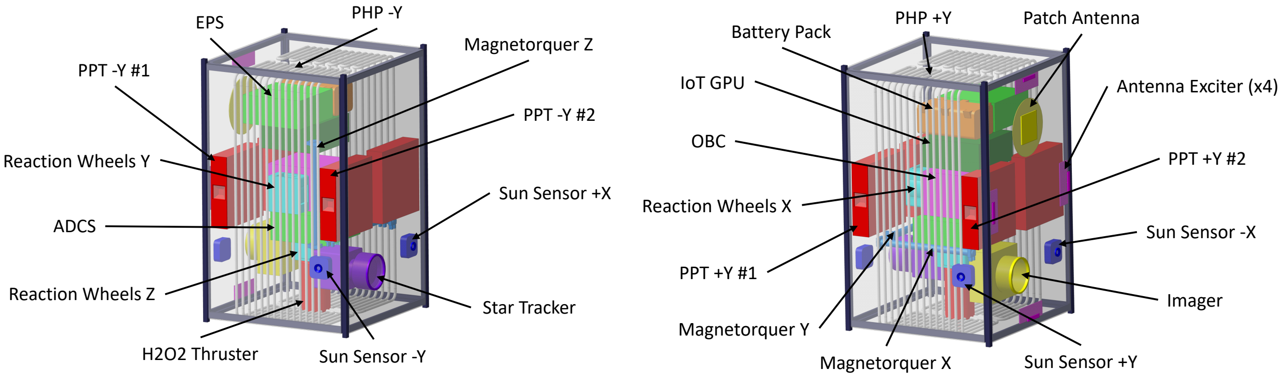


Figure 6. Schematics of the subsystems arrangement on EXCITE.

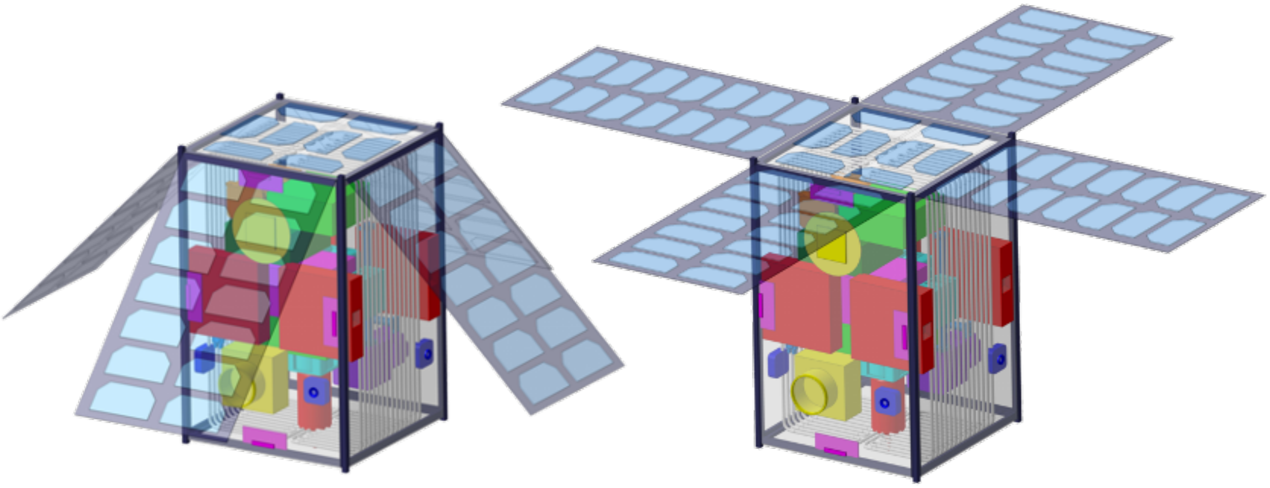


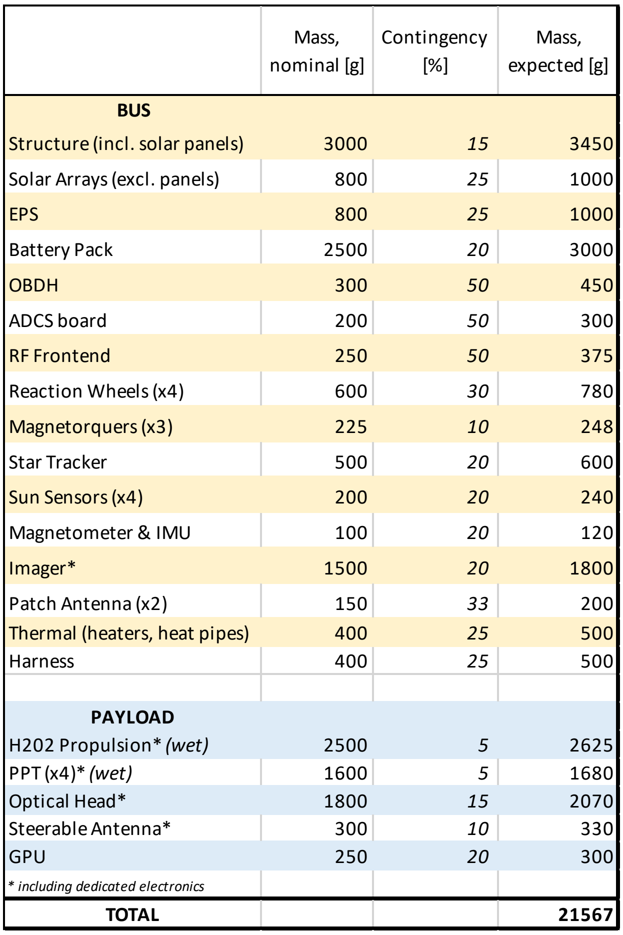
Figure 7. Solar panel deployment.

The **thermal control system** is essentially based on passive techniques. A radiator will be mounted on the surface opposite to the solar panels; the Pulsating Heat Pipe (PHP) experiment will be integrated with the platform thermal control, but will be configured so that thermal control is guaranteed also in case of malfunctioning of the experiment. Each PHP consists of a long capillary pipe wound in parallel segments. Two PHPs will be embedded in the structural panels to transfer the heat generated by the +z face solar cells to a radiator placed on the shadowed -z face. The two PHPs will have the same geometry but will operate on different working fluids. Each PHP will transfer about 10 W of thermal power, so to maintain the solar panel at a temperature of 298 to 308 K.

Attitude determination and control will be performed with a suite of sensors and actuators typical of LEO Cubesat missions. In its nominal attitude, the spacecraft will be obviously oriented so to present the solar panels normal to the Sun. However, frequent attitude maneuvers will be required to acquire the correct orientation for a variety of tasks, such as: pointing the antennas (platform's patch antennas or ReconfAnt) towards a ground station; pointing the thrusters (either PPT or H2O2) in the required direction for maneuvers; pointing the onboard camera towards specified targets. The sensors included in the preliminary design are: four sun sensors, one star tracker (possibly with another one in cold redundancy), one 3-axis magnetometer, one Inertial Measurement Unit (IMU), and one GNSS receiver. As attitude actuators, magnetorquers will be used together with a COTS 4-wheel reaction unit. The PPT experiment will interact with the spacecraft attitude and will be tested as a possible additional attitude actuator, also in a dedicated wheel desaturation sub-experiment.

Telecommunications will be provided through COTS RF hardware. Basic telemetry/telecommand will be assured through patch antennas. The ReconfAnt experiment (providing high data rate downlink) and the IoT GPU experiment will both access the RF front end, but they will be configured so to not affect telemetry/telecommand in case of experiment failure. A dedicated ground station based on available commercial solutions will operate at UniPi's premises in Pisa.

Table 2. Mass budget



	Mass, nominal [g]	Contingency [%]	Mass, expected [g]
BUS			
Structure (incl. solar panels)	3000	*15*	3450
Solar Arrays (excl. panels)	800	*25*	1000
EPS	800	*25*	1000
Battery Pack	2500	*20*	3000
OBDH	300	*50*	450
ADCS board	200	*50*	300
RF Frontend	250	*50*	375
Reaction Wheels (x4)	600	*30*	780
Magnetorquers (x3)	225	*10*	248
Star Tracker	500	*20*	600
Sun Sensors (x4)	200	*20*	240
Magnetometer & IMU	100	*20*	120
Imager*	1500	*20*	1800
Patch Antenna (x2)	150	*33*	200
Thermal (heaters, heat pipes)	400	*25*	500
Harness	400	*25*	500
PAYLOAD			
H2O2 Propulsion* *(wet)*	2500	*5*	2625
PPT (x4)* *(wet)*	1600	*5*	1680
Optical Head*	1800	*15*	2070
Steerable Antenna*	300	*10*	330
GPU	250	*20*	300
** including dedicated electronics*			
TOTAL			**21567**

A COTS imager (optical camera) will be included as a source of high rate data source for the S-Band ReconfAnt experiment. In addition to provide a stream of data to test the ReconfAnt, the imager will be used to provide additional attitude information to the ground controllers, and to perform a variety of training and educational tasks for the EXCITE academic and scientific community. According to availability and cost, the imager will be either a panchromatic or a simple multi-spectral unit operating in the visible and NIR bands; the choice of which specific unit to embark, among the various commercial offers, will be done in Phase A.

The spacecraft mass budget is shown in Table 2. The predicted total mass is 21.5 kg including ample contingency, leaving a margin of 2.5 kg, or 10.5%, with respect to the 24 kg maximum of a standard 12U CubeSat.

The power budget is shown in Table 3 for different operational situations:

- housekeeping: experiments and imager are inactive. Normal attitude, thermal and power control systems functions are active;
- communication: downlink at high data rate;
- imaging: the imaging sensor is in acquisition mode. All experiments are off;
- H2O2, PPT, ReconfAnt, IoT GPU, PHP: the relevant experiments are active. No imaging or data downlink activity.

In all cases considered, power consumption is much less than the power input from the solar arrays, nominally 79 W at EOL. Of course, many “mixed” operation modes can be envisaged, featuring combinations of the onboard subsystems and one or more experiments together; such interesting options are made possible thanks to the ample power margin.

Table 3 - Power budget.

	Power [W]							
	Housekeeping	**Communication**	**Imaging**	**H2O2**	**PPT**	**ReconfAnt**	**IoT GPU**	**PHP**
BUS								
Solar arrays (produced)	*79*							
EPS	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
OBDH	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
RF Frontend		13					13	
Reaction Wheels (x4)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Magnetorquers (x3)	2.5	2.5	2.5					
Star Tracker	0.8	0.8	0.8					
Sun Sensors (x4)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Imager			10					
Thermal Control	3	3	3	3	3	3	3	3
PAYLOAD								
H2O2				5				
PPT (x4)					7			
ReconfAnt						13		
IoT GPU							15	
PHP (x2)								1.5
TOTAL	**15.6**	**28.6**	**25.6**	**17.3**	**19.3**	**25.3**	**40.3**	**13.8**

4. EXPERIMENT PROFILES

Special safeguard criteria were followed in planning the propulsion experiments because of the associated risks. PPTs experiments involve perturbations of CubeSat attitude and the related burns last several minutes. Continuous monitoring is needed both to ensure that all the involved subsystems are correctly working and to maintain satellite control; then the resulting spacecraft state is checked at the end of the burn. The complexity and the possible consequences of the PPT burns demands them to be executed after the telecom experiments. Finally, the H2O2 thruster demonstrations aims to change the nominal orbit conditions, hence they can irreversibly compromise the entire mission (e.g., should a failure in thrust throttling occur).

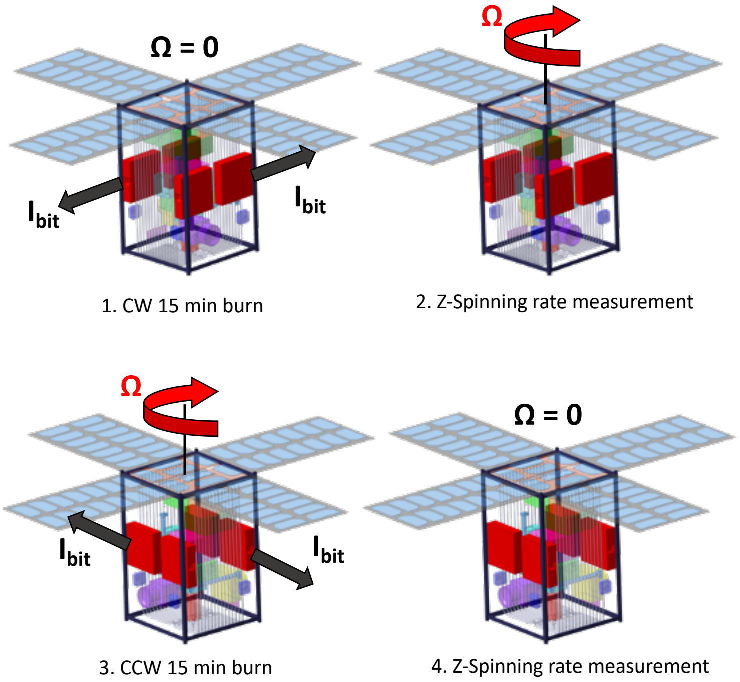
4.1. Monopropellant thruster

The H2O2 propulsion system occupies a volume of about 2U, including a propellant mass of about 2 kg. The demonstration maneuvers are designed to change different orbital parameters in a sensible way, demonstrating both in-plane and out-of-plane maneuvers, while deviating minimally from the nominal flight trajectory. Starting form the nominal orbit at 550 km, the maneuvers envisaged are as follows:

1. apogee lowering to 500 km. The required consumption is about 22% of the initial propellant mass equivalent to 27 m/s of ΔV.
2. apogee raising back to 550 km; propellant consumption and ΔV approximately as before;
3. change of RAAN by 0.5 degrees; the maneuver is best performed providing a 65 m/s ΔV by firing at argument of latitude almost equal to 90 degrees, for a 50% propellant consumption;
4. the remaining propellant is used for the final de-orbiting maneuvering phase.

4.2. Pulsed plasma thrusters

The PPT tests are designed to demonstrate the capability to carry out precision maneuvres. Four independent thrusters will be installed on EXCITE, so to have the possibility to generate either pure thrust or pure torque by selecting thrusters in pairs.



1. CW 15 min burn
2. Z-Spinning rate measurement
3. CCW 15 min burn
4. Z-Spinning rate measurement

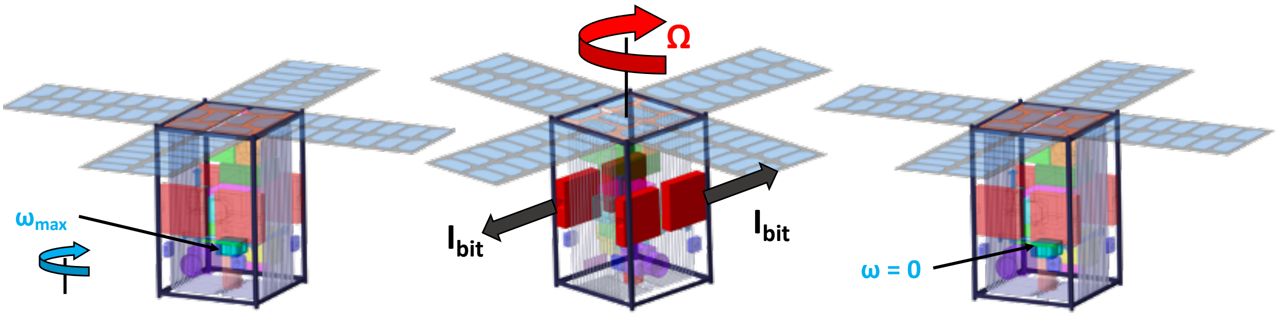
Figure 8. PPT experiment: spin up/spin down

It is envisioned to perform three experiments:

1. validate the use of PPTs to control the attitude of the satellite in one axis (Fig. 8), by spinning up the satellite using a pair of thrusters pairs on opposite sides of the spacecraft body. The burns last 5 minutes in order to reach a spin rate of about 0.8 deg/s. The resulting angular rate measured by the AOCS sensors provides a measure of the impulse delivered. The opposite pairs of thrusters are then fired to spin the spacecraft back to zero angular speed;
2. provide off-loading capabilities of reaction wheels of the on-board 3-axis AOCS (Fig. 9), by momentarily taking over the task of the magnetorquers to provide de-saturation torque to the reaction wheel assembly;
3. provide translational thrust, needed e.g. for precise proximity operations (rendez-vous, close formation control), by firing thrusters on the same side of the spacecraft. In the latter case, the spacecraft orientation will be set so to have the thrusters oriented along the orbital velocity direction. Firing for a few minutes at nominal rate (1 Hz) and impulse bit (40 µN s) will provide enough delta-V to change orbital altitude by a few tens of meters, a change that can be easily detected by the onboard GNSS sensors.

4.3. Pulsating Heat Pipes

The PHP experiment is totally passive; it will automatically start as soon as proper thermal conditions are established, which will occur almost immediately after acquisition of the nominal Sun pointing attitude and deployment of the solar panels.



1. Saturated Z-RW 2. Burn start 3. Ending burn

Figure 9. PPT experiment: reaction wheel desaturation

4.4. GPU IoT Demodulator

Various demonstration activities will be performed:

1. generic utilization of the GPU for onboard data processing, anytime during flight;
2. a designed IoT signal is transmitted by MBI's IoT ground terminal when EXCITE is passing within its visibility area. In particular, an innovative spread-spectrum waveform named IURA (IoT Universal Radio Access) will be used. The signal collected by on-board telecommunication hardware is demodulated and stored by the GPU;
3. during a generic orbit, S-Band I+Q samples from different world areas are collected by the RF front-end radio, recorded by the GPU and processed onboard;
4. when the spacecraft is in view of the mission's ground station, or of another suitable receiving station located elsewhere, the GPU generates a Continuous Wave (CW) signal in S-band that is broadcast by the RF front-end. The receiving ground terminals can perform a detailed analysis of the received beacon for performance assessment and for additional auxiliary scientific purposes.

4.5. Reconfigurable Antenna

The reconfigurable antenna (Figure 10) will be tested by rotating the spacecraft to different attitude angles with respect to the ground station and measuring the strength of the received signal. The experiment can be performed anytime, provided visibility with the GS is ensured and the instantaneous power balance on board allows for the RF front end operation. On basis of future risk analysis results, the telecommunication activities can be arranged to perform combined IoT GPU - ReconfAntenna experiments.

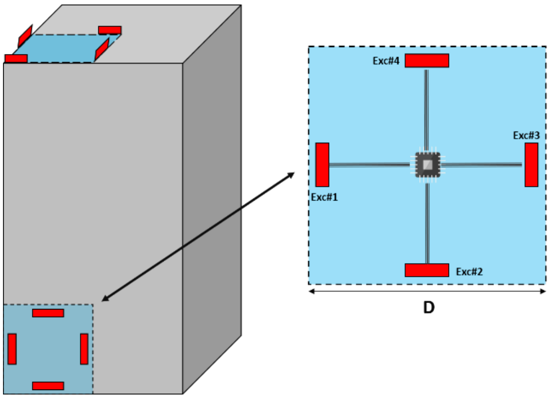


Figure 10 - Possible placements of the proposed S-band radiator on the platform, non-resonant exciters arrangements and cable connections of four exciters to the RF front-end (not to scale)

5. PLANNING

The EXCITE project will be developed along the following phases:

- Phase A (9 months) - feasibility study;
- Phase B (12 months) - preliminary design;
- Phase C/D (15 months) - design, manufacture, assembly, qualification, acceptance;
- Phase E/F (12 months) - launch, operations, end-of-life disposal.

The duration of the project is three years from kick-off of Phase A to the Flight Readiness Review concluding Phase C/D and starting Phase E. Phase E/F has a nominal duration of one year; however, in principle extended operation of the EXCITE microsatellite is possible. At the end of the nominal mission, a decision will be taken on whether to proceed for an additional three years, conditional to the availability of funding for the extended operation period.

6. CONCLUSIONS

The EXCITE mission will test and validate several small satellite technologies, providing a much needed in-orbit demonstration opportunity to SME's and university researchers. In addition to that, the spacecraft bus itself, built with a customized approach, will be effectively validated and will be ready for further applicative implementations, also including one or more of the technologies tested in flight. With low structural mass providing a good payload mass ratio, about 80 W of onboard power with advanced heat management, high-speed S-band connectivity, GPU-based high computing power, propulsion for orbital maneuvers and for proximity operations, the EXCITE platform will be a very attractive option for future scientific and commercial missions.

7. REFERENCES

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