LeSTAR

Lessius Satellite for Teaching and Autonomous Research

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Abstract: When bringing people to the hostile space environment, success of long duration missions depends highly on the availability of effective and efficient life support systems. Experience shows that due to the high costs or the unavailability of missions, experimenting on life support systems in manned missions and traditionally large satellites has become very difficult for research institutes and virtually impossible for SME's.

Pico- and small satellites could fill the gap for performing necessary experiments, if tests can be automated, controlled and monitored from earth in a cost-effective way. Ample initiatives to provide easy access to space and multi-orbiting of pico-satellites, ensure the participation of research and educational institutes which can take an important role in vital biological research and in the spread of this innovative know-how.

The intrinsic qualities of CubeSats, relatively cheap, easy orbiting, fast development, makes it an excellent research instrument, complementary to experiments on-board the ISS.

When considering space related studies, and investing in CubeSat-projects, it is advisable to use an educational and scientific relevant payload with high potential for future space applications to attract students keen on working in high-innovative sectors and to augment the availability of high-educated technical profiles, engine of today's economy.

The challenge of bringing living organisms in space brings along a whole set of difficulties, such as design and production of a miniaturized bioreactor, provision of environment measurement and control, all of this in the given mass, power, volume budget.

1. INTRODUCTION

As long duration manned missions (see Fig. 1) are considered in the near future, a lot of experiments on regenerative life support systems, including biological components, and space environment will be necessary. For example, bacteria can be used for waste recycling and resource recuperation, but can also be hazardous to astronauts when travelling along in confined spaces, such as the ISS or because of corrosive properties.

Fig. 1: Commander Frank De Winne: supporter of the LeSTAR mission

To investigate the change of conduct due to microgravity and cosmic radiation a lot of tests need to be done with a variety of biological loads.

On the other hand experimenting in manned missions and traditionally large satellites has become very difficult for research institutes (queues are long and getting tests on a mission is difficult) and virtually impossible for SME's due to limiting capacities of existing systems (no more Space Shuttle flights, ISS experiments too expensive and scarce, lack of proper funding).

This calls for a new approach. Pico and small satellites could fill the gap for doing necessary experiments on life support systems. Pico-satellites (CubeSats) are a solution to do more frequent and cost-effective research, if tests can be automated, controlled and monitored from earth.

Defining a proper biochemical experiment, compatible with a pico-satellite, is still a challenge, as for now recovery of reaction products is not feasible.
As the possibilities to use CubeSats in research projects increase, due to ample initiatives to provide easy access and multi-orbiting of pico-satellites, research and educational institutes can now take an important role in vital biological research and in the spread of this innovative know-how.

This in turn will lead to low-cost accessibility for SME's to perform their own space research in the field of space microgravity and radiation.
More and more organizations and universities want to take part in the design and development of small satellites. This leads to a quick emerging market in off-the-shelf, space-tested satellite subsystems. Use of these proven systems can prove to be helpful since that scientific teams can focus their effort in defining and designing proper biological payloads.

In this paper the development of a biological payload that fits a pico-satellite design is presented, i.e. the LeSTAR satellite.

2. MISSION OBJECTIVES

1. Proof-of-Technology: we will prove that complementary microgravity research can be performed onboard CubeSats, more frequent and cost-effective, than tests onboard the ISS or in large satellites, if tests can be automated, controlled and monitored from earth.
2. Development of biological payload:
    - production of a miniature bioreactor
    - environment control (light, temperature, pressure)
    - micro fluidic network for reagent distribution
    - automation, digitalization and communication of the measured results
    - biocompatibility of the biochemical load and the materials used for the bioreactor
3. Integration of biological payload: interface with the satellite command and data handling system
4. Benchmark biological space research and set up different requirements for future missions: what kind of research can or what cannot be performed, including experiments on bacteria which are potentially hazardous to astronauts or with corrosive properties. Since such tests are forbidden in the ISS, an alternative instrument would be more than welcome.

3. CONCEPT OF OPERATIONS

3.1 Pico-satellite

The LeSTAR experiment will be conducted in a 3 unit CubeSat, of which one unit is dedicated to the satellite subsystems, such as on-board computer (OBC), communications, attitude control and electric power system (ADACS). The other two units will contain of the payload module.
A preliminary investigation shows that total power available will be around 4 Watts, and total mass less than 4 kilograms. When we deduct mass, volume and power for the necessary subsystems, we have the following budgets for the biological payload:

- Power: 2400 mW
- Mass: 2091 g
- Volume: 130x96x90 mm

All numbers are calculated with a 20% worst-case margin. [1][2]

3.2 Biological Payload

For the biological payload, prokaryotic blue-green algae, also known as cyanobacteria, are selected.

They are used for CO_2 and nitrate removal and they produce oxygen and biomass due to photosynthesis. A sample can be seen in Fig. 2

These bacteria are:

- high on proteins, essential fatty acids, minerals, vitamins and nutritional pigments
- antioxidants
- resilient to ionizing radiation up to 3200Gy

Fig. 2: Cyanobacteria

To grow the bacteria three conditions must be fulfilled, being the presence of a light source, warmth and nutrient supply. In order to actively control these three process parameters we need to select

- LEDs for light control
- a suitable heating device for temperature regulation
- a peristaltic pump for nutrition distribution

To reproduce the experiment in earth conditions, as reference material, the following process parameters need to be controlled:

- biomass growth (optical density @ 750nm)
- pressure
- PAR-data: Photosynthetic Active Range
- pH
- fluorescence
- temperature [3]

3.2.1 Light

Cyanobacteria need light for growth (light is their energy source).

The culture vessel, where the algae are grown in, needs to be placed adjacent to a light source, e.g. an array of high-power light emitting diodes (LEDs), that

- generates a highly uniform irradiance flux in terms of spectrum and intensity over the reactor volume,
- preferentially can be dynamically modulated and controlled
- produces a flux in a predefined range between 0-2500 μmol (photons).$m^{-2}.s^{-1}$, or ca. 0 – 555 W/m^2, with preferably a low light intensity above 5 W/m^2, to ensure photosynthetic growth and oxygen production.
- is situated within the PAR (photosynthetic active range) spectrum, being the continuous white spectrum (400-700nm).

In a preliminary test set-up, 8 LEDs are implemented, distributed uniformly on the lighting module, where the central LED can be pulse-width modulated. Other LEDs have a simple on/off control. In this configuration, checking the optimal lighting for growth is possible and some measurements on irradiance flux in PAR, with a chemical actinometer, can be done.

The LEDs have a luminous intensity I_v of 370mcd, with a viewing angle A of 110 degrees, at 3.6V and 20mA.

Using the formula [7]:

$$F = I_v \, . \, 2\pi \, (1 - \cos A/2) \qquad (1)$$

this results in a approximate luminous flux F = 0.991 lumens/LED with a power consumption of 72mW/LED.
Total flux for the 8 LEDs over the total surface of the dish (with 5.7cm diameter) is 7.93 lumen over 25.52cm². This results in 4,578W/m² (at 555nm wavelength).

A light sensor is used to measure the light on/off status and the light level in lux, with a 15-bit resolution. It has an I²C serial interface, which makes it easy to communicate with the OBC.
It also combines two photodiodes in one package, with one of them covered with a metal shield, so dark output can be cancelled out, as well as the presence of IR, due to the heating of the vessel or other IR-emitting devices. Power consumption in operation is 750µW. In software power down mode, this is reduced to 22µW.

3.2.2 Temperature
Thermal requirements for the biological payload is between 22°C and 35°C. An increased temperature will rapidly result in serious degradation of the experiment. A temperature > 36°C will kill the cells (at 40°C, half of the population is dead). As it is difficult to keep temperature in a very close range of 35°C ±1°C, as required for an ISS experiment, the ambition is to keep reaction temperature between 25°C and 35°C. This must be achieved within the predefined limitation of a heating budget of 1W and closely monitored. Cooling is not feasible.

As far as heat transfer is considered in space, only two major transfer modes are important, being conduction and radiation.
Heat conduction per unit time is calculated with the following equation [8]:

$$Q = kA\frac{\Delta T}{L} \qquad [W] \qquad (2)$$

with k: thermal conductivity [W/(m.K)]
A: surface of the conductive path [m²]
ΔT: temperature difference [K]
L: length of the conductive path [m]

The emitted radiation by a black body can be found using this equation [8]:

$$Q = \sigma A T_s^4 \qquad [W] \qquad (3)$$

with $\sigma = 5.67\text{x}10^{-8}$ the Stefan-Boltzmann constant [W/(m^2.K^2)]
A: the radiating surface [m^2]
T_s: the surface's temperature [K]

When the surface is "grey", a reduction with factor ε (emissivity) is used (between 0 and 1).
When the object is surrounded by a large ambient environment at T_{amb} the equation becomes [8]

$$Q = \sigma A(T_s^4 - T_{amb}^4) \qquad [W] \qquad (4)$$

The temperature of the aquatic medium in which the algae grow, is calculated from the equilibrium of the added heat to the reaction vessel and the transferred heat away from the vessel into satellite structure and space environment. Added heat comes both from within the satellite, originating from dissipated power of satellite subsystems and a dedicated heater and from the outer thermal environment in space. The heat sources in space are represented in Fig. 3:

- direct solar flux depending on sun distance, with a mean value around 1367 [W/m^2] at 1 astronomical unit

- albedo planetary reflected radiation. For Earth, the mean reflectivity is assumed to be near 30%. But it can vary locally up to 40 or 80% above shiny clouds and between 5 to 10% for oceans and forests.
- Earth infrared radiation. Earth can be modeled as an equivalent black-body emitting at 255 K.

During the eclipse, only three heat sources are still present : earth's infrared, internal dissipation and the dedicated heater. So the spacecraft will be cooler.

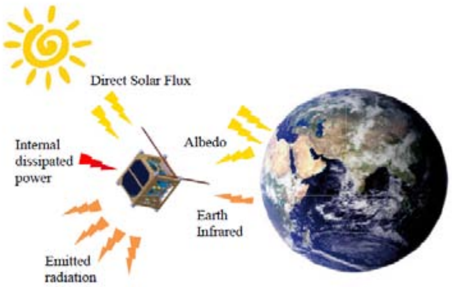

Fig. 3: Heat sources in orbit

Preliminary calculations on radiation and the thermal resistance network of the satellite structure, give an internal variation of the subsystems between -6°C and 8°C.
If we divide this thermal behavior into the hot case and cold case, for the first situation the inner systems will heat up to around 35°C – 38°C and in the latter situation the temperature will drop to -2°C to -22°C.
The difference between hot and cold case depends on orbital parameters. For the hot condition (Fig. 4), this implies a very short eclipse due to a high inclination, and already a reasonable amount of albedo flux. In the cold case the eclipse, this is the time without direct sunlight, is maximal.

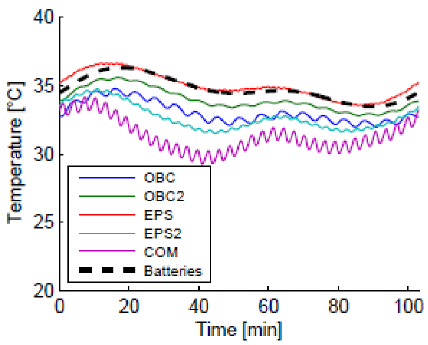

Fig. 4: Temperature (hot case)

We can conclude that an optimal orbit can be defined, for which inner temperature is optimal for the growth of the bacteria, without the need for excessive heating.

In general, we want the heat control to be as predictable as possible, so external heating and cooling is to be ruled out as much as possible. This calls for a good insulation, and a good modeling of the heat conduction resistance network from the vessel to the surface of the spacecraft. Care should be taken to the surface treatment of the satellite, so that heat loss through radiation can be limited, as far as this is possible due to the presence of solar panels.
There are two options to consider the heating of the reaction medium, being heating the reaction vessel or heating the nutrient vessel. If we heat up the reaction vessel, we control temperature at the location where the heat is needed and the temperature is measured. Heating up the 50 ml container does not require much energy, and control is quick and easy. On the other hand, the local heater can interfere with the other sensors and the heat capacity of the smaller container is limited. Keeping the

nutrient vessel at a steady temperature requires more energy, but also provides a buffer of heat energy that can be built up.
The energy needed for heating up the reaction container of 50ml from 10°C to 25°C is 3135 Joule.

$$Q = m \,.\, c \,.\, \Delta T \qquad [J] \qquad (5)$$

To calculate the heat needed for the 300ml container this must be multiplied by six, resulting in 18810 Joule.
With a 1 Watt heater, given that all electrical power is converted to heat energy, heating up the reaction vessel takes 3135 seconds, being more or less half an orbital period. For preheating the nutrient vessel, this will take 3 periods.
The efficiency of the heater and the heat transfer from this device to the selected vessel must be considered more closely, as this can be optimized with the use of different materials. For glass the conductivity is about 1.1 [W/m.K], but for aluminum this is 237 [W/m.K], so an aluminum vessel will absorb the energy more easily, but will also dissipate it more quickly, if not proper insulated.

The temperature sensor used has a serial interface and also has a thermostat built in so an hysteresis loop can be programmed in, to reduce fluctuations in the heater. The programmable resolution is between 9 bits and 12 bits, with a 2°C accuracy. With a supply voltage of 2.5V and in active mode, this sensor consumes 2,5mW. When in communication mode only, this is 250µW.

Also temperature transitions at launch conditions must receive close attention, as the heat transfer by convection is not negligible on the outside of the launch vehicle. It is important to know how this can affect inner equipment and satellite payloads of the rocket.
As the satellite must be powered down during launch and at least ½ hour after deployment in orbit, it is of key importance to which inner temperature this leads and if the algae are still viable at this temperature. One thing is certain, the algae cannot be frozen and revived again, because the ice crystals pierce and damage the inner cell membrane. The conduct of the algae between 15°C and 1°C shall be tested in lab conditions.
The temperature curve between access in the spacecraft and the first communication with earth should be logged and communicated for reproduction of the test on earth.
Preheating of the nutrient container and late access to the launch vehicle must be considered as of major importance, along with the possibility to log temperature data during lift off and flight. [4][5][6][7][8]

3.2.3Nutrition

The nutritive environment is Zarrouk-UBP. Zarrouk is an alkaline culture medium for blue-green photosynthetic cyanobacteria, with mineral salts dissolved in it. It is available in two different solutions. The dissolved elements are K_2HPO_4, $NaHCO_3$ and Na_2CO_3, for solutions 1, in well-defined concentrations.

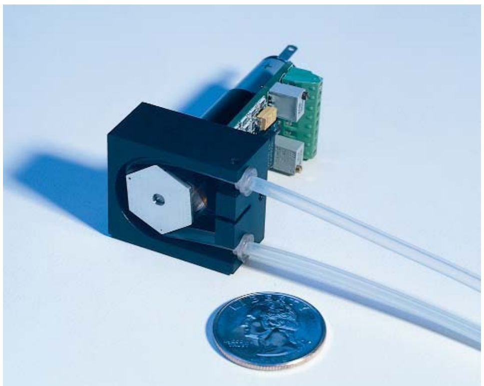

Fig. 5: Peristaltic pump

Distribution of the medium is done by a peristaltic pump, shown in Fig. 5, with a flow rate between 0.34µl/min and 275 µl/min. The necessary flow rate is about 0.9ml/hour, this is 15µl/min. Supply voltage is $10V_{DC}$ and motor power is 0.3W. When in rest the pump consumes 75mW. Dimensions are 3.18 x 2.70 x 5.06 cm.

3.2.4 Process Parameters

There is a need to monitor other important process parameters of the bacteria's growth in zero-gravity conditions with the use of sensors.
Since the power budget and available space in the 3-unit CubeSat with biological load is limited, sensors should be low-power, small-sized, highly-accurate and radiation-hard.
The expected data-output consist of

- Optical density (OD at 750nm and at 690nm) measurements will be used for growth rate calculation and chlorophyl concentration.
- Oxygen production (pressure increase) rates will provide additional data for fluorescence data evaluation.
- PAR data for the amount of light energy, which is important for estimation of growth rate and productivity.
- pH will provide a back-up measurement of photosynthetic activity and support data for carbon availability.
- Fluorescence data could reveal actual physiological status of the culture during all phases of mission, possible acclimation of the cultures (or stress response) could be observed. Pigment (chlorophyl) analysis of samples from the onboard culture could reveal the changes of photosynthetic activity during the space-flight.

3.3 Pre-Launch and LEOP-conditions

Because algae need to be delivered to the bio-container as late as possible, late access to the launch vehicle is needed. This is well possible at Baikonur, where an ESA laboratory is present, where the necessary sterile conditions for the experiment can be guaranteed. Temperature conditions must remain above zero degrees Celsius.
In launch and early operations phase (LEOP) a boot sequence is performed. All systems checked and made operational and the satellite needs to be de-tumbled. Temperature of the payload should always be logged and communication with the ground station will be established.
If all systems function normally, and the satellite is in a steady state, the lights can be turned on, additional heating provided and nutrient distributed, the algae will start to grow and all parameters can be measured.

3.4 Flight software

The on board software is a critical part of the CubeSat design since most tasks, operations, functionalities . . . will be performed by the flight software. All this software will run on the OBC or on a subsystem, depending on the chosen hardware architecture.
The OBC will run a real time operating system.
The following functionality must be provided at a high level of the software architecture (Fig. 6):

- Satellite control: it is necessary that the whole system can be checked for faults and can be recovered if possible. These faults can be e.g. the malfunction of a component or a fault in a piece of software. In the design stage these possible faults will have to be identified and a recovery solution must be provided.
- Command and data handling (CDH): during the mission, housekeeping data and telemetry data about the state of the subsystems will be collected. These can be requested from a ground station by a telecommand. A telecommand is a collection of actions to be performed by the satellite. In order to perform these actions, this module will call other functions from other modules.
- Subsystem control: all subsystems will be controlled by a software interface with the CDH or satellite control. Therefore it needs drivers to control the hardware and some functionality to handle commands. This command handler can perform commands requested by another function.
- Data communications with ground station: the satellite must be able to receive and transmit telecommands and telemetry data. This way the ground station can request actions to control the satellite or a subsystem by a telecommand.
- Time keeping and synchronization: when housekeeping parameters are stored, a timestamp is added to the data. Therefore the time on board the satellite will be kept by a RTC.
  It is possible to synchronize with the time from the ground station by a telecommand. This can be useful after a system reset. [9]

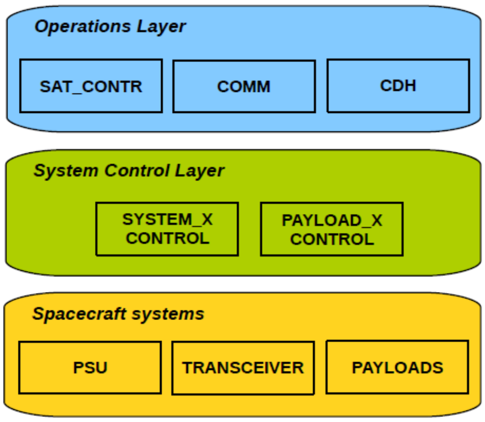

Fig. 6: Software architecture

3.4 Ground station network

Sensors for the biological load and for telemetry don’t produce too much of data, so a daily data retrieval of 1Mbit is largely enough for telemetry and payload data, including error correction and packaging overhead. Sending and receiving can be done in the amateur band, with a 1200 bits/s uplink and a 4800 bits/s downlink. This is easily done with a low-cost ground station.

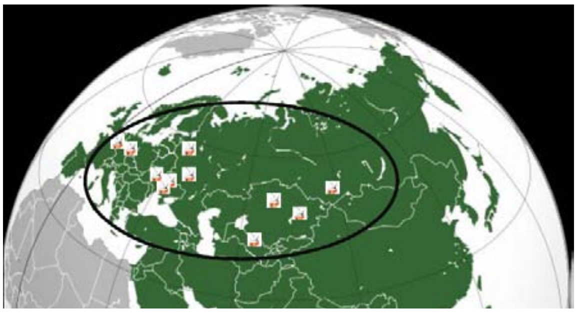

Fig. 7: Groundstation network

It is advisable though to provide a back-up ground station or several ground stations (see Fig. 7). Lessius established partnerships with other universities for this purpose, from Belgium to Siberia. All partners have identical ground station hardware, which is remotely accessible over the Internet.

4. KEY PERFORMANCE PARAMETERS

The key performance parameters must prove the cost-effective, fast and representative research capabilities onboard CubeSats compared to more traditional research onboard the ISS.
Short development time, low hardware cost, lower launch costs and less stringent design and operational demands, should justify complementary research with CubeSats.

To measure the performance of the system we must check the bacteria grow in the reaction vessel and that the growth dynamics can be measured and modeled with the parameters mentioned before. This growth should have comparable results with other experiments, for instance in the ISS or in laboratories on earth.

A very important parameter is the reproducibility of the experiment with earthly conditions. So the temperature curve of the biological load monitored from access to the reaction vessel to the start of the experiment and during the experiment should be known afterwards.

Microgravity is key to the experiment, so steady conduct in orbit must be guaranteed. The dynamics of the spacecraft should be measured with gyroscope and accelerometers.

A last, important parameter is comparing the economic relevance and benefits which are to be gained when performing the research onboard a CubeSat to traditional space research. In addition we want to find a possible client base in local SME’s who can perform their own space research, due to lowered start-up costs.

5. SPACE SEGMENT DESCRIPTION

A 3-unit CubeSat is envisaged. A standard bus configuration is selected with COTS components.
Prices and budgets are available from the CubeSat Shop. Table 1 gives a overview of the different budgets.
Details of the satellite subsystems are limited to the on board computer and the attitude determination and control system.
Fig. 8 gives a CAD model of the satellite configuration, with the payload centrally located. One can clearly see the nutrient vessel (gold), the reaction vessel (blue) and the peristaltic pump (brown – grey).

Table 1: Budgets

Power Budget	Value
	mW
EPS	820
C&DH	220
Comm	220
ADACS	510
Structure	
Payload	1000
Total	2770
Margin	554,00
Total + Margin	3324,00
Sollar Arrays	3600,00
Available	276

Mass Budget	Value
	g
EPS	665
C&DH	205
Comm	168
ADACS	195
Structure	355
Payload	1000
Total	2588
Margin	517,60
Total + Margin	3105,60
Maximum	4000,00
Available	894

Volume Budget	Value
(in height)	mm
EPS	26
C&DH	40
Comm	25
ADACS	15
Structure	
Payload	140
Total	246
Margin	49,20
Total + Margin	295,20
Total Height	300,00
Available	5

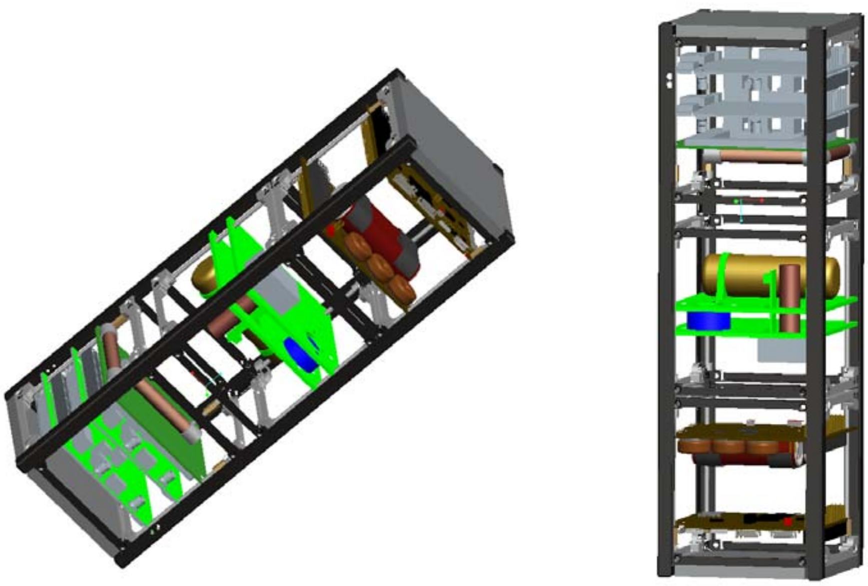

Fig. 8: LeSTAR CAD-model

5.1 On-board Computer (OBC)

The OBC selected for this mission is the GomSpace NanoMind 712b, with a 32-bit ARM7 RISC CPU. This OBC is an on-board computer specifically designed for low-power space missions. In charge of dispatching commands and collecting housekeeping and payload data from the satellite bus, the OBC is the brain of the satellite and therefore the master of the bus.

5.2 Attitude Determination and Control Subsystem (ADCS)

For attitude control, we principally only need passive control, as the only demand is to keep the satellite steady and not tumbling, to prevent gravitational forces on the biological load. As microgravity is very important for the experiment, we add a small-sized active ADACS. This will work if the passive one is not sufficient. We use magnet torques to do this control. Sensors are onboard, to check if microgravity conditions and steady flight are reached. The de-tumbling phase must not take more than one week, after launch. Then the biological experiment is started.

6. ORBIT/CONSTELLATION DESCRIPTION

Orbital demands are quite low, as we only need microgravity for our experiment. This helps a lot to

reduce cost, as piggybacking with several other missions is possible.
For better communication a near polar orbit is preferred, at a minimum height of around 320km, to have a reasonable long lifetime of some months.
To comply with international law, the orbit mustn't be higher than 600km, to not pass the maximum allowed life span of satellites of 25 years.

7. IMPLEMENTATION PLAN

7.1 Project organization & partners

Fig. 9 gives an overview of the project organization, with the scientific team at given work packages.

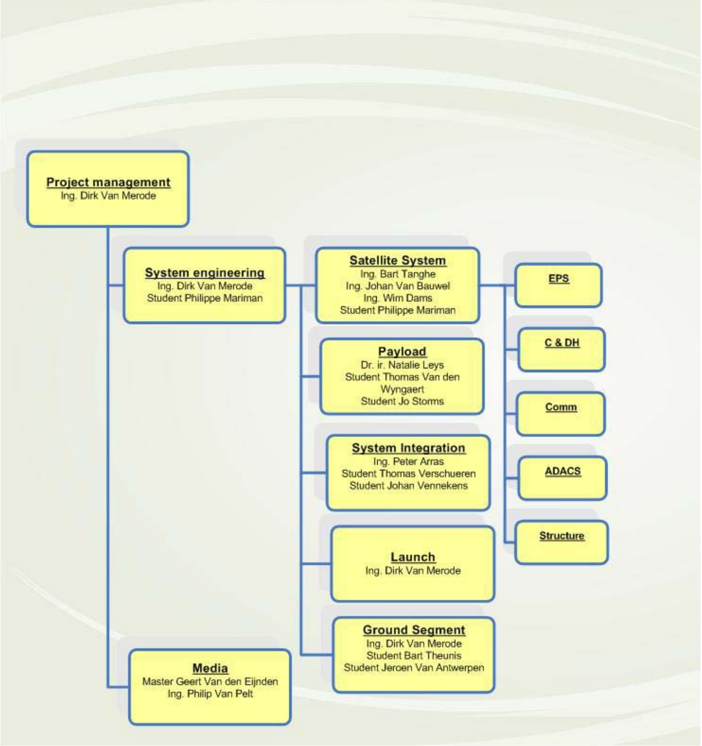

Fig. 9: Project Organization

The possible partners in the project are SCK/CEN, the Belgian Nuclear Research Center, with the Microbiology Unit as an experienced biological microgravity research center, Belspo, the Belgian Scientific Policy Organization as a supporter to get PRODEX funding from ESA and the Technical University of Berlin, as sounding board.

7.2 Schedule (Fig. 10)

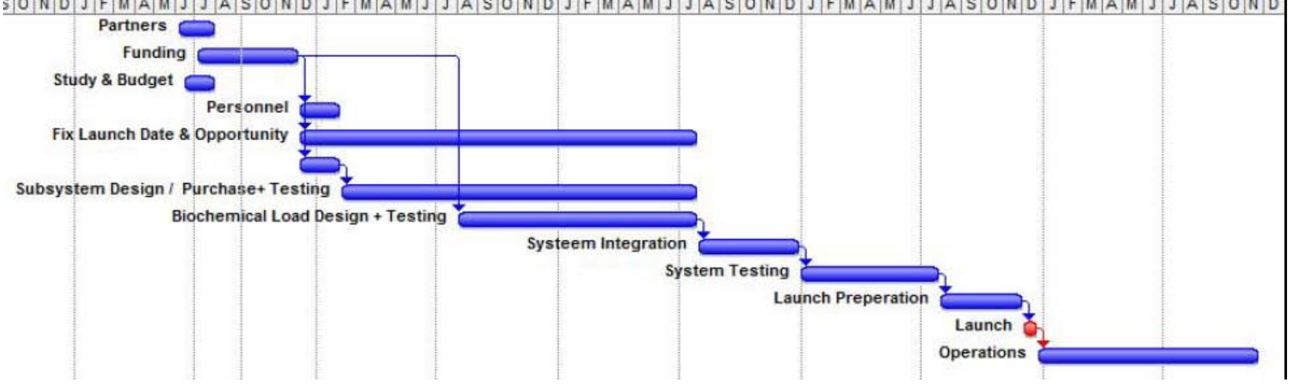

Fig. 10: Schedule

7.3 Costs

The total start-up cost for a first mission is reasonably high, but still quite low compared to an experiment onboard the ISS.

Institutional costs, mainly to pay for researchers, laboratory costs, equipment, travel and overhead, are around €500.000 ROM.

Hardware costs are estimated around €300.000 ROM.

In future missions hardware and launch costs will remain somewhat the same, but institutional cost can drop dramatically, as the same set-up can be used for testing different reaction products.

7.4 Facilities

No strict clean room is needed for development, but a sterile laboratory to fill the bio-container is needed for preliminary testing and at the launch site. This is possible in SCK-CEN in the test phase and at Baikonur before launch. A system engineer and biological research engineer from the LeSTAR project must be present at the launch site.

Test facilities to do certified testing for launch and orbital conditions are present at Lessius University College.

7.5 Risks

The top 5 risks are, in arbitrary order:

- Lack of funding
- Launch vehicle malfunction
- Bio-container malfunction
- Communication malfunction
- EPS malfunction

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