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Sensitivity study of the ABEP (Air Breath Electric Propulsion) System in the feasibility of EO (Earth Observation) missions at VLEO (Very Low Earth Orbit)

BACHERLOR'S DEGREE THESIS
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Report

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Álvaro Juzgado

Abstract

This project consists on the sensitivity study of mission parameters on the feasibility of the implementation an specific propulsion system, ABEP, in small satellites, specifically Cubesats in order of increasing the orbit they can be on orbit. Also materials will be taken into account to increase the lifetime they remain usable on orbit until they completely degraded. DISCOVEX, a cost model value tool used for the project is briefly explained. The feasibility study results will consist on a comparison of the benefits for different cases, with the reference case simulating the Planet constellation mission. After the comparison of various scenarios, the feasibility of developing and implementing the technologies is discussed.

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Aim

The aim of this study is to evaluate the economic feasibility of a EO (Earth Orbit) mission using an ABEP (Air Breath Electric Propulsion) system and refractory materials, identifying and characterizing the economic ratios at a VLEO earth observation mission. The objective is to estimate a cost for the ABEP and materials to make feasible the mission.

Requirements

Some common requirements for the scope of this project are:

- Small satellites are the focus of this study.
- For the state of the art, only LEO orbit will be studied.
- For the estimations required, ABEP system and specific refractory materials will only be studied on a Very Low Earth Orbit (VLEO) : between 200 km and 450 km above Earth's surface.
- The small satellites will incorporate an ABEP system and refractory materials.
- The study will focus on earth observation missions, and the payload will be for photographic images.
- The mission used for the study will be related to the Cubesat constellation of PLANETS.

Scope

The scope of this study will be addressed to the feasibility study of the implementation an ABEP system and refractory materials on Cubesats constellations for missions of Earth Observation purposes. The feasibility study will be done through the calculation of the possible investment for the technologies above mentioned.

For studying the feasibility, a value chain of a earth observation mission will be done, specifically Planet mission. The costs to set up the Cubesat constellation and all the costs associated to provide the imagery service will be quantified and used to develop a tool able to have as an output the investment necessary for the implementation of the technologies.

After the value-chain, a reference case will be studied, giving as output a value of investment. Some studies on variation of the parameters to do a sensitivity study of the investment will be done. Finally a feasibility analysis of the whole constellation will be done, giving as output parameter values for different lifetimes, and a conclusion of the feasibility of these technologies will be explained.

Chapter 1

Introduction, VLEO

A brief introduction at the current state of the VLEO missions, ABEP system and materials is exposed here:

1.1 VLEO Background

Very Low Earth Orbit can be defined as the orbits with a mean altitude below 450 km. During the last years, there has been and increasing interest on this type of orbit, especially on the field of earth observation, as the spacecraft operates closer to the earth surface. However, this may be seen as a challenge, mainly due to aerodynamic forces caused by the atmosphere. A brief summary of VLEO benefits for Earth Observation tasks is presented, extracted the information from (13).

As the operating altitude is reduced, the resolution and radiometric performance of the optical payloads are automatically increased, and also the accuracy the signal that wants to be measured. The same benefit applies to and increase of payload mass, or reducing the costs of launching the same payload mass. This can also be used to launch a constellation of Cubesats using the extra mass available at reducing the altitude. Also, as the lower the orbit is, the timeliness of revisit is higher. The images taken can be geolocated with a greater accuracy, as the position of the spacecraft have smaller uncertainties.

In VLEO, no deorbit is required, because of the short lifespan caused by the aerodynamic forces. These same reason causes a lower risk of collision with space debris, because of the atmosphere cleaning the debris a much higher rate than in order orbits, and also because low orbits have been less targeted along the years.

However, the are some challenges flying on VLEO, being the main ones:

1. Operating at lower altitudes reduces the pass duration, decreasing the communication windows with the ground station. A mission that generates lots of data, such as earth observation, need a major design driver.

2. The atmosphere present at those altitudes mainly consists on atomic oxygen, a highly reactive species. It can interact, decreasing their performance, with optical coatings and sensor surfaces. These atmosphere also causes aerodynamic forces, mainly drag. These forces make the spacecraft orbit decay, an undesirable effect that needs to be compensated by propulsion systems. Another way is reducing the drag, so the propulsion system requirements can be reduced, is shaping the aircraft into aerodynamic shapes, even using the these shape and aerodynamic forces to stabilize the aircraft.

1.1.1 ABEP & Material Background

Atmosphere-Breathing Electric Propulsion (ABEP) is a possible strategy to enable longer mission lifetime in VLEO by compensating the drag in orbit, while reducing propellant mass requirement. The thrust is provided by collecting, using a specially designed intake, the incoming residual atmosphere present at VLEO altitudes and using it as propellant for an electric thruster. This means and ideal infinite propellant, and therefore, the satellite lifetime would be equal to the sub-systems lifetime (3).

Air breathing propulsion system, apart from a thruster suitable to handle atmospheric gases, requires an intake capable of collecting the necessary mass flow and pre-compression and a S/C Core for accumulation and further compression. In Figure 1.1 is shown.

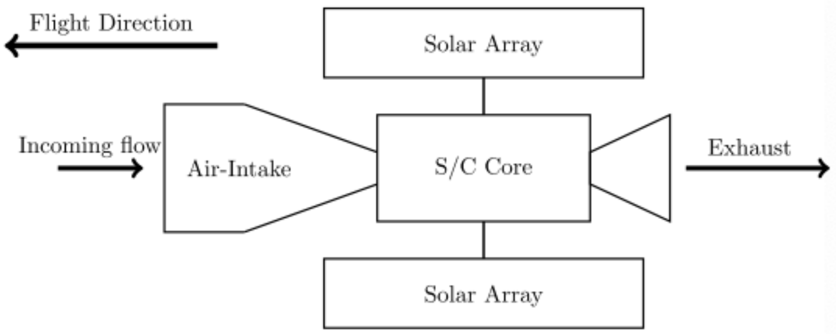
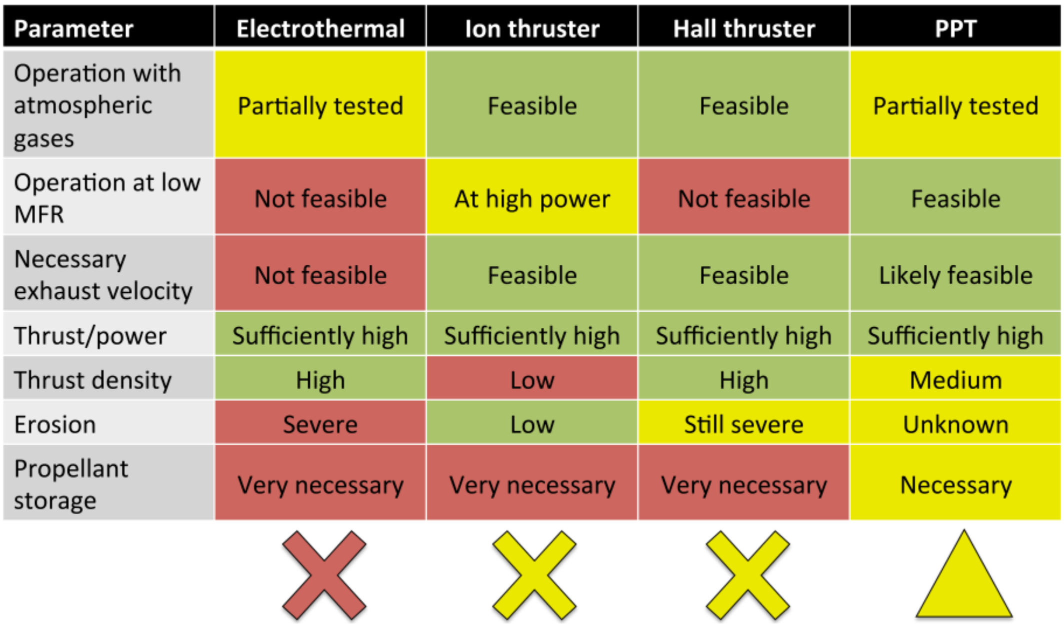


Figure 1.1: ABEP scheme (1)

There are several propulsion systems which have been studied, most of them involve the use of current electric propulsion technology, such as Hall-effect thrusters, ion thrusters, pulsed plasma thrusters (PPT) or newer concepts such as inductive plasma thrusters (3). On Figure 1.2, it's shown a summary of different characteristics of the thrusters commented above. In general, there isn't yet an specific type of functional thruster that can be assured is feasible to use for this task. For this reason, researchers keep investigating on new and better solutions.



Parameter	Electrothermal	Ion thruster	Hall thruster	PPT
Operation with atmospheric gases	Partially tested	Feasible	Feasible	Partially tested
Operation at low MFR	Not feasible	At high power	Not feasible	Feasible
Necessary exhaust velocity	Not feasible	Feasible	Feasible	Likely feasible
Thrust/power	Sufficiently high	Sufficiently high	Sufficiently high	Sufficiently high
Thrust density	High	Low	High	Medium
Erosion	Severe	Low	Still severe	Unknown
Propellant storage	Very necessary	Very necessary	Very necessary	Necessary
	✗	✗	✗	△

Figure 1.2: Comparison of breathing electric propulsion systems (1)

The atmosphere present at those orbits, mostly atomic oxygen (AO), interact with many spacecraft materials to produce surface recession and mass loss. The high speed of the satellites increases the erosive potential of the AO, resulting on degrading the performance of the satellite systems, significantly affecting the mission performance, even resulting on premature mission failure. Development of new materials and protective coatings which in order of negating the adverse effects of AO erosion is of significant importance (14).

1.2 Justification

It can be noticed that the success rate of CubeSat missions has increased, as it can be seen in Figure 1.3, while Cubesats failing during the the early stages of operation practically remained constant. When a CubeSat fails during commissioning or during the early stages, it is said to have died as an infant (2). It was considered success if the satellite survived early operational stages. The Figure 1.3 does not count the launch failures.

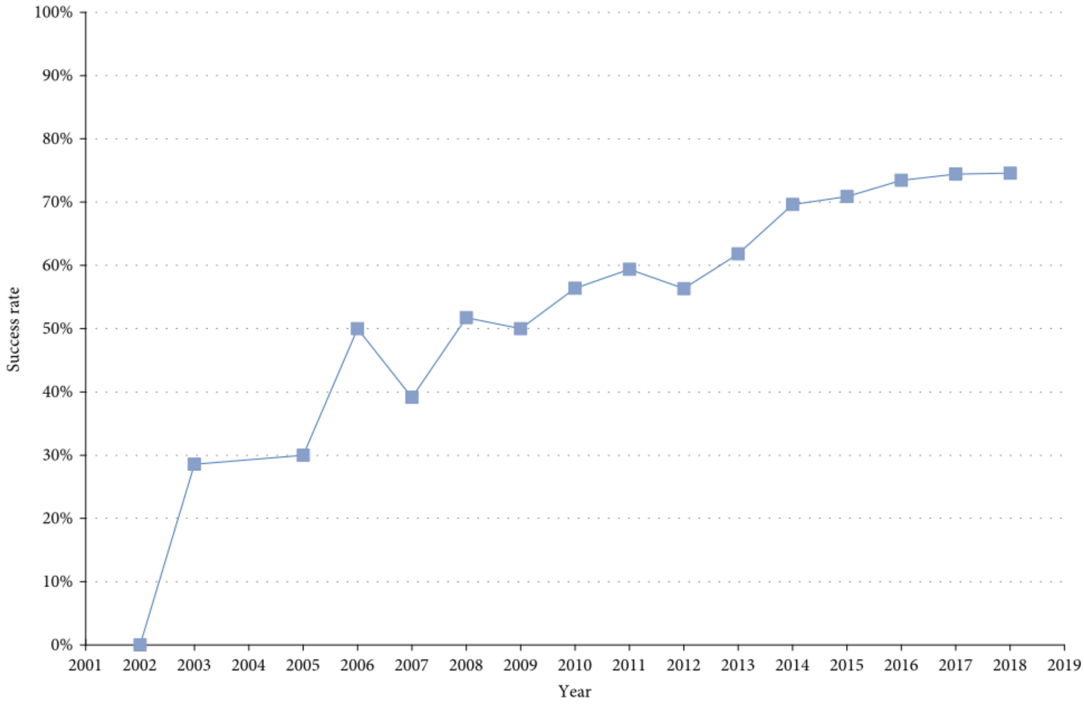


Figure 1.3: Success rate of CubeSat missions as a function of time.(2)

These success rate decays if the CubeSats are deployed at VLEO, and their lifetime also decays abruptly, because of the fast energy loss due to atmosphere interaction. There is a market opportunity for these orbits, but the abruptly orbit decay has to be solved first. In Figure 1.4, an exponential tendency growth of CubeSats launching can be seen.

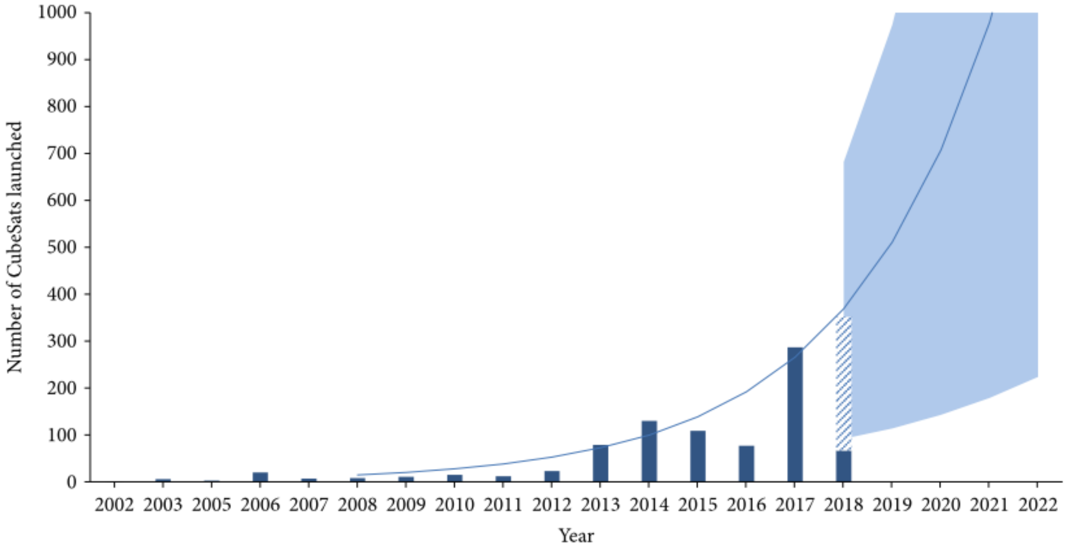


Figure 1.4: Best fit for the number of CubeSats launched per year (solid line). The shaded area represents 95% confidence interval for future launchings.(2)

Chapter 2

State of the art

Here a state of the art of Earth Observation, Cubesats design and the technologies of the ABEP and materials is done.

2.1 Earth observation (EO)

Earth observation is to gather information concerning the Earth, either physical, chemical or biological, with remote sensing technologies. This information is then used normally to monitor the status or changes in natural environments or man-made structures. The most common way to are satellite-based sensors. Earth observation is used in many fields, such as forest observation, global monitoring of agriculture, crisis management, maritime surveillance or land parcel information, amongst others (15). For the governments, EO delivers information to make political and social decisions.

2.1.1 Parameters related to EO imagery

In this section, a set of parameters that distinguish the capacities of EO satellite systems are defined. These parameters are important for EO decision process (16).

2.1.1.1 Spatial resolution

This parameter establishes the level of detail that can be extracted from an image. The most common way to measure this parameter is the Ground Sample Distance (GSD), defined by the distance between two adjacent pixel centres measured in the ground. The lower the GSD, the more detail can be extracted from the scene. In table 2.1, we can see the detail in GSD scale.

GSD	Visible	Radar	Multispectral
>4.5m	Distinguish between taxi-ways and runways at a large airfield	Detect a large cleared swath in a densely wooded area	Distinguish between urban and rural areas
2.25 - 4.5m	Detect large buildings	Detect road pattern, fence, and hardstand configuration	Detect timber clear-cutting
1.25 - 2.25m	Identify a large surface ship in port by type	Detect medium-sized aircraft	Identifty major street patterns in urban areas
0.6 - 1.25m	Identify individual tracks, rail pairs, control towers	Detect all real/road bridges	Detect small boats(15-20 feet in length) in open water
0.37 - 0.6m	Identify rad as vehicle-mounted or trailer-mounted	Count all medium helicopters	Detect ditch irrigation of beet fields
0.20 - 0.37m	Identify the spare tire on a medium-sized truck	Distinguish between variable and fixed-wing fighter aircraft	Detect foot trail through tall grass
0.10 - 0.20m	Identify individual rail ties	Detect road/street lamps in an urban residential area	Distinguish individual rows of crops
0.05 - 0.10m	Identify the rivet lines on bomber aircraft	Identify the dome/vent pattern on rail tank cars	
<0.05m	Identify vehicle registration numbers (VRN) on trucks	Identify trucks as cab-over-engine or engine-in-front	

Table 2.1: Scale related to GSD (Source: http://fas.org/irp/imint/niirs.htm)

2.1.1.2 Revisit time

It can be defined in two ways. The first one, from the point of view of the satellite, is the elapsed time for the satellite to pass over the same exact point on the ground surface. From the EO user, it is the length of time to wait for the satellite system to be able to observe the point same point of interest. This difference exists because of the capability of the satellite to modify its attitude.

2.1.1.3 Geolocation accuracy

This parameter depends completely on the satellite swath, the Earth surface area imaged by it. For example, in some applications such as meteorological forecast studies is needed a global coverage, since there is a need to cover all Earth surface.

2.1.1.4 Imagery price

Another important parameter is the cost of the product, meaning how much does it cost a portion of surface of Earth, $\$/km^2$. This price grows when the imagery has better resolution and better geolocation accuracy.

2.1.1.5 Others image quality-related parameters

Parameters which also affect the quality of the image are:

- **Off-nadir angle**: The angle the camera acquires respect to the ground when taking the image. A low off-nadir angles is desired.

- **Sun-elevation angle**: Angle of the sun above the horizon. If the image is taken with low sun elevation angles, it may be too dark to be usable.

2.2 Cubesat

A Cubesat is a standard design for nanosatellites, which structures relates to a cube of 10cm edge and a mass below of 1.33kg. These simple specification allows to design and manufacture low cost nanosatellites. Some benefits of using cubesats are:

- It is fast to built.
- The cost is far lower than large satellites.
- Its technology is simple, since the standard parts are available in which is known as off-the-shelf (commonly known as COTS).
- The design is simple.
- They doesn't generate space debris, since they burn up in the atmosphere.

However, it has cons. The capacity is very limited, and the mission duration is not quite long, since most of them are operational for a period of three to twelve months.

2.2.1 Design

Thank you to the size reduction of the satellite, the deployments cost is very reduced, being able to be launch in multiples, or being part of the excess capacity of a larger satellite/vehicle launch. The standardization simplifies the launch too, since all Cubesats, no matter the length, are 10x10 squares. This enables the utilization of the launch in short notice periods, using the Poly-PicoSatellite Orbital Deployer (P-POD), a common deployment system developed by Cal Poly (17). In this section, the subsystems of the Cubesat will be also explained. In table 2.3, a summary of considerations on the subsystems.

2.2.1.1 Cubesat Design Specification

The structure of the Cubesat must be compatible with P-POD. An example of some specifications it must comply follows, extracted from the Cubesat Design Specification (CDS) of Cal Poly, (17):

- Rails must be smooth and edges must be rounded to a minimum radius of 1mm.
- At least 75% of the rail must be in contact with the P-POD rails. 25% of the rails may be recessed and no part of the rails may exceed the specification.
- All rails must be hard anodized to prevent cold-welding, reduce war, and provide electrical isolation between Cubesats and the P-POD.

In the CDS, also are dimensional and mass requirements, as well as other operational requirements the Cubesat has to follow. This standardization provides safety, simplicity and reliability for the launch vehicles and the Cubesat itself.

2.2.1.2 Attitude and Control Determination Subsystem

For Cubesats, the attitude control fact deeply relies on the fact of miniaturizing the technology without a significant withdraw in performance, since even when at the beginning, when it is deployed, tumbling exists due to forces and bumping. For EO, since the Cubesat has to be stabilized to take the image, it has to be detumbled. The ACDS modifies the satellite position according to external or internal references. It is compounded by two main components, sensors and actuators. On Cubesats, is common to be redundant on the ACDS components, to ensure the lifetime mission, even if it increase the final cost.

Attitude sensors provides information of the position or orientation of fields, objects or other outside the Cubesat. Exist multiple types of sensors, such as Horizon sensor, an optical instruments that detects light from Earth's atmosphere, or the Orbital gyrocompass which uses a pendulum to sense local gravity, pointing the gyro to north due to the force generated. There are other multiple sensors, each one with different accuracy and performance. The magnetometer is the smallest and less power consumer. It uses the Earth magnetic field strength, or if used in a three-axis triad, also the direction, generating a Earth's magnetic field map, determining the position of the spacecraft. However, it is vulnerable to electromagnetic interference. Sun sensor, which senses the direction to the Sun from the radiation signature. A sun sensor can be some solar cells, therefore, if the spacecraft features them, this attitude sensor is usually a redundant one. The most accurate one is the star tracker, which measures the position of the stars using an optical device. It calculates the relative positions of stars around it using the brightness and spectral type of the stars. Since it's the most accurate, it is also the most expensive.

Attitude actuators are the responsible to provide the necessary torques needed to modify the Cubesat attitude, based on the information received from the sensors and the operation the Cubesat is at the moment. Magnetic torquers or magnetorquers are usually the responsible of producing the torque on Cubesats. Magnetorquers use the magnetic field and permanent magnets to exert a moment. However, their response is very low to be considered primary actuators. For these reason, reaction wheels, with a higher response time and a higher power consumption and complexity, are the responsible of producing the primary torque to control the attitude of the Cubesat.

2.2.1.3 Energy Power Subsystem

EPS is the responsible of electrical power generation, storage and distribution. The bigger the Cubesat is, more power consumption will have. If the design of the other subsystems is done, a preliminary power budget can be done and therefore find a suitable EPS.

Solar power generation is the most common method on Cubesats. At 2010, approximately 85% of all nanosatellite were equipped with them, and also rechargeable batteries (18). Solar cells are placed on each Cubesat side, and in bigger cubesats more cells are placed. But this doesn't mean the power grows proportionally to the size, since it depends to the orientation of the sun rays, being much less efficient as the Cubesat size grows. Deployable solar arrays are a solution, providing extra power generation when the Cubesat is deployed in orbit.

Since solar energy is not always available when Cubesat operating, storage of energy is needed. For these, primary and secondary batteries. Lithium-based batteries are the most common, since they offer low weight, high energy and good recharge-ability. Are usually connected to the solar array, and able to recharge power on-demand. Power management and distribution (PMAD) control the flow of power to the Cubesat. It protects the electronics and batteries from off-nominal current and voltage conditions.

2.2.1.4 Communication subsystem

An essential part of the Cubesat, since it enables it to transmit data to the ground and receive the information and commands from Earth. This system commonly consists on a transceiver and an antenna. Since Cubesats operate at maximum altitude of LEO, whip or patch antenna can generally maintain communication links, even if the Cubesats does tumble. The greatest challenge for this system is to downlink all the amount of data the spacecraft can generate, like images in earth observation. The greater the downlink rate, the more data the Cubesat will send to the Earth, if the communication window remain constant.

UHF and VHF frequencies are used for Cubesat communication, even S-band is also common in Cubesat. These bands are good for not big data, but mid-high quality images needs every day in case of some applications, is needed more. X-band is used for this, since higher data rates can be achieved, but at a higher power consumption. To optimize the power comsumption and communication window, some Cubesats have more than one different transceiver, therefore, different downlink data is sent at the most optimal band depending on the size of this data.

2.2.1.5 Optical subsystem

This subsystem is one of the most important for earth observation Cubesats. It provides the components to spacecraft in order of fulfilling the service it was built for. There are already designed camera modules for Cubesats for many requirements, with a low power consumption and with a good resolution. But for Planet requirements, a higher quality resolution than the ones provided by the designed module was needed. Then, an own design of the optical subsystem was needed. This fact carried a better scaled of the technology needed, but more time and efforts to put in the design of the Cubesat, since the final product/service will be delivered by it. Planet does already design PS0, PS1 and PS2, three variants of these kind of subsystems 2.2. In Figure 2.1, it can be seen the Payload design of Planet. It is compounded by a telescope, and a frame CCD camera. The CCD sensor converts filtered photons, filtered with Bayer-mask filter, into electrons, later amplified to produce digital numbers corresponding to each pixel in each band (5).

Instrument	Spectral Bands (nm)	Field of View and GSD		
		620km (Altitude of Planet labs Flock 1c)	475km (Target altitude for future SSO Flocks)	420km (ISS Flocks altitude)
PS0 and PS1	Red = 630-714 Green = 515-610 Blue = 424-478	HFOV: 16.1km VFOX: 10.7km Area: 173km sq GSD: 4m	NA (Instrument not flown at this altitude)	HFOV: 10.9km VFOX: 7.3km Area: 79km sq GSD: 2.7m
PS2		NA(Instrument not flown at this altitude)	HFOV: 24.6km VFOX: 16.4km Area: 405km sq GSD: 3.73m	HFOV: 21.8km VFOX: 14.5km Area: 316km sq GSD: 3.3m

Table 2.2: Spectral Band and Field of View (FOV) Information for PS0, PS1 and PS2 Instruments, flown at various altitudes. Source:(5)

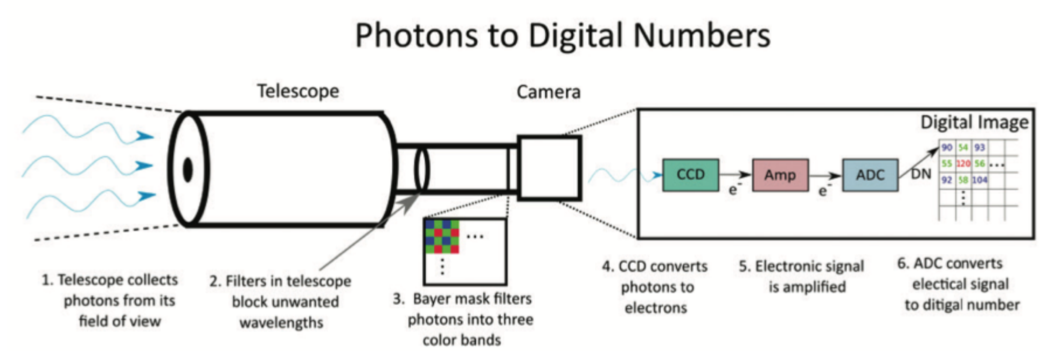


Figure 2.1: Planet Labs Opticals System and Camera

Subsystem	Considerations
ACDS	Performance decays with time, so there is a need of redundancy systems. Power consumption and accuracy. Kits are avalaible at market.
EPS	Design efforts for complete solar arrays asemblies. Designed after the requirements of the other subsystems.
Communication	UHF and S-band doesn't allow high amounts of data. Therefore, not used for image downloading. X-band allows higher data rate, but has higher power consumption. It defines the amount of data the Cubesat can send.
Optical	The most time consuming on design stage. It will define the quality of the final product. Resolution, GSD, focal lenght are important parameters.

Table 2.3: Considerations on the Cubesat subsystems.

2.3 Propulsion

This section will consist on a brief summary of propulsion option for micro satellites on very low earth orbit.

As commented con the background, the cost reduction of this type of mission, and also the prevention of space debris has increased the interest on microsatellites on VLEO. But, there is a challenge, and it is the rapid orbit decay due to the atmosphere, unless the microsatellites relies on a propulsion system able to maintain its orbit.

2.3.1 VLEO microsatellite missions

Some benefits of this missions, commented on the Background section, are the increased payload mass to orbit and the better optical resolution and radiometric performance, which both increases when the altitude is lowered. Two others benefits are a better compliance with space debris mitigation policies and reducing cost missions, although the costs due to drag, orbit decay and propulsion systems are not contemplate.

There is a big technological and operational challenge with the implementation of a propulsion system with severe mass, volume and power limitation. Some propulsion options were evaluated, taking into account spacecrafts between 10-100kg and mission altitudes between 250-500km.

2.3.2 Micropropulsion options

In this section, micropropulsion options for microsatellites and a propulsion system feasibility analysis from (19) is analyzed.

2.3.2.1 Cold gas thrusters (CGT)

CGT areconsists on a valve and a nozzle, producing thrust releasing the gas contained in a pressurized tank, without heating. These type of propulsion systems are relatively light, usually using relatively inert gases with low molecular mass, meaning a combined mass of system and propellant below 2 kg. Low fuel efficiency restricts makes it not suitable for missions with low total impulse requirements and the need of pressurized propellant, since current regulations do not allow high-pressure tanks on small satellites, are the major drawbacks of the propulsion system.

2.3.2.2 Resistojet thrusters

This propulsion system is similar to the CGT, but resitojets heat the propellant with electrical resistance, improving the fuel efficiency but also increasing the power consumption. Hence, unless a energy storage unit is adopted, some microsatellites are not compatible with resistojets. Another drawback can be the lifetime, which is strongly influenced by the the number of thermal cycles of the resistance element. An advantage is the propellant type, since it can use stored liquid butane, being able to use the vapour pressure to feed the thruster, while thruster heating ensures that not liquid-phase butane or propellant is expelled. The main advantatge for this butane liquid resistojet is the no need of high pressure tanks and regulation valves.

2.3.2.3 Electrostatic/electromagnetic thrusters

Electrostatic and electromagnetic uses electric energy to accelerate an ionized propellant to high velocity to produce thrust. The potential options for satellites could be miniaturized Hall and radio-frequency ion thrusters(HET AND RF), which use gases propellants; field emission (FEEP) and pulsed plasma thrusters (PPT), which uses liquid and solid propellants. Their propellant consumption is much lower than the provided by the previous propulsion systems.
Just for interest, for 100-kg-class microsatellites, HET and RF thrusters are preferred to use, due to their relatively high thrust and total impulse capacity. And, for smaller satellites, FEEP and PPT thrusters, because of the lower thrust, power consumption and impulse capacity.
But, also this type of propulsion system haves disadvantages: high power consumption, need of a complex power porocessing unit (PPU) and a challenging integration on board small satellites. Also, as in CGT, for hall and radio-frequency thrusters a pressurized tank is required.

CGT, resistojet and monopropellant are advantatgeous for EO microsatellite missions, since they can be fired in short bursts and it is advisable to use a low-power propulsion systems, but for 350km or below altitude missions may not be feasible. Instead, hall or radio-frequency electric propulsion can be considered, due to their low power-to-thrust. PPT is limited by a very low thrust and total impulse capacity, while FEEP by power contraints.

2.3.2.4 System feasibility analysis

Propulsion unit mass, volume and power fraction were evaluated, and compared for the technologies explained. The missions were defined following the next assumptions:

1. The satellite is in a near-circular Sun-synchronous orbit
2. In order of nullifying the perturbation of the orbital eccentricity and argument of perigee due to the Earth obliqueness, a frozen orbit configuration is adopted.
3. The effect of minor perturbations of the orbital inclination is not considered.
4. The spacecraft bus layout is modeled as a cube.
5. Two microsatellites configurations are considered, Table 2.4.
6. Solar flux and magnetic indices are also set, and denoted by HA for high solar and geomagnetic activity, and LA for low activity.

Configuration	Mass m (kg)	Side-length l(m)	Power p(W)
C1	100	0.65	100
C2	10	0.25	15

Table 2.4: Microsatellite parameters, where p is generated by solar panels.

After some calculations of the propulsion system mass fraction, (19), it can be seen that for C1 configurations at altitudes close to 250km for HA case, and below 350km for LA cases, HET/RF are advantageous, while between 285-340km(LA) or 350-450km(HA) altitudes, monopropellant thrusters are prefered. For higher altitudes cold gas and resistojet systems are considered. For C2 configurations, it is not possible at altitudes below 300km in the HA case.
As to volume fraction, the propellant density has a key impact. It is more evident for HET/RF thrusters.
On the other hand, for power fraction, for LA vase, HET/RF are suitable for altitudes from 250km, while PPT/FEEP meet power constraint at 260-280km. For HA case those altitudes increase to 300-350km and 350-370km respectively. Under the assumptions done, for power fraction doesn't matter the configuration in this case, since both the available power and the drag force are proportional to the side-length (19).

2.3.2.5 Earth observation case studies

The cost of an EO mission for a 10kg spacecraft can be in order of 1M$, and the cost of HET or RF system suitable for the space has the same cost, or greater. This makes HET and RF no viable economically for missions with small spacecrafts. In (19), two case studies are reviewed:

For example, for a configuration like C1 from Table 2.4, with assumption of LA. It is a high-resolution EO mission at an altitude of 275 km, with a repeat period of 1 day and a design lifetime of 4.5 years and performed by a microsatellite of 100 kg. The optical payload has a GSD of 0.7m. Without a propulsion system, the mission would last weeks. A HET system thruster is chosen. At conclusion, the operability of the HET system only affected marginally to the payload operability and to the spacecraft subsystems.

2.3.3 ABEP systems literature review

Here will be a review of existing ABEP concepts from (3). Most of the ideas have a current electric propulsion technology involved, like Hall-effect thrusters or pulsed plasma thrusters, explained before. Some of them, may not be suitable for VLEO due to some issues:

- Propulsion system will face variations on propellant composition, due to solar activity and changes of the orbit position inducing to atmosphere density variations.
- VLEO is composed basically of atomic oxygen, known to be very corrosive for surface

materials. This means the intake needs to be able to resist erosion. Also, the components of the thruster in contact with the plasma, have to guarantee the lifetime of the system.

- Propulsion system should be able to function with low mass flow or low pressure for ignition, or both.

2.3.3.1 ABIE(JAXA)

The ABIE (Air Breathing Ion Engine) is one of the most advanced ABEP concepts, consisting on a Electron Cyclotron Resonance ion thruster, which generates an electric field with a microwave emitting antenna, and a magnetic field with magnets. Both fields ionise the propellant before accelerating it through a set of grids. The intake would be ring-shaped, surrounding the satellite core, increasing the size and the drag compensation required.[Fig 2.2]
It is designed for an altitude of 150-200km and it operates at low injection pressures, therefore additional compression is required (1). Increasing the corrosion resistance of the intake and its design would increase lifetime and thrust density, improving the thruster performance.

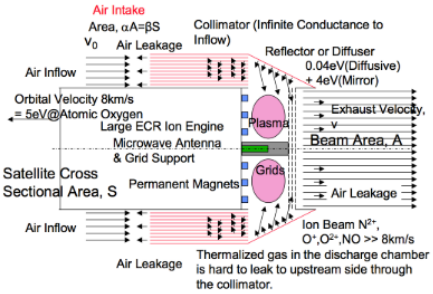


Figure 2.2: ABIE Concept.(1)

2.3.3.2 ESA RAM-EP

Another design is the RAM-EP, presented by the ESA. In this case, the thruster and the intake are physically separated, as seen in Fig 2.3. In this case, four Radio frequency Ion Thrusters (RIT) are the chosen thrusters. Is designed for an altitude range of 180-250km. Above 250km it's not as competitive as conventional electric propulsion systems, because of less mass flow delivered into the propulsion systems.

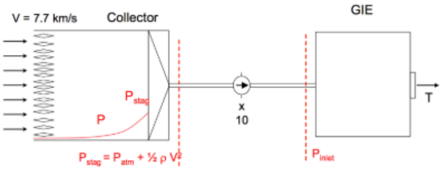


Figure 2.3: RAM-EP Concept.(3)

2.3.3.3 Air-Breathing Cylindral Hall-effect Thruster (ABCHT)

Proposed by Diamant, it was chosen a 2-stage cylindrical Hall thruster,Fig 2.4, with a previous electron cyclotron resonance ionization stage. This ionization stage was selected due to being an electrodeless operation, thus a good tolerance to oxygen exposure,capability to operate at relevant pressures, and the necessity to achieve good efficient despite low pressure, low molecular weight and mass flow, (4). However, two anticipated problems are the oxidation and the incapacity of compression of the incoming air. For the second one, is proposed to use Ar or Xe as propellant, meaning that is necessary to carry aboard an small amount (3).

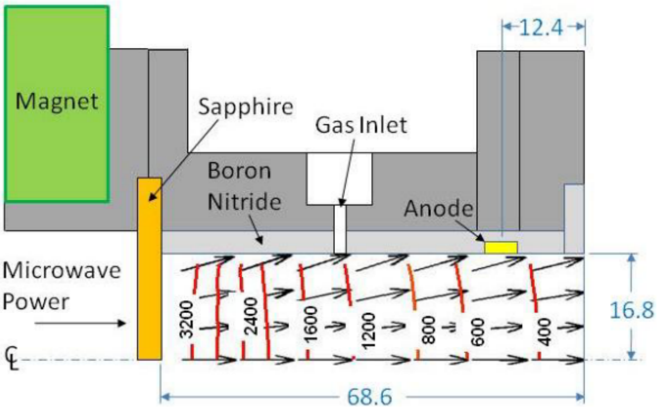


Figure 2.4: ABCHT concept, with magnetic field (red) and direction (black arrows) in the plasma-occupied region.(4)

2.3.3.4 MAHBET, BUSEK

Another Hall-Effect Thruster was proposed. Is a design for small spacecraft at Martian atmosphere orbits. As seen in Fig 2.5, it consists on solar arrays and batteries as power source, the last ones for eclipses or power peaks; a cylindrical intake and a Hall-Effect Thruster. After some calculations carried out by BUSEK, there is a estimated power enough for full drag compensation at altitudes of 150-180km, in martian atmosphere, proving the feasibility of this concept.

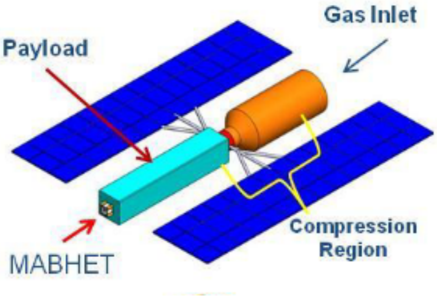


Figure 2.5: MABHET concept.(1)

2.4 Atomic oxygen effect at VLEO

Depending on the type of material, the degradation effect is major or minor. Since the orbits for the mission chosen will be located at more or less 400 km, this effect will be the main contributor to the degradation and deorbit off the Cubesats.

2.4.1 Atomic oxygen on metals

On Long Duration Exposure Facility (LDEF), at the European Retrievable Carrier and on ground, experiments on metal materials were conducted. Silver was at the moment very interesting, since the Hubble Space Telescope was using it for the solar cells interconnectors (20). Also, other materials investigated were Cu, Au, Al, stainless steel and many others. Non of them had a good performance or were too expensive to fight against the phenomenon. For example with Cu, the copper oxides adhered to the surface, changing the optical properties.

2.4.2 Atomic oxygen on no-metals

Predicting the AO durability of a material in space environment can be very complex, since every material may or not be sensitive to another component in the atmosphere, since tests conducted, indicate that for each polymer, is not the same the magnitude of erosion by AO exposure (21).

Silicones, fluorides, oxides and noble metals were believed to be kind of inert for exposures of AO, but it was shown that at long-term exposure they appeared to be severely degraded. And hydrocarbon polymers are known to be highly reactive towards orbital AO.

2.4.3 Atomic oxygen on graphene

Several experiments on graphene with atomic oxygen degradation are showing good results. Even further, results on AO erosion resistance on epoxy with a 0.5wt% of graphene nanocomposites mixture are improved, achieving almost a 50% decrease on erosion yield and decrease in mass loss.

2.5 Planet

2.5.1 Introduction

This thesis will take into account for the study a the Dove constellations of Planet. Planet mission is ”to image the entire Earth every day and make global change visible, accessible and actionable” (22). The company uses lean, low-cost electronics and designs iterations in order of launching satellites faster and cheaper than others. Every three or four months Planet is launching new satellites into orbit.
Planet constellation is formed by 200 cubesats, manufactured and designed by them. Each satellite weights 5 kg and the payload is a camera for capturing the imagery with 3-5 ground sample distance, or meter optical resolution. Thanks to the design iterations mentioned before, the company is capable of using the **Agile Aerospace** philosophy, testing the improved or new satellites and imagery cameras on space on real missions, thanks to the relatively low cost of their cubesats.
The Flock, how Planet constellation is named, is launched into two types of orbits, the International Space Station orbit (ISS) and the Sun Synchronous Orbit (SSO). In Table 2.5 some differences between both.

Orbit	**ISS**	**SSO**
Sun angle	Varies over time.	Consistent, can drift over several years.
Thermal environment	Solar beta angle maxima, need special handling.	Minor variation over the year.
Orbital Altitude	390km - 450km at deployment.	Over 500km.
Inclination	51.6º	∼ 98º
Orbit lifetime	12-18 months (depending on solar activity).	4-5 years.
Coverage	Missing northern Canada and Russia, Antarctica, southern tip of South America.	Full earth, with seasonal polar gaps.

Table 2.5: ISS & SS0 characteristics (6)

2.5.2 PlanetScope

PlanetScope constellation consists on a total of 120+ active satellites, named by Flocks, launched in different groups, forming the largest commercial fleet of satellites. Thanks to the Agile Aerospace, the on-orbit constellations is constantly improving in capability and quantity with the improvements deployed at a great pace. The constellation is able to image the entire land surface of the Earth every day, being equally to 265 million km^2/day with a 3-5 meter resolution imagery. Each satellite is calibrated to have an absolute accuracy better than 5%, and the precise geolocation assures an accuracy below 10m (7). The 3-5 meter resolution is enough to analyze changes on vegetation, flood activity or to cover track of large construction projects.

Operator	Planet
Launch date	12 Satellites 22 June 2016, 88 Satellites 15 February 2017, 48 Satellites 14 July 2017, 4 satellites on 31 October 2017, 4 satellites on 12 January 2018, 16 satellites on 29 November 2018, 3 satellites on 3 December 2018, 12 satellites on 27 December 2018, 20 satellites on 1 April 2019
Mission Status	Operating
Orbit Type	Sun-syncronous
Orbit altitude	475 km ($\sim$ 98º inclination)
Number of satellites	120+
GSD	3.7
Image capture capability	265 million km^2/day

Table 2.6: Mission details PlanetScope (7)

	Q3 2015	Q4 2015	Q1 2016	Q2 2016	Q3 2016
Estimated Operation satellites	20	25	30	50	150
Estimated Collection Capacity (Global Land Areas)	1.5	2	5	10	50
Latitude (Northern Hemisphere)	Days to revisit Average (90% Certainty)				
70º	60(70)	70(80)	50(60)	3(5)	1(2)
60º	50(60)	60(70)	20(36)	2(4)	1(2)
50º	22(35)	14(21)	8(16)	1(3)	1(2)
40º	28(38)	15(25)	13(19)	2(3)	1(2)
30º	30(40)	17(30)	15(20)	2(4)	1(2)
20º	35(46)	23(33)	16(22)	3(4)	1(2)

Table 2.7: Estimated Operational Satellites, Collection Capacity, and Days to Revisit Based on Northern Hemisphere Latitude (8).

As shown in Table 2.7, the expectation for Planet at June 2015 for Q3 of 2016 was to already have 150 operational satellites that could image the entire Earth land surface, everyday. Nowadays, it is orbiting 175+ satellites, being the largest constellation Earth imaging satellites. Planet scan each pole once every 90 minutes.

2.5.3 Planet cubesat

Although Planet does manufacture the satellite, it does not manufacture all the components from their satellites, but they buy them to Cubesat specialized providers. It is expected for the design to be similar as the prototype Dove series. In this section, the Cubesat components will be very briefly explained.

The Cubesat can be decomposed in: ACDS (Attitude Determination and Control Subsystems), EPS (Electrical Power Subsystem), Mechanical Bus and Flight Module, the communication subsystem and the optical payload(6).

The ACDS is composed by magnetometers, gyros and photodiodes in order of sensing the attitude, and then magnetorquers and reaction wheels are used to control it. In the EPS, the bus provides central power control through a power supply to the camera, the flight computer and magnetorquers. The power supply is provided by Lithium-ion cells, and the batteries recharged by body-mounted Triangular Advanced Solar Cells. Communication subsystem was formed by a VHF radio beacon for transmitting telemetry and S-band frequency hopping spread spectrum modem for two-way communication and as the primary radio for data downloading, but now, the latest versions of the Flocks satellites consist on a 2-way UHF transceiver, a S-band uplink receiver ,a X-band downlink transmitter and a helicoidal antenna. For the optical payload, Planet builds their own solution, as seen in 2.2.1.5.

Chapter 3

DISCOVEX-Cost model feasability tool for cubesats

For this thesis, a Cost model tool, initially developed for a master thesis by Antonio Cabeza Doña, has been used. In this chapter, the initial tool will be explained and also the features added to find the results of this project.

The tool was developed for a quantitative assessment of a low-cost model Cubesat constellation value-chain, implemented on Microsoft Excel. The tool estimates the cost of preparing and exploiting an earth observation Cubesat service, giving as an output the cost and several KPIs for the comparison with alternative products of the same technology.

How does it work? The model decompose the project as much as possible in details, in order of detecting the smallest work-packages and components. This will make easier to identify the cost, and therefore, the cost estimation will be specified on components and tasks with some cost information. Then, the total sum of the cost will be the cost itself. This tool uses costs for defined components and services, if it was necessary other costs, the user should enlarge the database present in the same tool in order to be able to use the desired components or services. For example, if needed another optical payload than the ones defined in this tool, the user should research the cost and specification and update the optical subsystem database.

The first section will describe the initial features of the Microsoft Excel tool.

3.1 DISCOVEX, initial features

The inital features of the DISCOVEX, developed by Antonio Cabeza Doña, allowed the user to do a quantitative assessment of a value chain study for the feasibility of a company focused on a constellation of Cubesats designed to fulfill an Earth observation images business. The tool provides a quantification of the value chain phases, CAPEX and OPEX breakdown, a Cubesat constellation cost breakdown and financial model for the business. This four main results are displayed on dashboards, letting the user to manage the information easily, and allowing some modifications on the parameters.

The Excel file is structured in the following way:

- **Input sheets:**The user can modify the information here. The sheets ask the information of the mission and the satellite constellation. They are colored in yellow.
- **Support sheets:** Most of them informative sheets, only contain information needed for the quantification value chain. Colored in light blue.
- **Dashboard sheets:**The purpose of these sheets is to display the results of the assessment and the feasibility study of the business. Colored in blue.
- **Menu sheet:**: The first sheet of all the file, it allows the user to navigate easily through all the other sheets. Also provides a little explanations of the tool.

3.2 DISCOVEX use for this study

The Excel tool was not originally able to apply a feasibility study when increasing the lifetime of the Cubesat, with a reference of case base. These expansion was the most extensive part of the study, since parameters values needed to be research and then implemented in a useful way. In this section, the feasibility study of a constellation and the feasibility study of one Cubesat tools will be explained, but first a brief explanation of the financial model, since it displays very useful results and inputs of the feasibility study.

3.2.1 Financial model

The Financial model is able to calculate the IRR, NPV and payback time for an EO business. It doesn't have to be Planet case, since the information it needs is the estimation of capital expenditures and operational expenditures. In the case of this study, it calculates based on a estimation of constellation of 140 Cubesats manufacturing costs and operating expenses. The original financial model had an historical period, from 2013 to 2017 on the financial model, where the costs where associated to historical data. From 2017, not included, to 2027 was forecasted data. In this study these periods were left that way, since it wasn't on scope to do an exhaustive business model of Planet. Also, the proportionally growth on the cost are assumed to the inflation rate already established.

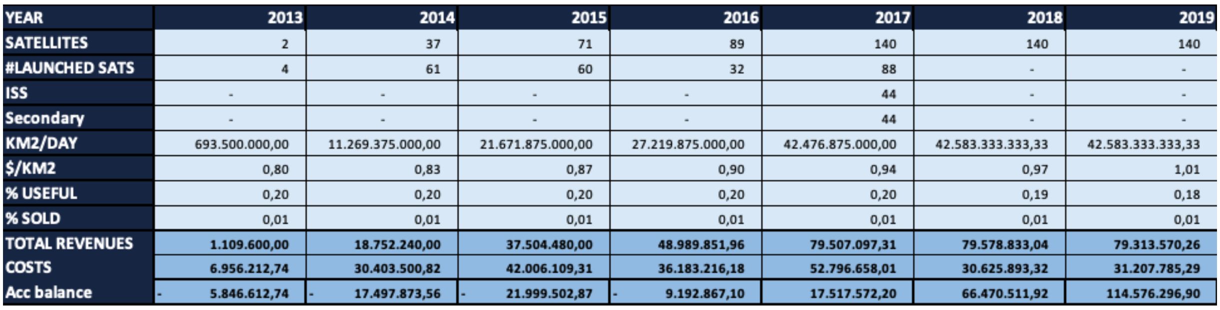
The incomes were modified from the original tool, since Antonio estimated the revenues to be a percentage share of the total incomes for high resolution imagery for Earth Observation, from all the world, estimated this share by the total revenues of the firm. The new estimation is explained at section 3.2.2 but it takes into account the price of the image and other modifiable parameters for the user.

On the next section, a Lifetime sensitivity analysis is explained, very linked to the financial model.

3.2.2 Lifetime sensitivity analysis for a constellation

This extra feature of the tool was developed to make able the Excel file to calculate easily the incomes and costs for the same mission, but for different lifetimes of the Cubesat. This feature, gives the user the ability to look how for the same inputs, how does the lifetime affect the revenues and the cost, and therefore, the economic values like NPV, PB time and IRR and the annual balance. Also some graphs are displayed to give the user an clearer vision.

The feature is divided in two principal tables, the calculation table, in Figure 3.1 an example of these table can be seen, and the results table, where the incomes and cost per year and lifetime are displayed, these table is displayed on Figure 3.4. Also, there is an initial input table and a economical values table. In the second one, when pressing a button that activates a MACRO tool, the economical values for different values with the inputs putted are displayed.



YEAR	2013	2014	2015	2016	2017	2018	2019
SATELLITES	2	37	71	89	140	140	140
#LAUNCHED SATS	4	61	60	32	88	-	-
ISS	-	-	-	-	44	-	-
Secondary	-	-	-	-	44	-	-
KM2/DAY	693.500.000,00	11.269.375.000,00	21.671.875.000,00	27.219.875.000,00	42.476.875.000,00	42.583.333.333,33	42.583.333.333,33
$/KM2	0,80	0,83	0,87	0,90	0,94	0,97	1,01
% USEFUL	0,20	0,20	0,20	0,20	0,20	0,19	0,18
% SOLD	0,01	0,01	0,01	0,01	0,01	0,01	0,01
TOTAL REVENUES	1.109.600,00	18.752.240,00	37.504.480,00	48.989.851,96	79.507.097,31	79.578.833,04	79.313.570,26
COSTS	6.956.212,74	30.403.500,82	42.006.109,31	36.183.216,18	52.796.658,01	30.625.893,32	31.207.785,29
Acc balance	- 5.846.612,74	- 17.497.873,56	- 21.999.502,87	- 9.192.867,10	17.517.572,20	66.470.511,92	114.576.296,90

Figure 3.1: Calculation table for Lifetime sensitivity analysis
DISCOVEX

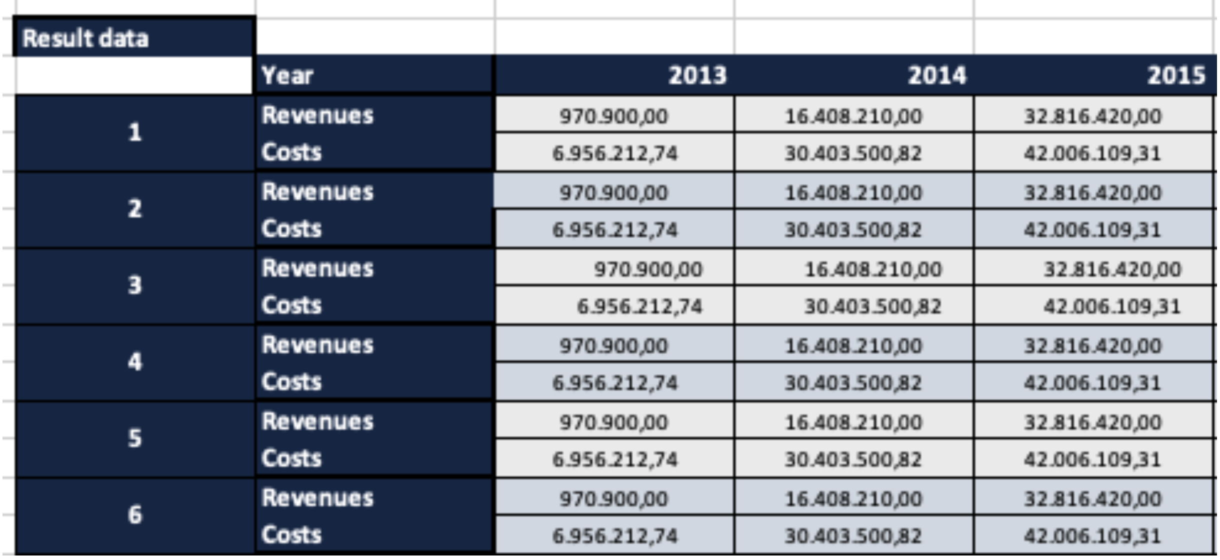
In Figure 3.1, can be seen the parameters. First, the numbers if active Cubesats is displayed on SATELLITES. All the parameters are explain in Table 3.1. The data displayed on these Figure 3.1, refers mostly to historical data. The quantitative information will be discussed and explained in Chapter 4.

Item	Description
YEAR	Year of the forecast
SATELLITES	Number of active satellites on orbit
#LAUNCHED SATS	Number of Cubesats launched that year
ISS	Number of Cubesats launched with ISS deployment
Secondary	Number of Cubesats launched as Seconady package
KM2/DAY	Square km per day, for all the Cubesats on orbit
$/KM2	Price of the square km of EO imagery
%Usefulll	Percentage of useful images taken by the Cubesats
%Sold	Percentage of sold photos
REVENUES	Annual revenues
COSTS	Annual CAPEX and OPEX costs, extracted from the financial model

Table 3.1: Calculation table, items description

The total revenues from the the calculation table, are calculated with a product of the square km the whole constellation covers during the day, the percentage of the images that are useful (there are no clouds for example) and a estimation of the percentage of this photos that is sold. The percentage of sold photos is estimated upon the original financial model, and the historical data of planet, in order to meet in some point. The price of the square km is also estimated for the first year, since there is information for 2017, in further sections it will be well explained. The # LAUNCHED SATS do take into account the satellites launched and deployed but did not survive to the deployment, that is the reason there is more launched satellites than active satellites.

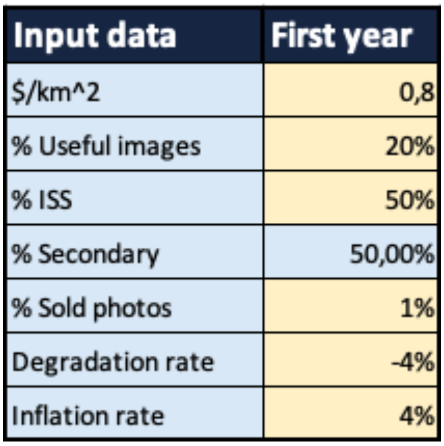
The result data table, Figure 3.4, is the result of a macro which change the lifetime of the mission data and then extracts the revenues and the costs from the financial model, and then proceed to copy it to the result table. It is a very fast way to see the sensitivity the costs and the revenues has on any parameter from the inputs table when the lifetime is changed. Some graphs are associated to the information of this data to make it easier to the user the visualization of it. The result data table, at the moment of the study, took into account lifetimes from 1 to 10 years, and the years displayed were from 2013 to 2025.



Result data				
	Year	2013	2014	2015
1	Revenues	970.900,00	16.408.210,00	32.816.420,00
	Costs	6.956.212,74	30.403.500,82	42.006.109,31
2	Revenues	970.900,00	16.408.210,00	32.816.420,00
	Costs	6.956.212,74	30.403.500,82	42.006.109,31
3	Revenues	970.900,00	16.408.210,00	32.816.420,00
	Costs	6.956.212,74	30.403.500,82	42.006.109,31
4	Revenues	970.900,00	16.408.210,00	32.816.420,00
	Costs	6.956.212,74	30.403.500,82	42.006.109,31
5	Revenues	970.900,00	16.408.210,00	32.816.420,00
	Costs	6.956.212,74	30.403.500,82	42.006.109,31
6	Revenues	970.900,00	16.408.210,00	32.816.420,00
	Costs	6.956.212,74	30.403.500,82	42.006.109,31

Figure 3.2: Results table for Lifetime sensitivity analysis DISCOVEX

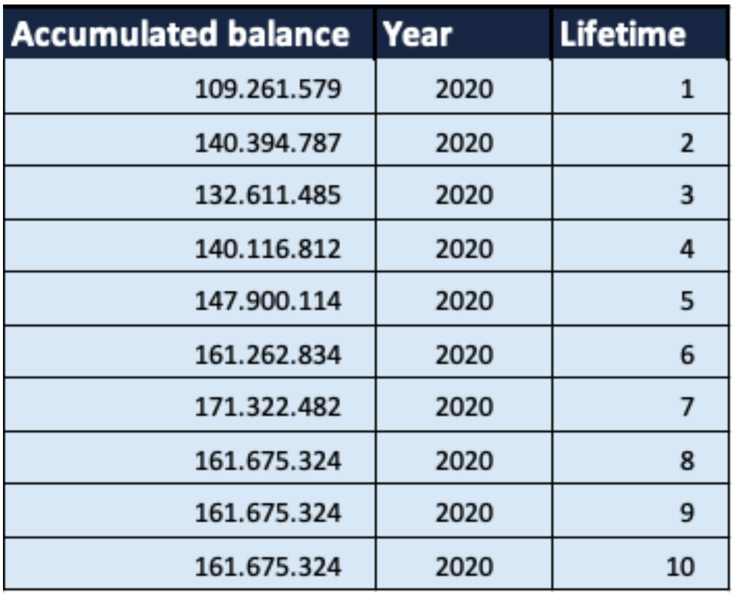
In Figure 3.3, the requested data in order to the tool be able to do the calculation is shown, most of the parameters are already explained, except the inflation rate and percentage of ISS and secondary. The inflation rate relates to the percentage the price of the square km grows annually. The percentage of ISS relates to the percentage of the launched satellites that year is deployed by the ISS deployment, and the % of secondary relates to the percentage of this launches carried as Secondary payload. The degradation rate is further explained in Section 3.2.3



Input data	First year
$/km^2	0,8
% Useful images	20%
% ISS	50%
% Secondary	50,00%
% Sold photos	1%
Degradation rate	-4%
Inflation rate	4%

Figure 3.3: Input data for Lifetime sensitivity analysis, DISCOVEX

The final result table for this feature is a display of the accumulated balance of the mission of the years 2025 and 2020, for lifetimes from 1 to 10. This accumulated balance is gross, since the discount rate has not been yet applied. Thanks to this results, the user can rapidly see the evolution of the accumulated balance at those specific years, considered to be remarking (at the middle of the mission and at the end of the forecast period).In this accumulated balance, the initial investment is not taken into account like in the financial model, just the revenues and the costs. As the other tables, the user can change the input parameters and the activate the MACRO with the button to update the results with the new parameters. In Figure 3.4, the table of the results display can be seen.



Accumulated balance	Year	Lifetime
109.261.579	2020	1
140.394.787	2020	2
132.611.485	2020	3
140.116.812	2020	4
147.900.114	2020	5
161.262.834	2020	6
171.322.482	2020	7
161.675.324	2020	8
161.675.324	2020	9
161.675.324	2020	10

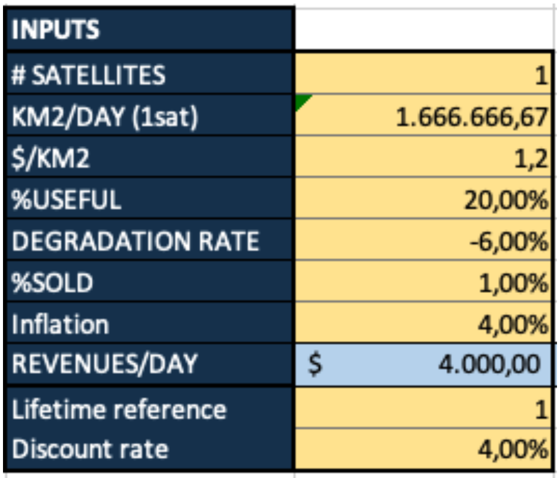
Figure 3.4: Results table for Accumulated balance analysis, DISCOVEX

This new feature give this study the possibility to extract useful results from the financial model quickly and easy for the next users, since adapting the tool was time consuming. The results extracted from this feature will be shown in further sections.

3.2.3 Investment estimation

This feature is the most used for this study, since the final output is the investment it can be done by the company in order to develop and manufacture a propulsion system or material that do not degrade, depending on the increase on the lifetime the possible maximum investment that can be done after some years of the mission is calculated. All the costs are divided and specified for an only Cubesat, but more Cubesats can be taken into account in the calculation if needed, and the feature will adapt to the input data. This estimation can be divided by: Inputs, Results summary and the calculation tables. Also there are graphs that displays the data to make it easier to the user to see and use.

The inputs are introduced in a table, like it can be seen in Figure 3.5. The values the user can change are the number of active satellites, the square km that that an active Cubesat images, the price per square km of image, the percentage of the images done is useful, the percentage of sold photos, the inflation rate for the revenues. The revenues per day the Cubesat provides, on the case base. The lifetime of reference and the discount rate. Also, a degradation rate has been include to take into account the degradation of the Cubesat capability of imagery during its lifetime. The images will not be the same the first year than if there has been degradation for five years.

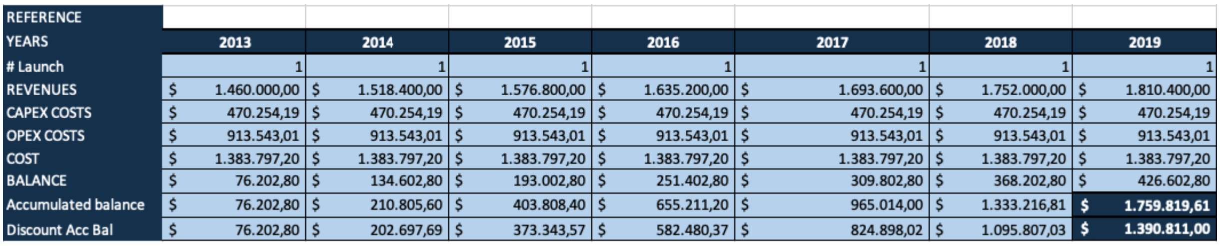


INPUTS	
# SATELLITES	1
KM2/DAY (1sat)	1.666.666,67
$/KM2	1,2
%USEFUL	20,00%
DEGRADATION RATE	-6,00%
%SOLD	1,00%
Inflation	4,00%
REVENUES/DAY	$ 4.000,00
Lifetime reference	1
Discount rate	4,00%

Figure 3.5: Input data for investment estimation DISCOVEX

Then a reference table is displayed, as seen in Figure 3.6. In this reference table includes the number of launches, the revenues, the CAPEX and OPEX costs, the balance, the accumulated balance and the accumulated balance taking into account the discount rate per year. The periods are from 2013 to 2030. Some of the parameters can be further explained.

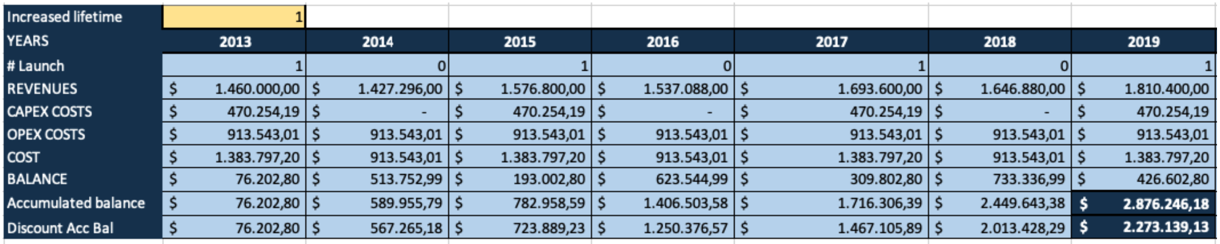
The CAPEX costs include the building and manufacturing Cubesat cost. For only one Cubesat, the learning curve applied to the financial model is not taken into account, since we only launch one Cubesat per year at maximum. Also, the launches cost are included, by an average of the ISS deployment and secondary launch cost. The OPEX cost are the related to the financial model, but the proportionally part for only the Cubesats that are being active on the study. The inflation rate is taken into account at the revenues calculation, increasing a 4% annualy in the case of the inputs of Figure 3.5.



REFERENCE							
YEARS	2013	2014	2015	2016	2017	2018	2019
# Launch	1	1	1	1	1	1	1
REVENUES	$ 1.460.000,00	$ 1.518.400,00	$ 1.576.800,00	$ 1.635.200,00	$ 1.693.600,00	$ 1.752.000,00	$ 1.810.400,00
CAPEX COSTS	$ 470.254,19	$ 470.254,19	$ 470.254,19	$ 470.254,19	$ 470.254,19	$ 470.254,19	$ 470.254,19
OPEX COSTS	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01
COST	$ 1.383.797,20	$ 1.383.797,20	$ 1.383.797,20	$ 1.383.797,20	$ 1.383.797,20	$ 1.383.797,20	$ 1.383.797,20
BALANCE	$ 76.202,80	$ 134.602,80	$ 193.002,80	$ 251.402,80	$ 309.802,80	$ 368.202,80	$ 426.602,80
Accumulated balance	$ 76.202,80	$ 210.805,60	$ 403.808,40	$ 655.211,20	$ 965.014,00	$ 1.333.216,81	**$ 1.759.819,61**
Discount Acc Bal	$ 76.202,80	$ 202.697,69	$ 373.343,57	$ 582.480,37	$ 824.898,02	$ 1.095.807,03	**$ 1.390.811,00**

Figure 3.6: Results table for the reference case of the investment estimation, DISCOVEX

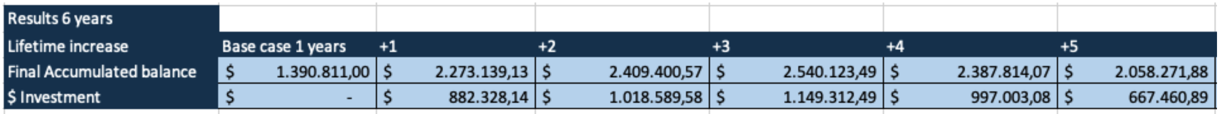
After the reference case, the analysis of the lifetime impact is carried out by several other tables where the lifetime is increased, as shown in Figure 3.7. The only difference is the cell where an increment of lifetime appears, being the final lifetime of this table the reference plus the increase.



Increased lifetime	1						
YEARS	2013	2014	2015	2016	2017	2018	2019
# Launch	1	0	1	0	1	0	1
REVENUES	$ 1.460.000,00	$ 1.427.296,00	$ 1.576.800,00	$ 1.537.088,00	$ 1.693.600,00	$ 1.646.880,00	$ 1.810.400,00
CAPEX COSTS	$ 470.254,19	$ -	$ 470.254,19	$ -	$ 470.254,19	$ -	$ 470.254,19
OPEX COSTS	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01	$ 913.543,01
COST	$ 1.383.797,20	$ 913.543,01	$ 1.383.797,20	$ 913.543,01	$ 1.383.797,20	$ 913.543,01	$ 1.383.797,20
BALANCE	$ 76.202,80	$ 513.752,99	$ 193.002,80	$ 623.544,99	$ 309.802,80	$ 733.336,99	$ 426.602,80
Accumulated balance	$ 76.202,80	$ 589.955,79	$ 782.958,59	$ 1.406.503,58	$ 1.716.306,39	$ 2.449.643,38	**$ 2.876.246,18**
Discount Acc Bal	$ 76.202,80	$ 567.265,18	$ 723.889,23	$ 1.250.376,57	$ 1.467.105,89	$ 2.013.428,29	**$ 2.273.139,13**

Figure 3.7: Results table for the increased lifetime case of the investment estimation, DISCOVEX

Then, the results table is displayed, where the user can see summary of the investment that can be done after six, eleven or seventeen years of mission for all the increments of lifetimes until plus ten years. In Figure 3.8 an example is shown. It displays the final accumulated balance with the discount rate applied after the six, eleven or seventeen years and the investment that could be done. The investment is calculated as the extra revenues acquired after the reference case. This results are graphed for the user to see more clearly the possible investment breakdown, an the evolution it has when the lifetime changes.



Results 6 years						
Lifetime increase	Base case 1 years	+1	+2	+3	+4	+5
Final Accumulated balance	$ 1.390.811,00	$ 2.273.139,13	$ 2.409.400,57	$ 2.540.123,49	$ 2.387.814,07	$ 2.058.271,88
$ Investment	$ -	$ 882.328,14	$ 1.018.589,58	$ 1.149.312,49	$ 997.003,08	$ 667.460,89

Figure 3.8: Results table for possible investment of the investment estimation, DISCOVEX

3.2.4 Conclusion of DISCOVEX

DISCOVEX is a very powerful tool and cost database that can be easily expanded for uses on not only Cubesat like is now prepared for, but for missions of other technologies like small satellites. The future user would only need to search for the information and fill it into the input sheets, allowing them to choose what is better for them. Also, it could be done a selection sheet, where the user could select the mission in a particular place as he or she desires, and the results would be displayed, without having to navigate through the Excel file, as me and my partner had to do for this study, this would ease the future work. Unluckily, this was out of the scope of this work. To prepare this tool for the study has been the major task, since it consumed most of the work-hours, to develop and the to use it in order of extracting the results.

Chapter 4

Feasability study

In this chapter the cost of a Cubesat mission will be shown and explained, from the Cubesat itself to the service needed to perform the mission. Afterwards, the investment that can be done studying the evolution during the years for one Cubesat for different parameters and lifetimes will be shown. Then, the feasibility of a Cubesats constellation will be studied with the economical values comparison from a reference case. A conclusion to finalize the chapter will be done.

4.1 Cost estimation

An estimation of the capital expenditures needed to build a Cubesat alone, and a Cubesat constellation, and the operating expenditures necessaries to run the business during a period are needed. In order of doing so, Planet mission was taken, making it easier to develop the case study and to get cost information. It is important to mention that the information was extracted and used from the cost model tool DISCOVEX, which Antonio Cabeza, (12), developed for the DISCOVERER project, while gathering and contrasting the cost information from other sources. Here is presented the summary of all the cost related to set up business. This costs will be taken into account for the further feasibility study driven in this project.

4.1.1 Cubesat cost decomposition

As said in Chapter 2.5, Planet design and build their on 3U Cubesats, but not all the components of them. They buy the components from specialized providers from the market. These components are commonly named Commercial-off-the-Shelf or COTS components. At this point, a bottom-up exercise was done with available information of the Cubesat subsystems and structure, estimating the price of each component comparing the COTS available on the market.

In order of doing the bottom-up exercise, Planet Cubesat information was needed. Since Planet doesn't public information of their satellites breakdown costs, assumptions made from technological trends will fill the gaps the Dove and Flock satellites specification available leave. There are different manufactures available for Cubesat modules, which price components are public and able for everyone, which will be used to make the estimation needed.

4.1.1.1 Attitude Determination and Control Subsystem

The Flock satellite implements the following components (6):

- **Attitude sensors:** Magnetometers, Gyroscopes, Sun Sensor, Star tracker and GPS.
- **Attitude actuators:** Magnetorquers and reaction wheels.

Following an estimation of cost extracted of manufactures, the ACDS cost is displayed in Table 4.1. All the prices were extracted from CubeSatShop (23) :

Component	Manufacturer	Price
Magnetometer	NSS Magnetometer	\$15.000
Gyros + Control Board	MAI-SS	\$17.150
GPS	GPSRM	\$8.580
Star tracker	MAI-SS	\$32.500
Magnetorquer	MT01 Compact	\$800
Reaction Wheel	MAI-400	\$21.300
Total		**\$97.330**

Table 4.1: Cost estimation for ACDS system

4.1.1.2 Electric Power System

For the EPS cost will take into consideration the Solar Arrays as the power supply subsystem, and the batteries and control electronics needed. A brief summary of the specifications and description will be done for both subsystems.

Solar Arrays

Planet uses triangular advanced solar cells (TASCs) on their satellites (6). The electrical parameters of TASCs are displayed in Table, source Spectrolab datasheet (24).

Cell Electrical Parameters	
$I_{SC} = 31mA$	$I_{mp} = 28mA$
$V_{OC} = 2.52V$	$V_{mp} = 2.19V$
$Pmp = 0.027W/cm^2$	$Cff = 80\%$
$Eff = 27 \pm 3\%$ Absolute	Temp. Coeff $V = -6.2mV/$žC

Table 4.2: TASCs electric parameters

The manufactures describe the product as:

- Delivers 4 times higher voltage than silicon cells. One Spectrolab's multijunction solar cells generates the same voltage as 5 Si solar cells connected in series.
- Are over twice as efficient than silicon cells.

There is no information cost for Planet deployable solar arrays, but an estimation searching similar manufacturers was done, Table 4.3:

Component	Manufacturer	Cost
3U Cubesat Solar Panels	ISIS	\$4.900
3U Panel Array Deployable	EXA DSA	\$10.000-16.500
6U Cubesat Solar Panels	Clyde Space	\$6.000

Table 4.3: Cost estimation for Cubesat solar panels

Batteries and Control Electronics

Power storage of Planet satellites is provided by 8 Lithium-ion cells, which provides 20 Ah of charge when at full capacity (6). But nowadays, on the market supplier do not longer provide Lithium-ion cells, instead they provide polymer-lithium batteries. As is the information we have, assumption of installing the polymer-lithium batteries is done, Table **??**. Control electronics, who coordinates and monitor the power supplied by the power generation subsystem, come as a unique module with the batteries.

Component	Manufacturer	Cost
Battery pack	Clyde Space	\$5.000

Table 4.4: Cost estimation for power storage

4.1.1.3 Mechanical Bus and Flight Module

Planet biggest challenge was to organize the space inside the Cubesat, since some modules occupy much space and leave no space for the other subsystems. Miniaturization of the components was the challenge when reorganizing the space in the Cubesat, and therefore, in the estimation of the MECH and OBDH, an extra cost due to workforce will be applied, since the price found was for a simple Cubesat kit. The over cost estimated for the initial DISCOVEX tool was 50% of the structure cost, a reasonable estimation. The extra cost also relies on extra structural elements to arrange and adapt the payload, solar cells and other components.

The flight module of Flock Planet Cubesat is compared to a 3U Pumpkin Cubesat kit, which price is 8.750\$, Table 4.5.

Component	Manufacturer	Cost
Cubesat basic kit	Pumpkin	\$8.750+\$4.375

Table 4.5: Cost estimation for MECH and OBDH

4.1.1.4 Communication subsystem

Planet communication subsystem satellites consists on a 2-way UHF transceiver, a S-band uplink receiver a high-speed X-band downlink transmitter, supported all by a helicoidal antenna, as explained in 2.5.3. The cost of all the components are displayed at Table 4.6.

Component	Manufacturer	Price
VHF downlink/UHF uplink Full Duplex Transceiver	ISIS	\$8.500
ISIS TXS S-Band Transmitter	ISIS	\$8.500
S-Band Patch Antenna	IQ Wireless	\$4.600
UHF/VHF deployable antenna system	ISIS	\$4.500-5.000
Xban transmitter	Endurosat	\$22.500
Helicoidal antenna	Helios	\$11.000
Total		**\$60.100**

Table 4.6: Cost estimation for Communication subsystem.

4.1.1.5 Optical payload

As mentioned before, in Section 2.2.1.5, Planet designs and manufactures its own optical payload. In Table 2.2, in page 13, the specifications of the three generations of optical instruments Planet has done can be seen, and in Table 4.7, the assembly of the instruments can be seen (8).

Generation	Telescope	CCD Sensor	Structure
PS0	2 element Maksutov Cassegrain	11 MP	Mounted relative to the spacecraft structure.
PS1	2 element Maksutov Cassegrain	11 MP	Mounted in an isolated carbon fiber/titanium telescope
PS2	2 element Maksutov Cassegrain	29 MP	Mounted in an isolated carbon fiber/titanium telescope

Table 4.7: Planet optical instruments specifications

There is no information available of commercial cameras with specifications comparable to Planet instruments. And due to uncertainty, the estimation of the camera Planet developed can't be done without doing assumptions not robust enough. Then, the optical payload selected was Gecko Imager optical payload, specifically designed for Cubesat and of medium-high performance. The cost is 16.000$.

4.1.1.6 Total Cubesat cost

The total cost estimation for a Cubesat of Planet constellation is shown in Table 4.8.

System	Cost($)
ACDS	97.330
EPS	27.000
MECH and OBDH	13.125
COMM	60.100
Optical Payload	16.000
Total	**213.555**

Table 4.8: Cost estimation Cubesat Planet

4.1.2 Launch service

Since Planet needs to replenish its constellation continuously, this cost is important to take into account and can't be isolated. Some assumptions were made when calculating this cost:

- We will only take into account successful launches as Capital expenditures, since the failed ones will be part of contingency costs.
- The launch service will be divided by: ISS launch at Table 4.9, Secondary payload launch at Table 4.10 and own rocket launch at Table 4.11.

4.1.2.1 Launch services cost

Item	Cost $
1U (Nanoracks)	85.000

Table 4.9: ISS deployment costs. Source: (9)

Item	Cost $
3U	295.000
6U	545.000
12U	995.000

Table 4.10: Secondary launch deployment costs at LEO. Source:(10)

Item	Max deployed satellites	Cost $	Insurance cost $	Company
3U	100	57.000.000	11.400.000	SpaceX
6U	104	15.000.000	3.000.000	ISRO

Table 4.11: Own rocket launch costs. Source: (11)

The type of launch Planet uses depends on the number of Cubesats send simultaneously, the orbit where are send (ISS or SSO) an the altitude of the orbit. The launches send to ISS orbit are considered to be ISS launch, and the launches send to SSO will be considered as secondary launch. When launching a big number of Cubesat simultaneously, a own dedicated launch will be taken into account. Therefore, the estimation done for the first 239 Cubesats send, is displayed in Table 4.12. After those launch, the model consider a launch or another with the considerations made before.

Type of launch	Cost $	Number of Cubesats	Total cost $
ISS launch	85.000	108	9.181.000
Secondary payload launch	295.000	43	12.685.000
Own dedicated launch	15.000.000	88	15.000.000
Total cost $			**36.866.000**

Table 4.12: Cost estimation for Planet constellation launch, the first 239 Cubesats.

4.1.3 Ground segment infrastructure

In this section, Table 4.13 is for ground segment and infrastructure costs to be displayed. All the information was extracted from (12), checked and contrasted before using it.

Segment	Cost $
Planet ground stations	7.143.000
Mission control center	650.000
Data Platform	1.100.000
Total	**8.893.000**

Table 4.13: Summary of Ground segment infrastructure

Google Cloud Platform was chosen for the data platform, and the cost information extracted from its corporate website. For mission control center, a design and project of Skybox imaging company Mission Control Center, with similar characteristics as the ones of Planet, is taken. Ground stations cost is the sum up of all the costs derived from the building and components. For more detail see (12).

4.1.4 Operational expenditures

In this section, will very briefly explain and estimate the cost that makes able to develop the normal service routine, without be considered assets. The following sources will be taking into account in this study: Labor and salaries, external services, supplies and the Cloud Platform services.

4.1.4.1 Supply expenditure costs

Supply costs include water, gas, power, office material and telecommunications consumption in order of daily service. The summary is displayed in Table 4.14.

Energy		
Rates for consumption and power sizing	Unit	Values
Office	Kwh/m^2/year	230
Ground Stations	W	450
Electricity	Unit	Values
Consumption Bill	$/kWh	0.085
Installed power and energy consumption	Unit	Values
Monthly consumption	kWh	424.625
Energy cost	Unit	Values
Consumption monthly cost	$	36.093
Annual energy cost	**$**	**433.118**
Gas		
Rates for consumption and power sizing	Unit	Values
Gas consumption	kcal/day	75
Conversion rate Kcal - KwH	kWh/kCal	0.00116
Consumption months	months	3.5
Gas pricing	Unit	Values
Gas pricing	$/kWh	0.046
Monthly constant price	$/month	80.97
Gas consumption	Unit	
Monthly consumption	kWh	13.729
Monthly cost consumption	$	708
Annual gas cost	**$**	**2.477**
Water consumption	**Unit**	
Water consumption per employee/day	$/employee	14.608
Annual Water cost	**$**	**4.098**
Telecommunications	**Unit**	
Employee monthly consumption	$/employee	150
Annual telecommunications cost	**$**	**45.000**
Office material	**Unit**	
Office material monthly consumption	$/employee	75
Annual office material cost	**$**	**22.500**

Table 4.14: Supplies cost, Source:(12)

4.1.4.2 External services expenditures

External services relates for the offices rental and maintenance. Planet in 2017 had five offices. Summary of costs is displayed in Table 4.15.

Offices	**Unit**	**Annual cost**
Number of offices	Num	5
Surface of office	Kwh/m^2/year	230
Office rent	**Unit**	**Annual cost**
Rent monthly cost	$/m^2	58
Annual rent	$	3.680.888
Maintenance service	**Unit**	**Annual cost**
Maintenance monthly cost	$/m^2	150
Annual maintenance cost	$	787.500
Cleaning service	**Unit**	**Values**
Cleaning service cost	$/m^2	1
Annual cost	$	504.800

Table 4.15: External services cost, Source:(12)

4.1.4.3 Labor and salaries expenditures

Only the salaries of the following departments: Spaceship captain and Mission Operation, Program engineers (launches), Product management, Software Engineers and Satellite and Ground Station engineers. These departments are the essential ones for the mission and fleet management, and it wasn't taken into consideration further detail, since it was out of the scope of the project. The cost information can be directly extracted from (12), and it is displayed in Table 4.16.

Item	US Staff ($)	EU Staff ($)	Monthly Staff Cost ($)
Operating expenses	1.291.469,66	312.222,03	1.603.691,68
Support operating expenses	593.554,42	147.728,49	687.282,90
Total	1.831.024,08	459.950,51	2.290.974,59

Table 4.16: Cost estimation Labor and Salaries.

4.2 One Cubesat feasibility study

In this section, the feasibility of implementing an ABEP system to increase the lifetime in orbit of the Cubesat and then the feasibility of implementing materials to support the ABEP and the Cubesat in order of not degrading when orbit, since there is no reason to be in orbit if there is no capability to give an imagery service. In order of studying the feasibility, a reference case is showed and studied. The values of investment and NPV are displayed and commented for different lifetimes and for different periods of years. When the reference case is explained, then a case were the degradation rate is lowered to 0 is explained to introduce the materials section. This change on the parameter will bring changes on the investment and the values, which will be commented.

4.2.1 Reference case

The first step of this feasibility study was to define the reference case. In order to do so, it was necessary to search for the following information, included in Table 4.17. Table 4.18 displays the input data values for the Reference case of the One Cubesat feasibility study:

Item	**Description**
Square km imagery per day and Cubesat	This information was extracted from Planet Imagery products specification, stated as 300 million square km per day for whole constellation Source:(25)
Price per square km image	This information was extracted from a paper where images of different companies where priced for agricultural purposes. Since the other prices available where from monthly and annual subscription, this one was taken Source:(26)
Useful percentage	This value was an estimation of the reliability of the imagery capability
Degradation rate	This value was an estimation of the degradation of the imagery capability per year in orbit. It is valuable to mention that for the reference case it was chosen a high degradation rate for a pessimistic view
Sold percentage	This value was an estimation based on Planet revenues
Inflation rate	This value is an estimation base on annual growth of Planet
Discount rate	This value was chosen taking into account normal discount rate for the European zone

Table 4.17: Inputs reference case

Item	Value
# Satellites	1
KM2/day (1sat)	1.666.666,67
Useful percentage	20%
Degradation rate	-4%
Sold percentage	1%
Inflation rate	4%
Revenues/day	4.000 $
Lifetime reference	1 year
Discount rate	4%

Table 4.18: Inputs values reference case

The result extracted for the reference case is the Figure 4.1. As we can see, the accumulated balance grow almost linearly, since the cost and revenues are almost constant during the years. For this reference case, the degradation rate has no effect, since the Cubesat does not last more than one year in orbit.

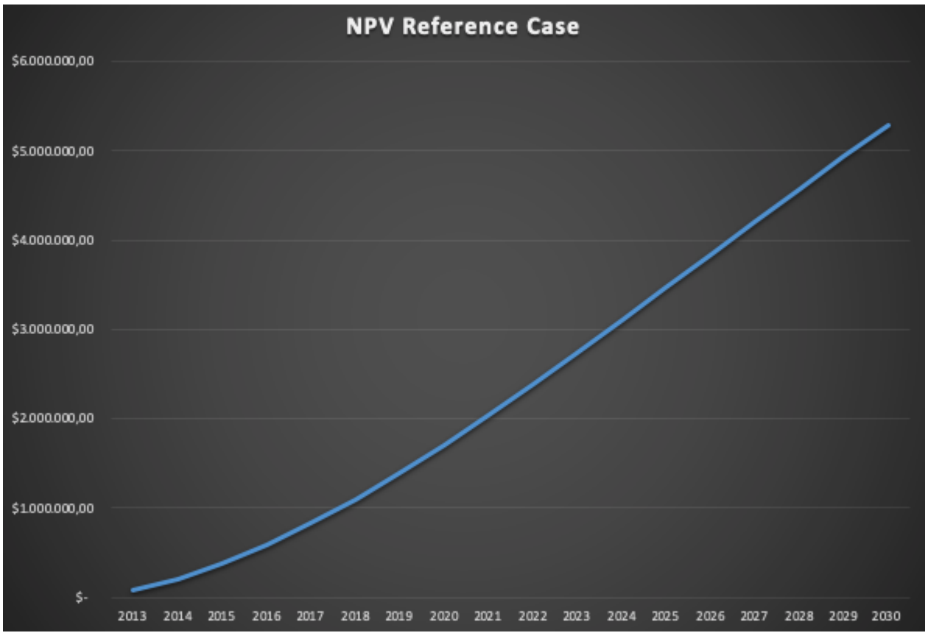


Figure 4.1: NPV during the years for the reference case. Lifetime 1 year

In Figure 4.3 the NPV evolution for different lifetimes can bee seen. When lifetimes is four years (+3), it starts to decay because of the degradation of the optical payload until lifetime of 6 years, were it remains flat. This is normal, since at six years from the beginning of the mission, when the lifetime is bigger than this period, it does not affect anymore. Then, at Figure 4.4, the evolution of the NPV at 2024 is displayed. Like in the previous one, the NPV has its peak at +3, but then it starts to decay almost until the reference case. In order of looking more into detail, figures with the investment per lifetime at 2024 will be displayed, and this phenomena will appear too. In Figure 4.2 NPV off different lifetimes can be seen for all the period mission. The same distribution there was in Figure 4.1 can be seen here. The NPV that should be higher because there are less CAPEX associated to it, the +5 lifetime, it is below the maximum, at +3 years during almost all the years above 2022.

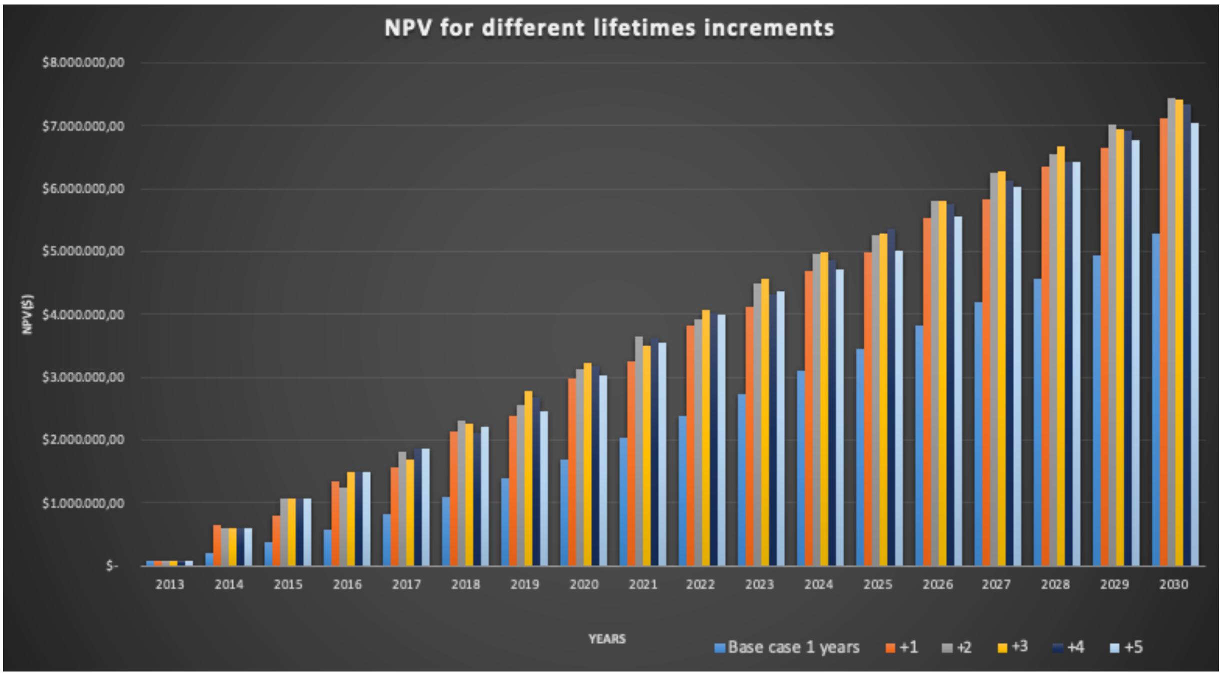


Figure 4.2: NPV for different lifetimes during the years for the reference case. Lifetime base case 1 year

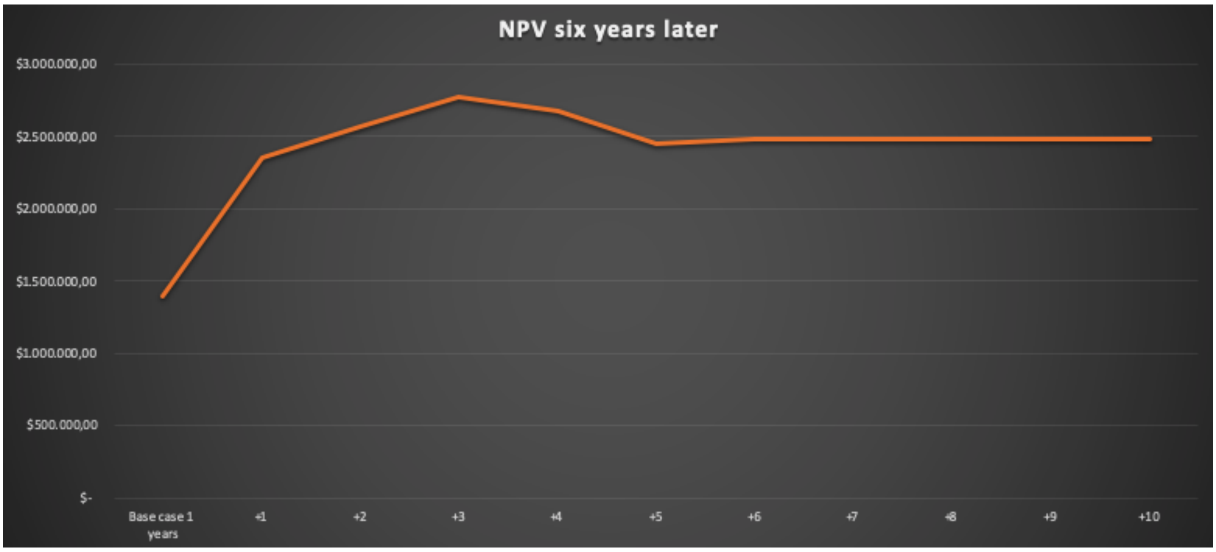


Figure 4.3: NPV at 2019 evolution for different lifetimes

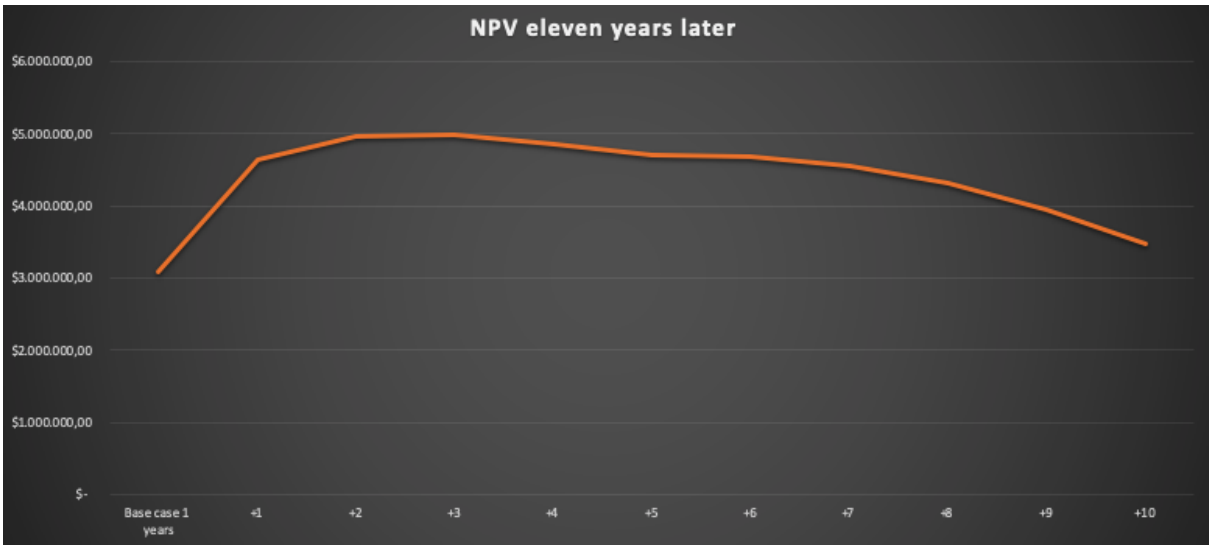


Figure 4.4: NPV at 2024 evolution for different lifetimes

Figure 4.5 shows that the maximum investment peak with the input parameters is at a lifetime of 4 years, with a maximum investment of approximately **1.8M** dollars. This shows that it doesn't matter if the ABEP system allows the Cubesat to stay longer in orbit if the atmosphere degrades it at a fast rate. Now, it will be presented what happens if the degradation rate is lower and not that high, since nowadays there are some Cubesats in orbit for 4-5 years but at more altitude. The degradation rate will be lowered to -2%, a half of the actual degradation on the reference case. In Figure 4.6 the tendency of decaying is there, but it starts at a lifetime of 6 years. Also, as the revenues are higher than in the reference case, since the degradation is less and more photos that can be sold are made. The peak in this case is almost **2.5M** dollars. In the next section, an evaluation of what happens when the degradation rate turns to 0% is zero.

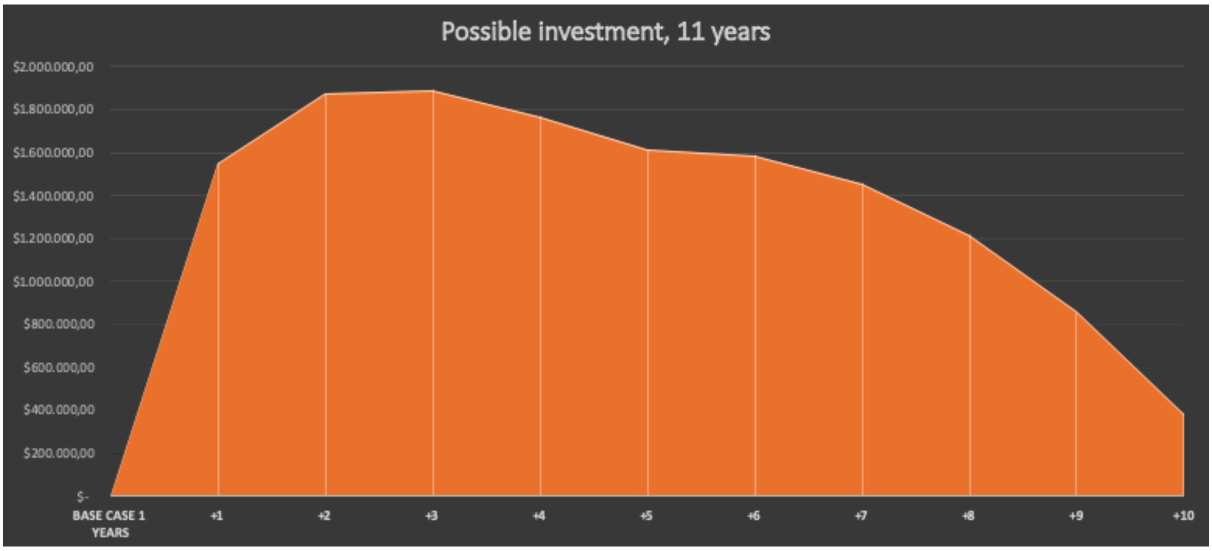


Figure 4.5: Possible investment at 2024 evolution for different lifetimes

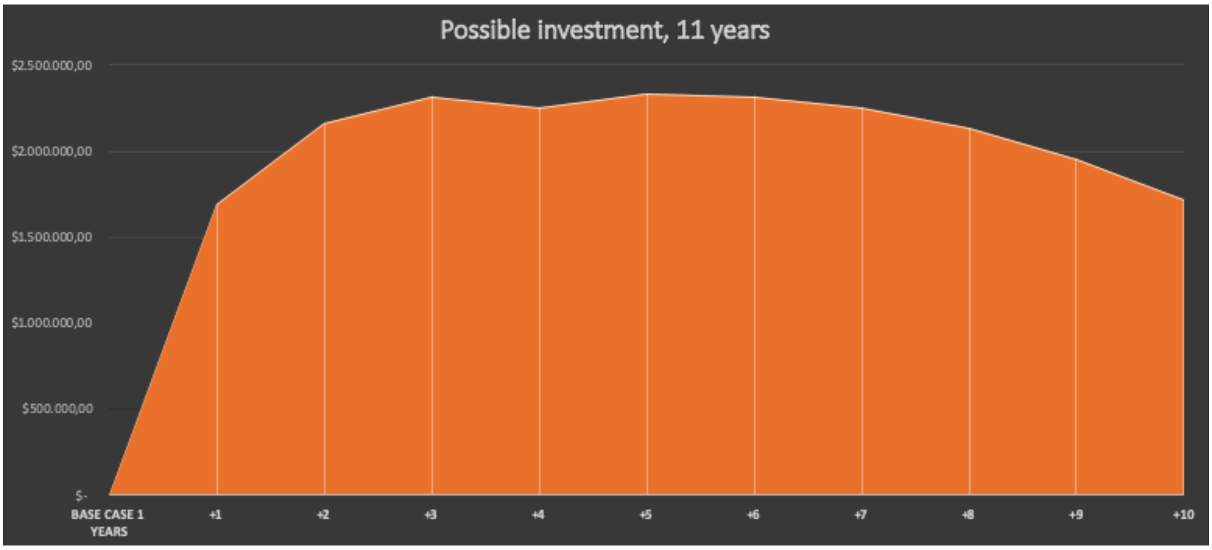


Figure 4.6: Possible investment at 2024 evolution for different lifetimes when degradation rate lowered to -2%

4.2.2 Zero degradation case

For this case we have to suppose that not only investment was done in order of developing an ABEP or other propulsion system able to maintain in orbit the Cubesat for many years, but also the same investment was focused on developing a material capable of resisting the degradation the residual atmosphere of that orbit applies on the Cubesat. In the Figures 4.7 and Figure 4.8 we can see that the decay does not appear from certain points, but it stabilizes in those points. For 2024, the maximum possible investment that can be done if the Cubesat survives six or more years, being almost **3M** dollars. If in the previous case, when degradation rate was -2%, the investment at +5 was a bit less than 2.5M dollars, exactly **2.3M** dollars. This supposes an increment of almost **0.7M** dollars that could be spent on researching, developing and manufacturing the new material, since the **2.3M** were the maximum investment for the ABEP system. When looking at long term, In Figure 4.8, can be seen that if the materials and the ABEP system are able to increase the lifetime of the Cubesat by eight years or more, the maximum investment would be of **3.8M** dollars.

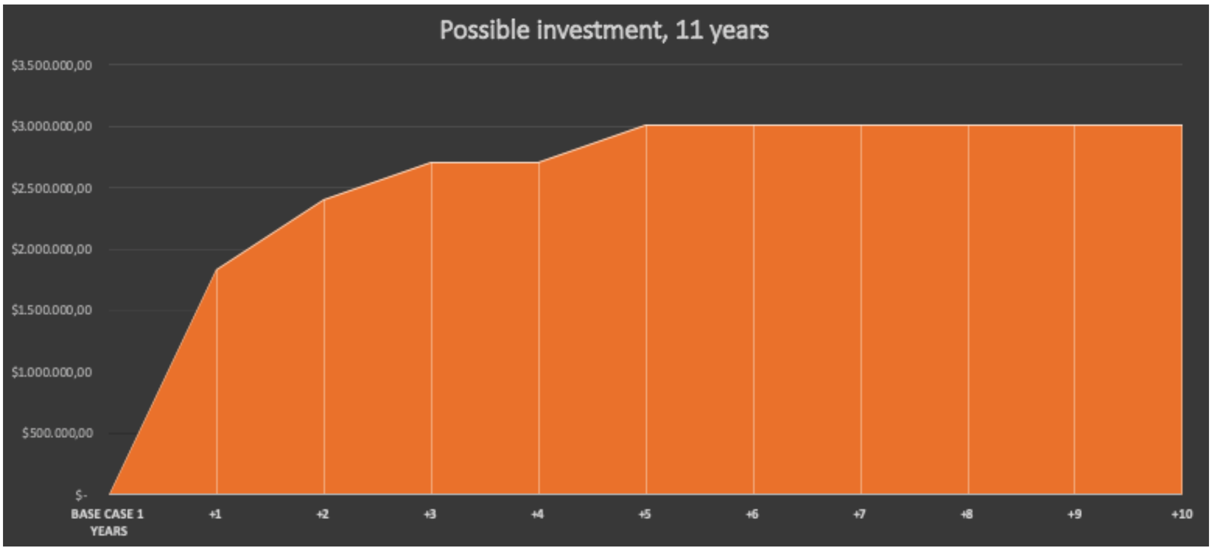


Figure 4.7: Possible investment at 2024 evolution for different lifetimes when degradation rate lowered to 0%

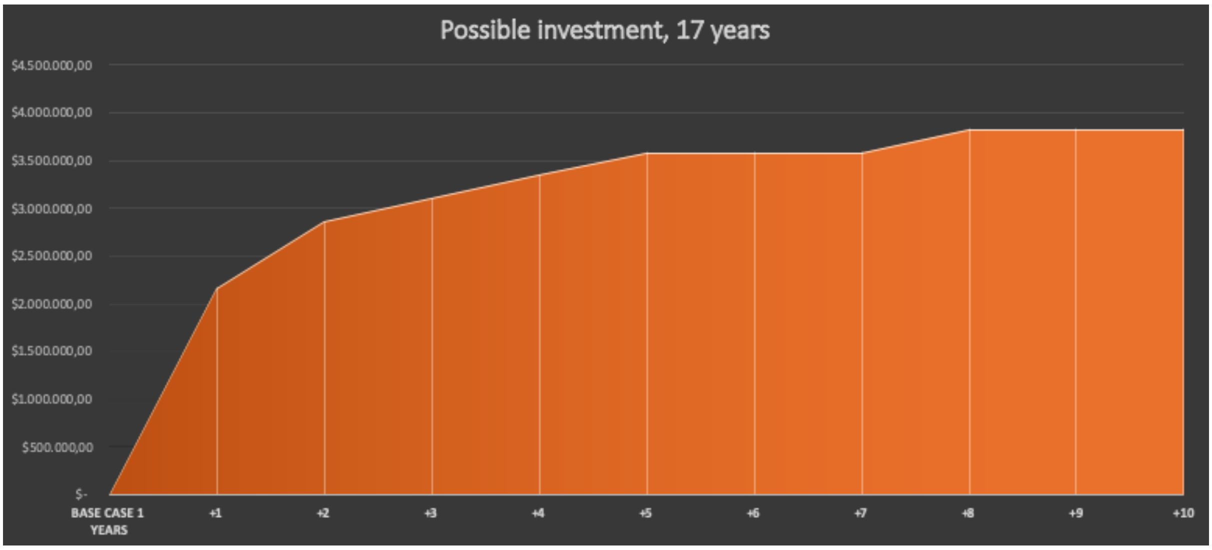


Figure 4.8: Possible investment at 2030 evolution for different lifetimes when degradation rate lowered to 0%

Regarding the importance of the degradation for the investment is this study, Figure 4.9 shows the variation of the possible investment for lifetimes from +1 to +10. This figure shows very clearly how the investment is drastically lowered when a high degradation exists and the Cubesat is on the atmosphere for +10 years.

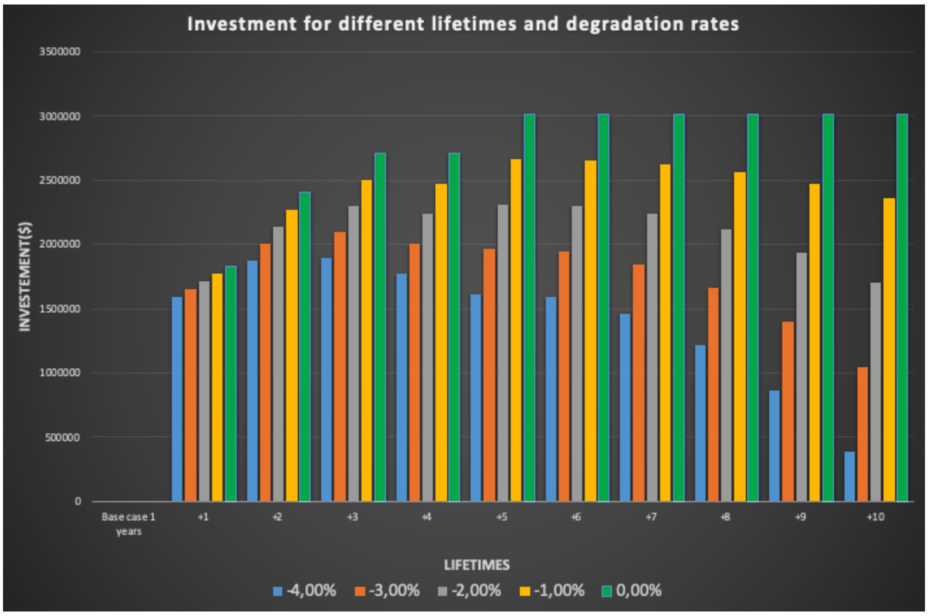


Figure 4.9: Degradation rates comparison for the investment at 2019

4.3 Constellation feasibility study

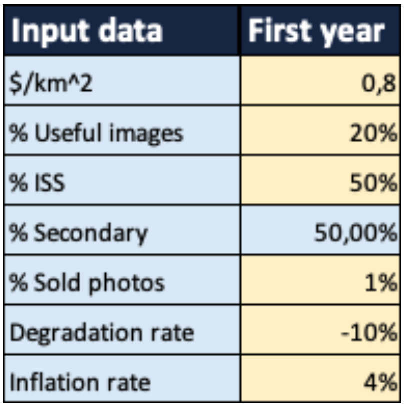
In this section, the feature commented in section 3.2.2 was used to study the economical values related to the feasibility of the constellation of Cubesat for an EO mission. First, the methodology used to study the values will be explained, and then the results will be shown.

4.3.1 Methodology

For this study the main parameters changed to study the sensitivity of the economical values are the Cubesat manufacture cost and the degradation rate. In order to do so, an estimation of how much does the implementation of the technologies should be done, but there is no information regarding the subject. Then, different extra costs will be studied. The degradation rate is lowered when the extra cost is taken into account, since the new material is prevents it, but as said before, no information is regarding a relation between cost and effectiveness, a therefore the each extra cost will be studied with a range of degradation rates. The extra cost is only taken into account as manufacture cost, the costs associated to the launch are obviated.

4.3.2 Reference case

Before the analysis, a case case is shown in order to establish some references. The following inputs are the chosen ones, Figure 4.10. The cost per Cubesat is **89.975$**, due to the learning curve effect applied when studying the constellation. This learning curve effect is associated to the decrease of the single Cubesat cost when multiple Cubesat are manufactured, optimising the design phase of the Cubesat, hence reducing the costs.



Input data	First year
$/km^2	0,8
% Useful images	20%
% ISS	50%
% Secondary	50,00%
% Sold photos	1%
Degradation rate	-10%
Inflation rate	4%

Figure 4.10: Inputs for the feasibility reference case

The Figure 4.11 the economical values of the reference case can be seen. The effect of the degradation for high lifetimes also appear at the NPV and IRR, but in at the PB it does not affect, since it is constant and flat for five years lifetime to ten years lifetime. The maximum NPV value and IRR is located at the lifetime for six years. A similar tendency than seen in the investment section appear here, like in Figure 4.5 at page 46, indicating a relationship between the one Cubesat feasibility and the whole constellation feasibility. In Figure 4.12, the accumulated balance at 2025 for a lifetime of six years is of **450M$**, being the maximum of all the lifetimes, but having less difference than the next maximum than in year 2020, where is more differentiated.

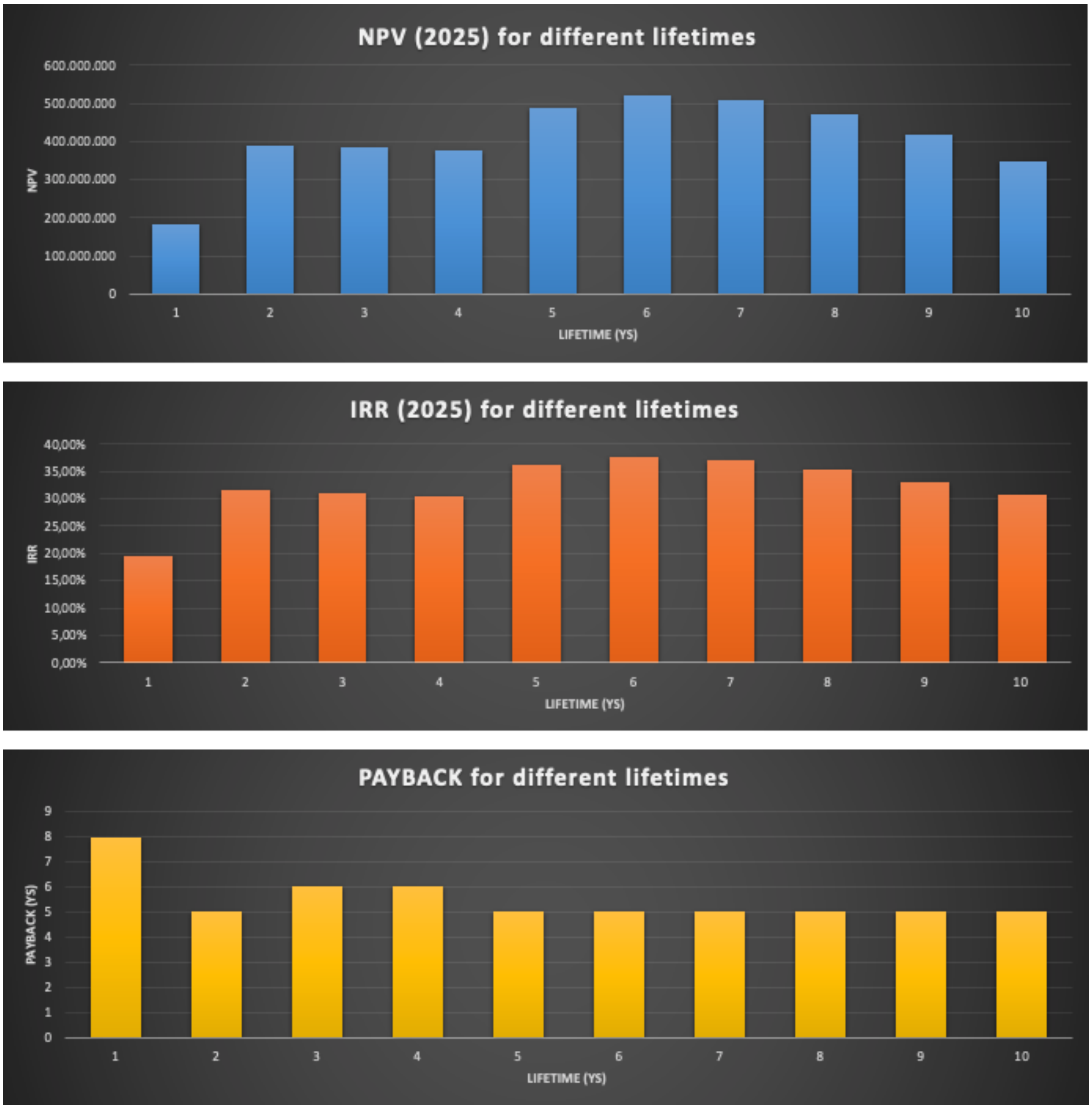


Figure 4.11: Economical values for the reference case inputs for the different lifetimes

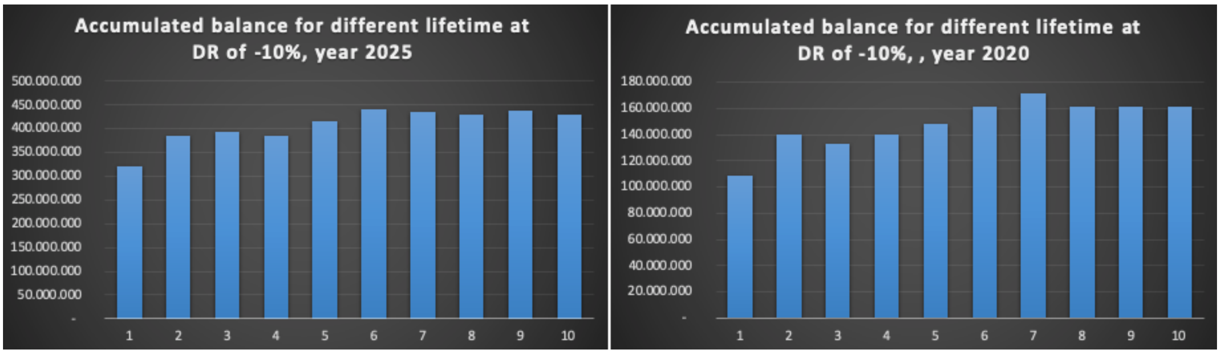


Figure 4.12: Accumulated balance for the reference case inputs for the different lifetimes

4.3.3 Degradation rate variation for fixed Cubesat cost

After the reference case, the degradation rates will be variated for Cubesat fixed costs. This costs will be with an extra **75.000$**, **150.000$** and **250.000$**. Applying this costs with the learning curve implemented by Antonio Cabeza, which made the Cubesat cost reduced because of the learning factor at manufacturing many Cubesat in relatively high rate, the **Agile Aerospace** factor. Then, the final cost are summarized on Table 4.19. The degradation rates will be: **-10%**, **-5%** and **0%**. Also, this study will only focus on five years of lifetime or more, since the ABEP and materials should allowed to the Cubesat to be active for those years.

Extra cost	Final unitary Cubesat cost	% of the total cost
75.000 $	111.518 $	21.11%
150.000$	135.062 $	34.86%
250.000$	166.453 $	47.14%

Table 4.19: Unitary Cubesat final cost for each extra cost

The results for each cost will be displayed on the following way. A figure with the accumulated balance for each degradation rate for both 2025 and 2020 years. Then the economical values following the same structure.

4.3.3.1 75.000$ extra cost

In Figure 4.13, the almost same distribution is seen than in Figure 4.12, but the main different is the reduction of the balance for the case of -10% and -5%, due to the cost increase on the Cubesat manufacture. In the 0% degradation rate the maximum accumulated balance is almost the same than in the reference case, but a little bit higher. Another feature we can see on the year 2025, is the tendency of only increasing the accumulated balance for all the lifetimes only on 0% degradation rate. In fact, is the only sequence of values that only increases, since in 2020 values for 0% remains flat from 7 to 10 years lifetime. The other values tends to low when the lifetimes becomes bigger.

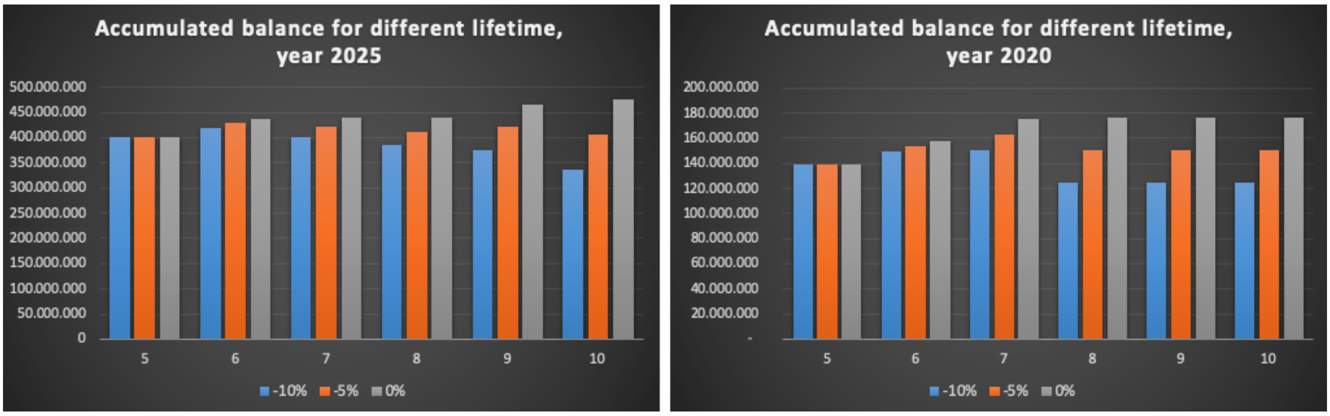


Figure 4.13: Accumulated balance for an extra cost of 75.000$

From Figure 4.14, a clear tendency for 0% values is to increase for NPV and IRR, and to lower for the Payback year, being 5 the lowest possible in this cases. For the -10% degradation rate is not sustainable, since NPV tendency is to not recover, and to only lower when passing the years. The cost is to elevated and the revenues decrease drastically. For the 5% it seem to have a tendency to maintain stable, for bigger lifetimes, but for lifetime 6 years it is almost equal to the 0% degradation rate case, after that, the other follows an non-linear tendency to increase. It's seems that the best scenario for a Cubesat with an initial extra cost in the first one of **75.000$** is 6 or 7 years lifetime, since afterwards starts to decay the benefits. In comparison for the reference case, in Table 4.20 the percentage the benefits grew can be seen. The lifetime of one year has been took as comparison. As supposed, a lifetime of seven years is the best case scenario. The 0% is quite unrealistic case for lifetimes that big.

5 year lifetime	6 year lifetime	7 year lifetime	8 year lifetime	9 year lifetime	10 year lifetime
130,63%	162,76%	170,17%	169,74%	162,60%	145,26%

Table 4.20: Increase on the NPV respect the case of one year lifetime reference constellation for 75.000 $ increase cost

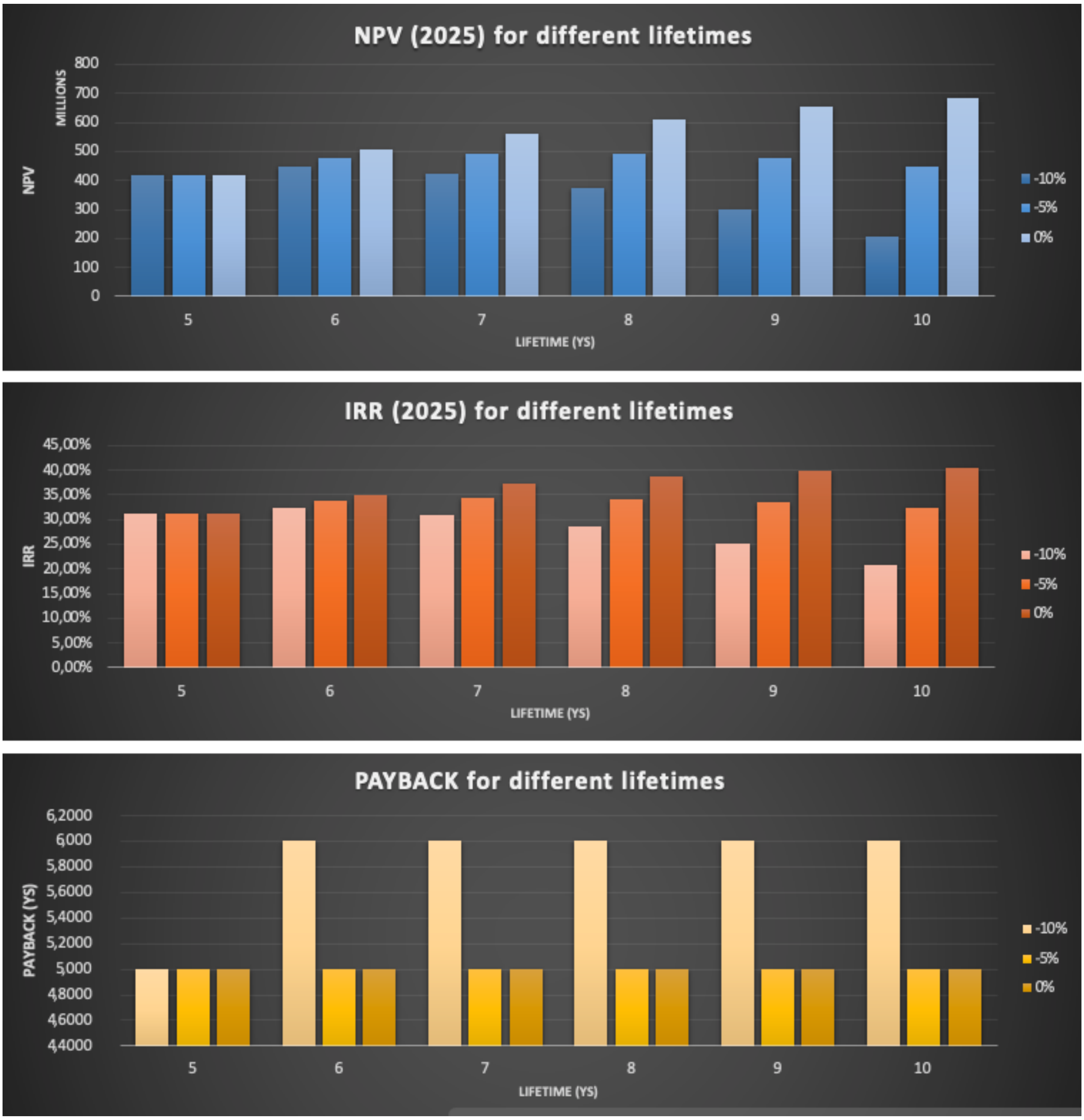


Figure 4.14: Economical values for an extra cost of 75.000$

4.3.3.2 150.000$ extra cost

For an extra cost of 150.000 the benefits are lower, as seen in the accumulated balances of Figure 4.15. Of course, it is expected. The case less desirable, -10% degradation rate gives a maximum accumulated balance of **400M$** at a lifetime of six years, with not much difference with the other degradation rates, which are both almost **450M$**. The distribution of the three values sequences follows the same tendency than in the other case, but with lower values. For a feasibility regarding shorter mission years, for example until 2020, a Cubesat with the lifetime of seven years and a degradation of -5% gives a final accumulated gross balance of more than **160M$**, this means a benefit of **30M$** more than the reference case.

Figure 4.15: Accumulated balance for an extra cost of 150.000$

In Figure 4.16, in the first graph, the NPV for the -5% vase tends to maintain stable during all the lifetimes, but as shown in Table 4.21, the maximum benefit ratio compared to the reference case is placed for a 6 year lifetime, at increase of the benefits of **113.04%**, almost the double than the reference case. For a more realistic case where the lifetime is increased to two years, the benefits increase is **30,25%**, almost **50M$**. The internal rate of return of the best case is **29%**, a 30% bigger than the reference case. For the 2 lifetime year, the IRR is only a 4% bigger than the reference case at a lifetime of 1 year. The PB remains almost constants for all the cases.

2 year lifetime	5 year lifetime	6 year lifetime	7 year lifetime	8 year lifetime	9 year lifetime
30,25%	93,27%	113,03%	101,85%	75,94%	37,53%

Table 4.21: Increase on the NPV respect the case of one year lifetime reference constellation for 150.000 $ increase cost

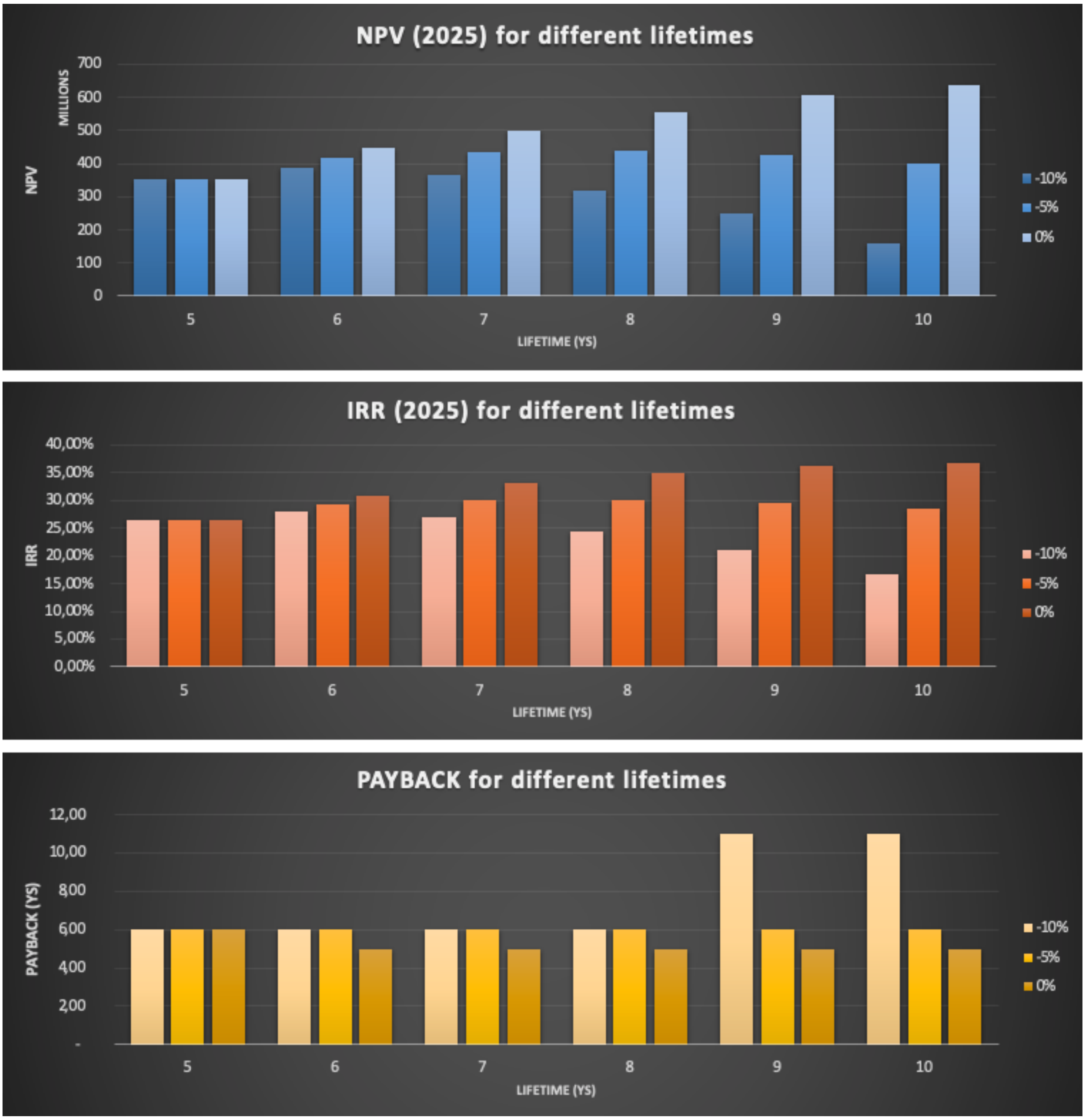


Figure 4.16: Economical values for an extra cost of 150.000$

4.3.3.3 250.000$ extra cost

This extra cost represents almost the 50% of the total cost of the Cubesat, which is a huge impact. It is expected to be not feasible unless the degradation effect is greatly lowered. For instance, in Figure 4.17 it can be seen that for 2025 there is not a great difference of accumulated balances for -10% is almost equal to the reference case, only a 14% bigger for a lifetime of six years, and even for bigger lifetimes it becomes lower. It is remarkable to say that for lower lifetimes of five years, this case is not feasible since the accumulated balance is lower than the reference case, due to the extra cost being to large. The same happens for the other degradation rates, even for the 0%. The lifetimes increase for these needs to be of four years or more. The maximum accumulated balance increase is a 27%, for a lifetime of six years and a degradation rate of 0%.

Figure 4.17: Accumulated balance for an extra cost of 250.000$

In Table 4.22 is shown that this cost is the least feasible of all, since it need to increase a lot the lifetime and the to decrease to the maximum the degradation rate, and even then, the increase of benefits compared to the cases of lower extra costs will be lower. It isn't feasible to a company to invest so much in a Cubesat component implementation (manufacturing each time). In Figure 4.18 the values of NPV can be seen to be much lower than compared to Figure 4.16 or Figure 4.14. The PB remains almost flat, a so does the IRR, they doesn't vary more than 5% from the other costs.

5 year lifetime	6 year lifetime	7 year lifetime	8 year lifetime	9 year lifetime	10 year lifetime
43,45%	84,39%	96,87%	101,51%	99,27%	85,04%

Table 4.22: Increase on the NPV respect the case of one year lifetime reference constellation for 250.000 $ increase cost

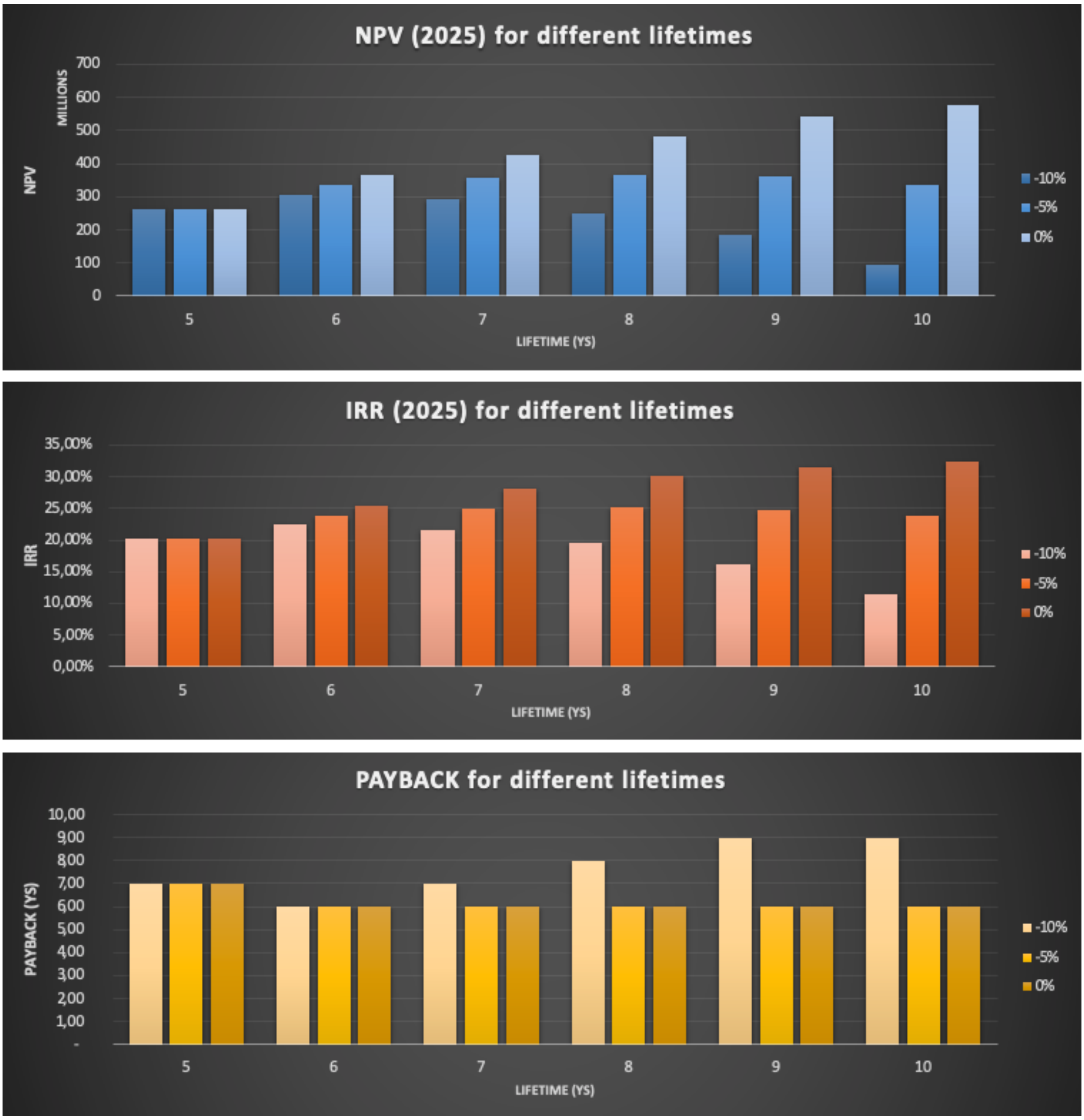


Figure 4.18: Economical values for an extra cost of 250.000$

4.4 Results conclusion

For the feasibility Cubesat mission for long lifetimes values a reduction of the degradation rate of the Cubesat is needed, as seen in both sections 4.2 and 4.3. For a optimistic case, when a lifetime extension of five years is achieved and the degradation rate is reduced for a cost increase of the 34% upon the total design cost, a 193,27% of benefits, Table 4.21, being a total of almost 180M$. This benefits are not mean to be the ones to invest on investigating an ABEP and materials, since this is for a whole constellation. The extra benefits where not achieved by increasing the revenues, but only saving costs from launches and manufactures, the costs referred to replenish constantly the constellation. For a more realistic case, where the ABEP and materials allows the Cubesat to survive on orbit for two whole years, the benefits increase a 30% respect the reference case, of one year lifetime with double degradation rate. This represents a total of 78M$. Even when the extra cost of the new technologies almost doubles the cost of the Cubesat, if it increases the lifetime to five years, five times more the reference case, it would be feasible to implement, otherwise not. For a optimistic case where the technologies only suppose the 21% of the total cost, and the lifetime was extended to two years, would give a 72% of benefit increase upon the reference benefit of 182M$.

The investment for a realistic case, where the lifetime the degradation rate is lowered to a half of the reference case, the investment that could be done for both ABEP and materials, is for 2.5M$ if the lifetime is increased to two years, or 2.6M$ if increased one year more. This maximum invested is for developing and investigating the technologies and to manufactures and implement it in the Cubesat. For an optimistic one, where the degradation rate is totally neglected, almost 3M$ could be invested for a two year lifetime, and the value achieves 0.23M$ more if the final lifetime is three years.

From the results extracted, in a economical view, it would be feasible to investigate the technologies if this maximum investment is not surpassed and the specified lifetimes and degradation rate are achieved.

Chapter 5

Enviromental Study

The use of ABEP systems is associated also with environmentally friendly use, since it does not use any fossil fuel in order of generating propulsion, but uses the atmosphere. Since, for example, Planet is constantly replenishing its constellation, if the Cubesat had any propulsion system (it doesn't right now), the fuel consumption implementing an ABEP would reduce the environmental mark. Also, as the aim of using an ABEP is to extend the lifetime, less Cubesat needs to be done, decreasing the use of materials. Also, since the Cubesat would be at very low earth orbit, the Cubesat when deorbit would destroy itself with the atmosphere when decaying, decreasing the space debris.

Chapter 6

Future studies

This feasibility could be extended for future studies with deeper investigations, as per:

- Acquire more accurate information for the inputs associated to the study, by investigating and studying different EO missions. With more accurate details the feasibility case could be further developed and more results could be included.
- Improve the Value chain model of a Cubesat design and manufacture and use.
- Propose a bigger range of prices for different services, since in this study only the price for a square km for a determined use was possibly to use.
- Develop the DISCOVEX tool with a better user experience interface, in order of allowing a user without a wide knowledge on technical details to choose the subsystems required for an specific mission.
- Increase the DISCOVEX database to allow an use for not only Cubesats, but for other technologies. Also, develop the tool for other space related services, not only Earth Observation, such as investigation purposes.

Chapter 7

Conclusions

The need of a propulsion system and better materials for small spacecraft operating at low orbits has increased throughout the last years. The expected launches forecasted indicates a tendency that this growth will keep for the like this for the future years. Specifically the EO market expected demand points to a increasing market, and new companies are emerging to meet this demand. This fact creates a competition to have the best technology, the most innovative, efficient, cheaper and environmentally friendly when no fuel is used. Cubesat constellation entered this competition and have disrupting all the other technologies. This project has tried to study the feasibility of a technological improvement for Cubesats at very low earth orbit and executing Earth Observation tasks.

The Cubesat and its related services cost estimation has served to detect and decompose the Cubesat subsystems and understand that the design and manufacture phases are not critical, even though the design defines the operational limits for the mission, and the manufacture is based on the design and it is improved every time thanks to the agile aerospace. An optimal design phase helps to reduce significantly the costs of a constellation.

The tool DISCOVEX have demonstrated to be very powerful, but yet needs to be upgraded and simplified. The ability that provides to have all the costs integrated on a database, and a tool able to extract economical results has been very useful. The development of this tool was the most time consuming part, although it helped to understand the values and results needed to study the feasibility of implementing an ABEP system and suitable materials on Cubesats. When investigating to extract all the necessary data to use realistic inputs for the results, the complexity of doing a sensitivity and feasibility study from an emerging study was also understood.

The final results showed that implementing an ABEP and materials could be potentially beneficial for a company with Cubesat constellations of EO mission, if the investment required to develop and implement those technologies does not overcome the extra benefit of a single Cubesat could be able to generate when extending its lifetime. It was also seen that the degradation rate supposed in this study is very important parameter to take into account, together with the lifetime, since they are the two key parameters that the extra benefits, maintaining sold and useful percentage of the imagery, depend on.

For further conclusion, more work should need to be done, as stated on Chapter , which would include the further develop of the tool DISCOVEX, since it has a potential value for the study of space missions, and to improve and detail more the inputs of the cases and estimations done.

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