

Università Politecnica delle Marche
Facoltà di Ingegneria
Corso di Laurea Magistrale in Ingegneria Meccanica



***Design e ottimizzazione strutturale di un deployer
modulare 12U per CubeSat***

***Design and structural optimization of a modular
deployer up to 12U CubeSat***

Relatore: Chiar.mo
Prof. Ing. Stefano Lenci

Tesi di laurea di:
Laura Gironella

Correlatore: Chiar.mo
Ing. Riccardo Silvestri

Anno accademico 2019/2020

Abstract

This paper is about the preliminary design and structural optimization of a deployment system for a standardized satellite format, named CubeSat.

The study is carried out in collaboration with and on behalf of SAB Aerospace, Italian company working in the field of aerospace for over 20 years.

Such partnership starts from the need emerged in the company activity to internally produce a deployer adaptable to different usage scenarios. The goal is to develop a modular and easily reconfigurable deployer to contain CubeSat up to 6U format.

After identifying the requirements, the study proceeds with the definition of the concept. Starting from that, we then carry out the structural checks and the optimization of the mass aimed at obtaining a preliminary design of the deployer.

Contents

1. Introduction	2
2. SAB Aerospace	6
3. CubeSat, little big satellite	10
§ 3.1 What nanosatellite is	10
§ 3.2 CubeSats project	11
§ 3.3 Applications. A universe of possibilities	13
4. How to get in space	17
§ 4.1 So close so far away	17
§ 4.2 Take a european ride	20
§ 4.3 Dispenser	24
5. Deployer for CubeSat	31
§ 5.1 Sharing is caring	31
§ 5.2 Deployment system	32
§ 5.3 Deployers market survey	35
6. Deployer design	41
§ 6.1 Requirement definition	45
§ 6.1.1 Functional requirements	45
§ 6.1.2 Physical properties requirements	46
§ 6.1.3 Interfaces requirements	47
§ 6.1.4 Environmental loads requirements	48
§ 6.1.4.1 Quasi-Static Loads	51
§ 6.1.4.2 Sine excitation	52
§ 6.1.4.3 Acoustic Loads	53
§ 6.1.4.4 Random excitation	54
§ 6.1.4.5 Shock excitation	56
§ 6.2 Preliminary design	57
§ 6.2.1 Looking for a new concept: Sketches	58
§ 6.2.2 Looking for a new concept: Cad model	63
7. FE Model	67

§ 7.1 Model check	70
8. Modal analysis	72
§ 8.1 Stiffness optimization	76
9. Stress check	78
§ 9.1 Quasi static loads check	78
10. Mass optimization	84
11. Optimized deployer: stress check	89
§ 11.1 Random response: Miles	90
§ 11.2 Random response: Nastran SOL 111	97
12. Preliminary design	106
13. Conclusion and future developments	109
14. Sunto in lingua italiana	113
15. Acknowledgment	115
16. References	116

List of Figures

1.1: Satellites function map	3
2.1: SAB Aerospace logo	6
2.2: Some of the projects developed by Sab Aerospace	7
2.3: Location of Sab Aerospace	7
2.4: SAB Holding	8
2.5: SAB Aerospace partnership	9
3.1.1: Satellites mass classification	11
3.2.1: CubeSat sizes from 1U to 16 U	11
3.2.2: CubeSat 1U and his multiple sizes example	12
3.2.1: dimensions of CubeSat	13
3.3.1: CubeSat future missions	15
4.1.1: CubeSat launch	17
4.1.2: Distribution of space debris	19
4.2.1: PSLV from ISRO (India)	20
4.2.2: Falcon 9 from Space X (USA)	20
4.2.3: Electron from Rocket Lab (New Zealand)	21
4.2.4: VEGA from ASI/ESA (Europe)	21
4.2.5: VEGA stages	23
4.2.6: VEGA-C	24
4.3.1: VESPA dispenser	25
4.3.2: SSMS dispenser, piggy back configuration	27
4.3.3: SSMS dispenser, Ride Share configurations	28
4.3.4: Flexi-3 Configuration (PoC)	29
4.3.5: Flexi-3 PoC Separation angles study	29
4.3.6: Vampire dispenser	30
5.1.1: MLB from PSC	31
5.1.2: Deployer for CubeSat	32
5.2.1: Deployer description	33
5.2.2: Deployer elements	33
5.2.3: Deployment process schematization	34

5.3.1: Deployer from PSC	36
5.3.2: Deployer from ISIS	37
5.3.3: Deployer from Astrofein	38
5.3.4: Deployer from Tyvak	39
5.3.5: Deployer from D-Orbit	40
6.1.2.1: Available space on SSMS door	46
6.1.3.1: Deployer - SSMS HM interface	47
6.1.3.2: Deployer - CubeSat interface	48
6.1.4.1: Acceleration from launcher to payload	49
6.1.4.2: Acceleration in terms of frequency	50
6.1.4.1.1: QSL for some launcher	51
6.1.4.2.1: Sine excitation	52
6.1.4.2.2: Sine loads examples	52
6.1.4.2.3: Sine loads examples	53
6.1.4.3.1: Launcher lift off	53
6.1.4.4.1: Random noise with normal amplitude distribution	54
6.1.4.4.1: Random signal over time	55
6.1.4.4.2: Random signal in terms of frequency	55
6.1.4.5.1: Shock signal over time	56
6.1.4.5.2: Shock in terms of frequency	56
6.2.1: Iterative action for preliminary design	57
6.2.1.1: Sketches (a)	58
6.2.1.2 Sketches (b)	59
6.2.1.1: Sketches (c)	59
6.2.1.2: Core module configurations	60
6.2.1.3: Slave modules configurations (a), (b), (c)	62
6.2.2.1: Core module. Base plate	63
6.2.2.2: Core module. Base plate and rails	63
6.2.2.3: Core module. Base plate, rails and side plates	64
6.2.2.4: Core module configuration for 12U CubeSat	64
6.2.2.4: Core module configuration for 2 x 6U CubeSat	65
6.2.2.5: Core module configuration for 4 x 3U CubeSat	65

6.1.3.1: Hypermesh interface	67
6.1.3.2: Base plate	68
6.1.3.3: Side plates	68
6.1.3.3: Assembly	69
8.1: First global mode in X direction	74
8.2: First global mode in Z direction	75
8.3: First global mode in Y direction	75
9.1.1: Vega specification loads	78
9.1.2: Stress on assembly	82
9.1.2: Detail of stress on assembly	83
10.1: First global mode in X direction	87
10.3: First global mode in Z direction	88
11.1.1: PSD	90
11.1.2: SDOF oscillator	91
11.1.3: Miles's formula	91
11.2.1: Random response on SPC	99
11.2.2: Random response on CubeSats CoG	99
11.2.3: Stress on assembly	101
11.2.4: Stress on base plate	102
11.2.5: Stress on base plate	103
11.2.6: Stress on corner brackets	104
11.2.3: Stress and MoS	105
12.1: Deployer preliminary design, detail of Base Plate	106
12.2: Deployer preliminary design, 4 x 3U configuration	107
12.2: Deployer preliminary design, 2 x 3U and 1 x 6U configuration	107
12.2: Deployer preliminary design, 2 x 6U configuration	108
12.2: Deployer preliminary design, 1 x 12U configuration	108
13.1: Clamping mechanism	110
13.2: Release mechanism	110
13.3: Slave module connection	111
13.4: Consolidated design	111

List of Tables

6.1: ECSS space project guide	41
6.1.4.1: Sources of launch environments	50
8.1: First 10 modes of deployer	73
8.2: First 3 modes of deployer, with directions of acceleration	73
8.1.1: First 3 modes of deployer optimized	77
9.1.1: Load cases	80
9.1.2: Material mechanical characteristics	81
9.1.3: Stress and MoS	81
10.1: Modification to optimize mass	85
10.2: Combined action to optimize mass	85
11.1.1: Random equivalent load in X direction	94
11.1.1 (a): Cross mode in Y and Z, due to random excitation in X	94
11.1.2: Random equivalent load in Y direction	95
11.1.2 (a): Cross mode in X and Z, due to random excitation in Y	95
11.1.3: Random equivalent load in Z direction	96
11.1.3 (a): Cross mode in X and Y, due to random excitation in Z	96
11.2.1: Qualification loads	100
11.2.2: Design loads	100

List of Abbreviations and Acronyms

CAC	CubeSat Acceptance Checklist
Cal Poly	California Polytechnic State University, San Luis Obispo
CDS	CubeSat Design Specification
cm	Centimeters
CSD	Canisterized Satellite Dispenser
ISIS	Innovative Solutions In Space
kg	Kilogram
LSP	Launch Services Program
LV	Launch Vehicle
LVC	Launch Vehicle Contractor
MIN	Minimum
mm	Millimeters
NASA	National Aeronautics and Space Administration
NLAS	Nanosatellite Launch Adapter System
P-POD	Poly Picosatellite Orbital Deployer
QSL	Quasi Static Load
REQ	Requirement
Rev.	Revision
SPC	Single Point Constricted
STD	Standard
TML	Total Mass Loss
μm	Micrometer

1. Introduction

Did you know that...

... Billions of people around the world rely on satellite infrastructure every day to communicate, travel and get informed and entertained

... Satellite networks underpin many voice, data and mobile networks, providing them with a means to carry traffic overseas when other alternatives like undersea cables are absent

... Internet connections on planes, cruise ships and oil platforms are all provided via satellites

... Satellites help the population stay healthy: measure air pollution and monitor air quality, monitor water quality in recreational water

... Satellites collect tons of data on temperature, precipitation, cloud movement and wind direction. When that data is analyzed, weather can be predicted

... To obtain their precise position in the sky, airplanes transmit a signal to a constellation of satellites. With these coordinates, air traffic controllers can ensure the safety of flying aircraft

... Even from 20,000 km up, satellites from the global positioning system (GPS) network can pinpoint your location. The signal they receive from your GPS allows you to see exactly where you are on a map, and that will help you get to your destination

... When using the card, a satellite link is established between the company and the bank. The space allows you to pay without making use of cash

... Thanks to satellites we are able to find urban areas where vulnerable population are exposed to extreme heat and to identify risk location for diseases carried by mosquitos and ticks

... Precision agriculture, tracking of fishery policies and weather and climate-change predictions all rely on satellites

... Thousands of companies and governments around the world use satellites as a “safety net” and for critical communications and data distribution

... Satellites offer Internet connectivity to all citizens in rural and remote areas in Europe and around the world

... Peacekeeping missions, troops abroad and border security around the world rely on secure communications provided by satellites

... German insurance company Munich Re is leveraging geospatial satellite data to accurately calculate costs and risks related to wildfires and to gain insights into the future probability of wildfires

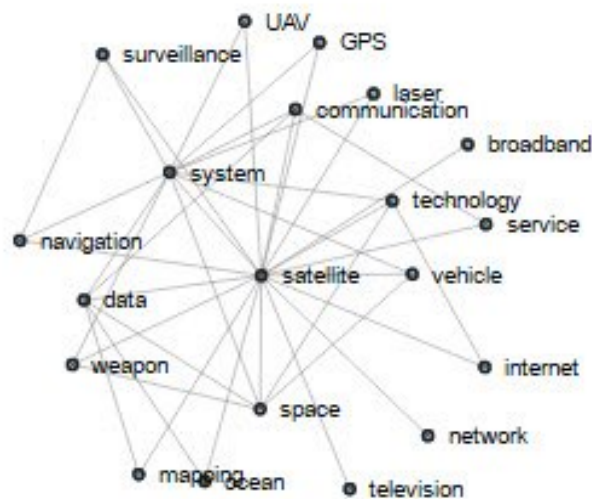


Figure 1.1: Satellites function map

And you could have guessed that in the near future...

... Satellites will play a vital role as the world's mobility patterns change from driver-operated to autonomous vehicles.

... Future satellites will focus on ocean data and Earth's atmosphere.

... 370 small satellites are expected to be deployed into low- or medium-orbit for communication services and Earth observation imagery which would represent a yearly market of \$1.6 billion on average over the next decade.

... The expanded fleet of satellites will send over 3 terabytes of data a day to more than 30 receiver stations spread around the Earth.

... UK space businesses will benefit from £70 million funding from the UK Space Agency to develop satellite projects to tackle problems such as flooding, drought and deforestation in developing countries.

... New satellite technology designed by Forest Trust and Airbus Defense and Space, the system (called “Starling”) will use radar and high resolution imagery to ensure plantations abide by the moratorium on deforestation, and will be adopted by big companies like Wilmar, Nestlé, Ferrero and others

... A new national positioning system accurate to between 2cm and 10cm will boost Australia's economy by \$73 billion or more over the next 20 years

... Six families of Sentinel satellites will make up the core of EU's Copernicus environmental monitoring network.

... The overall demand for satellite data will grow annually at 30% between now and 2025.

... The global market for new launch technology for small satellites will be worth £25 billion over the next 20 years.

... In the decade to come Russia will face strong competition from China for the commercial launch of satellites for developing countries

... Boeing Co. is taking steps to build satellites more quickly through new production practices that will rely more on 3-D printing and involve fewer workers.

... Paris-headquartered space consultancy Euroconsult anticipates that a total of 560 satellites will be launched by 40 commercial companies from 2016 to 2025.

... Revenues from cellular and satellite connectivity fees will reach more than \$138 million in 2017.

Since the first satellite was launched into orbit in 1957, space technology has evolved rapidly.

Today, a growing number of satellites orbit around the Earth, making various Earth observation, communications, navigation and science applications possible. While we may not always realize or acknowledge their existence, the important role these systems play in our daily lives cannot be underestimated. They contribute considerably to our well-being and enable us to achieve our objectives in new and innovative ways.

As technology advances, the potential of satellites will undoubtedly continue to grow. New markets will emerge along with new opportunities to push the boundaries of what space technology currently offers.

It is evident that in this perspective, the study of all those systems related to the satellites becomes proportionately important: from the launcher carrying the satellite into his orbit, to the smallest mechanism that constitutes the satellite itself.

As Richard Hollingham said, “without satellites, the world would be a very different place, [since] the infrastructure we all rely on has become increasingly dependent on space technology.”

2. SAB Aerospace

The thesis work that is exposed is the result of the activity carried out during the internship at Sab Aerospace, Ancona office.



Figure 2.1: SAB Aerospace logo

Sab Aerospace is present in Italy, the Czech Republic and Poland; its core business is focused on the development of space mechanical systems and subsystems.

Starting from the project requirements, SAB performs:

- design analysis
- structural and thermal verification
- production
- environmental tests
- qualification process

The company has also expanded the fields of activity with the introduction of a shaker for vibration tests and a mechanical workshop for the production of space components; over the years it has also ensured a network of collaboration with research centers for the development of advanced materials, flight management systems and optical systems



Figure 2.2: Some of the projects developed by Sab Aerospace

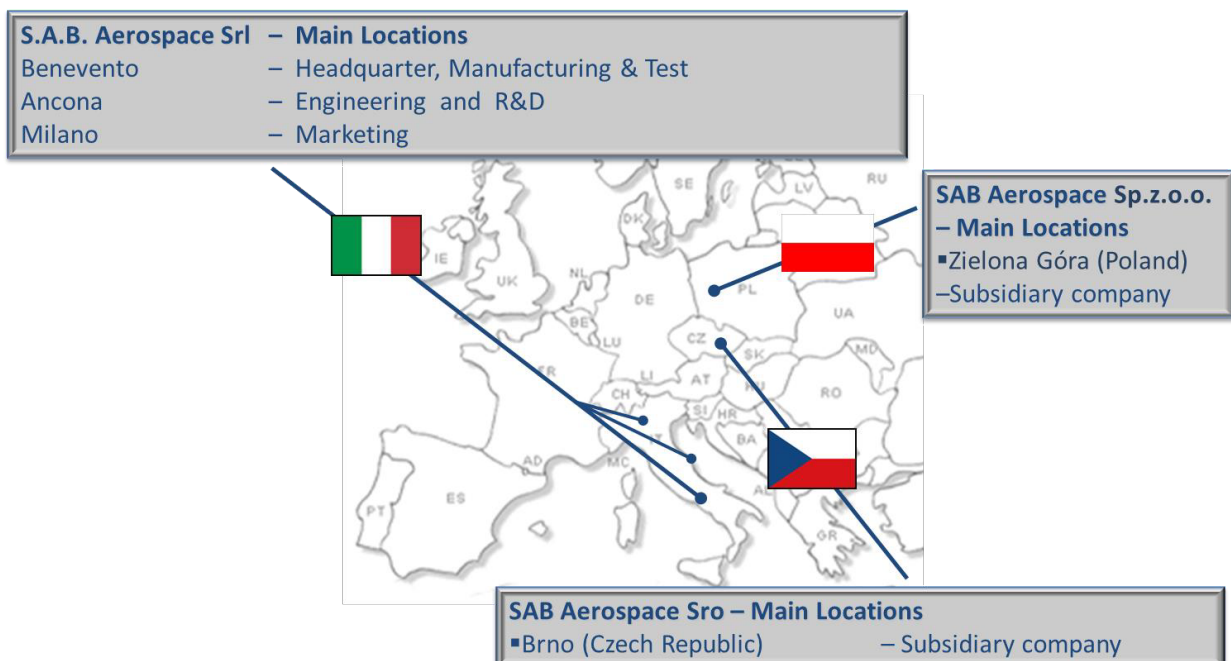


Figure 2.3: Location of Sab Aerospace

Since 2004 the headquarters of Sab Aerospace has been located in Benevento, where the production and testing activities are carried out. Later it settled in Ancona for the engineering and R&D activities and Milan for the marketing ones.

Following the process of internationalization and strategic diversification, a series of companies was created which since 2018 have been grouped under the Holding SAB:

- SAB Aerospace s.r.l.
- SAB Aerospace s.r.o., company associate located in Brno,
- SAB. Aerospace Sp.z.o.o., located in Poland, under development
- SAB Launch Services s.r.l., specialized in intermediation activities towards the CubeSats market and in the management of contractual and legal aspects relating to launch services
- Ermesat s.r.l., which deals with the processing of radio signals and electrical support equipment for satellites



Figure 2.4: SAB Holding

2. SAB AEROSPACE

Here are some of the activities carried out and related companies / entities with which Sab Aerospace has collaborated and / or collaborates.



Figure 2.5: SAB Aerospace partnership

3. CubeSat, little big satellite

§ 3.1 What nanosatellite is

"Just because a spacecraft is small, it doesn't make it easy. A highly constrained spacecraft can push the engineering, push the ingenuity of the team in a way that, in every way, is comparable to some of these big missions that we're doing." - Thomas Zuburchen, NASA associate administrator.

CubeSats (CubeSatellite, Cube Satellite), as mentioned, are a type of nanosatellites defined by the CubeSat Design Specification (CSD), unofficially called the CubeSat standard.

In mass-classification and in strict terms, a nanosatellite (nanosat, nano-satellite) is any satellite with mass from 1 kg to 10 kg. In this database, "nanosatellite" covers all Cubestats, PocketQubes, TubeSats, SubCubes, ThinSats and non-standard picosatellites, unless otherwise stated.

But actually, all are part of the same CubeSat revolution and modern electronics technology leap. Limiting to 1-10 kg would be confusing and troublesome.

To date CubeSat can be 0.8 kg, but also 1.3 kg: commonly used CubeSat can be less or more than 10 kg. Note, among other things, how most satellites masses are not public.

In the light of what has been said, it is more correct to speak of a mass range covered by the category of satellites, the one shown in [Table 3.1.1].

Satellite mass classification		
Large satellites	>1000 kg	
Medium satellites	500 to 1000 kg	
Small satellites	<500 kg	
	Minisatellites	100 to 500 kg
	Microsatellites	10 to 100 kg
	Nanosatellites	1 to 10 kg
	Picosatellites	1 kg to 100 g
	Femtosatellites	100 g to 10 g
	Attosatellites	10 g to 1 g
	Zeptosatellites	1 g to 0.1 g

Table 3.1.1: Satellites mass classification

§ 3.2 CubeSats project

CubeSats are a class of nanosatellites that use a standard size and form factor. The standard CubeSat size uses a "one unit" or "1U" measuring 10x10x10 cm and is extendable to larger sizes; 1.5, 2, 3, 6, 12, and even 16U, as shown in [Figure 3.2.1].

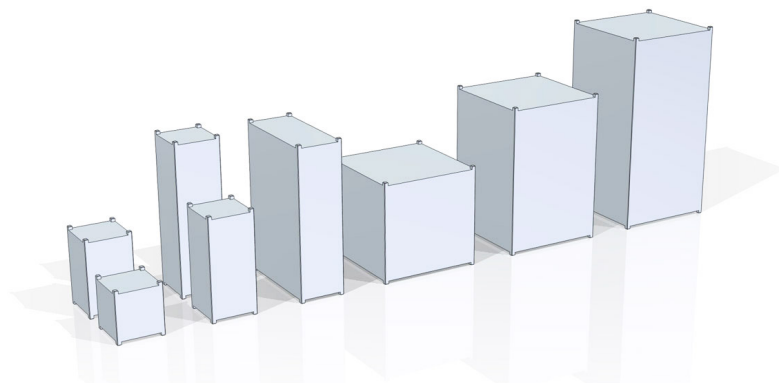


Figure 3.2.1: CubeSat sizes from 1U to 16 U

3. CUBESAT, LITTLE BIG SATELLITE

Originally developed in 1999 by a collaborative effort between Prof. Jordi Puig-Suari at California Polytechnic State University (Cal Poly, San Luis Obispo) and Prof. Bob Twiggs at Stanford University's Space Systems Development Laboratory (SSDL), the purpose of the project was to provide a platform for education and space exploration: the goal was in fact to obtain a standard for design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches.

The development of CubeSats has advanced into its own industry with government, industry and academia collaborating for ever increasing capabilities. CubeSats now provide a cost effective platform for science investigations, new technology demonstrations and advanced mission concepts using constellations, swarms disaggregated systems.

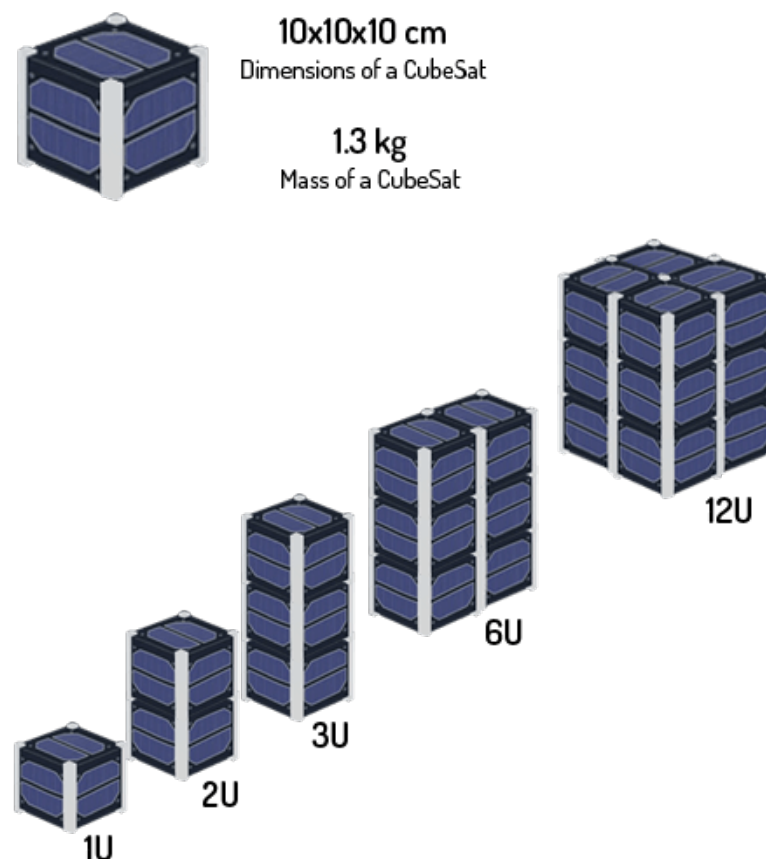


Figure 3.2.2: CubeSat 1U and his multiple sizes example

In [Table 3.2.1] we find the dimensions of the CubeSats most in use today. The principle of modularity that inspires this dimensioning is evident.

1U	10 x 10 x 11.35 cm
2U	10 x 10 x 22.7 cm
3U	10 x 10 x 34.05 cm
6U	22.63 x 10 x 34.05 cm
12U	22.63 x 22.63 x 34.05 cm

Table 3.2.1: dimensions of CubeSat

§ 3.3 Applications. A universe of possibilities

CubeSats have appeared in the last 15 years and represent a new paradigm in the satellite industry: in effect this type of satellite has very quickly become the “poster child” of the NewSpace Industry.

From the original concept as an educational tool for university students, it has evolved, spread, and been adopted by emerging space nations, new industries, nonprofits, space agencies, and traditional aerospace and military companies.

CubeSats are radically smaller than conventional satellites, resulting in lower costs, which offsets the reduced risk of failure and shorter useful life, which is nevertheless acceptable for numerous applications.

The special nature of nanosatellites does not prevent them from carrying out the same tasks as larger devices. The features naturally differ, but are sufficient for multiple industrial applications.

Currently these satellites are used for the purpose of:

- **Earth Observation:** collecting and interpreting data is essential for the correct management of natural resources and developing sustainable economies. Analyzing human impact on agriculture, forest, geology and the environment is crucial in order to improve the population's living conditions.
- **Communication and IoT:** nanosatellites have laid the foundations for developing the Internet of Things (IoT) on a global scale, connecting areas of the world without land communication cover via infrastructures in space. There is a growing number of sensorised objects and networks requiring global connections and communications.
- **Geolocation and Logistics:** locating and handling assets (aircraft, ships, vehicles, etc.) can prove impossible or at best extremely costly in areas where there is no land cover. Located in space and offering a global vision, nanosatellite constellations can provide immediate monitoring of various asset groups anywhere on the planet. Nanosatellites can complement current networks by providing complex logistic management solutions.
- **Signal Monitoring :** nanosatellites can monitor radio signals transmitted from Earth. This means that in the event of a disaster, they can provide initial information regarding the degree of impact and the most seriously affected areas, allowing for more effective planning of rescue and relief work.
- **Scientific Applications:** in addition to commercial solutions, CubeSats can also be used for space observation programs, interplanetary missions, systems testing in orbit or biomedical research. They also represent a gateway for the development of space programs in those countries that have not yet joined the space race.

It should also be remembered that as part of ESA's discovery and preparedness activities, many studies focusing on CubeSat have been funded and how "technological challenges" are regularly opened to obtain the brightest proposals for new space technology.

3. CUBESAT, LITTLE BIG SATELLITE

Thanks to the interesting representation of [Figure 3.3.1], provided by the European aerospace agency, we can have an idea of how the CubeSats are acquiring progressive relevance in the scenario of aerospace missions.

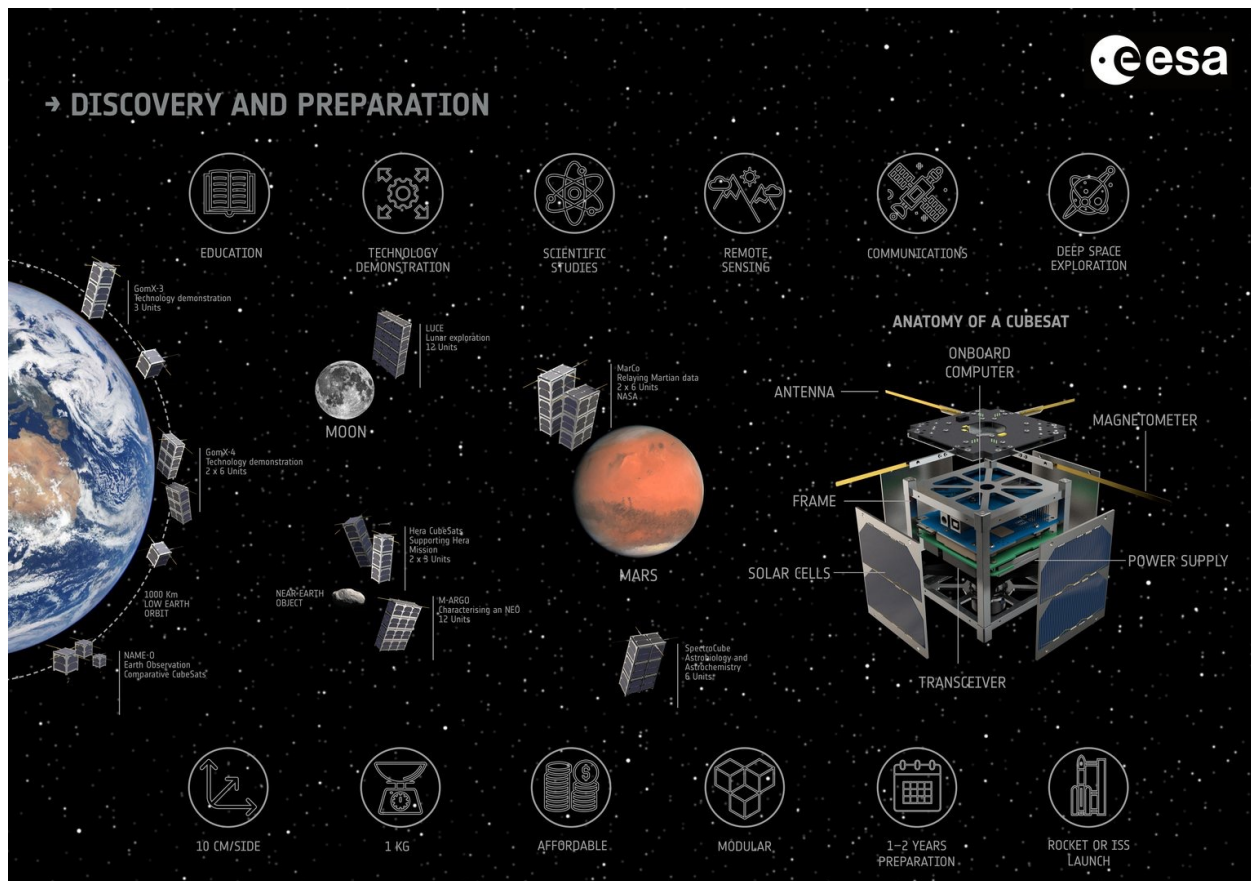


Figure 3.3.1: CubeSat future missions

Some of the missions that involve the use of CubeSat satellites will in fact be for example:

- Lunar CubeSats for Exploration (LUCE)

To support ESA's lunar exploration objectives, four innovative CubeSat concepts were recently selected for possible flight over the coming decade. The LUCE CubeSats would piggy-back on a lunar transfer vehicle before being released into orbit around the Moon.

- SpectroCube

In 2020, ESA will launch SpectroCube, a mission that will travel far from Earth to carry out astrobiology and astrochemistry experiments. The key science objectives of SpectroCube are to assess the impact of space on the biology and chemistry of the building blocks of life.

- M-ARGO

ESA's CDF has also been assessing the feasibility of the Miniaturized Asteroid Remote Geophysical Observer (M-ARGO), a stand-alone deep space CubeSat which would meet and characterize a near-Earth object. M-ARGO is intended to investigate the potential of using miniaturized technologies to lower the entry-level cost of space exploration.

- NAME-O

In 2014, ESA welcomed teams of scientists to design a project that would use cooperative nanosatellites for Earth Observation. This resulted in the NANosatellite Multiple channel Earth Observation (NAME-O) — a mission designed to carry out remote sensing using five cooperative nanosatellites.

Both past and future launches, for each specific mission, indicate a great variability in the format and number of CubeSats that should be allocated in the launcher.

If it is indeed true that the CubeSats that most often took part in past missions were of the 1U and 3U type (and this trend motivates the fact that the most produced deployer for CubeSat, especially in the first years, was the P-POD type, which allows you to house 1U to 3U type satellites), it is equally true that by observing the data collected from the most recent and planned missions, we note the introduction of CubeSats in different formats, in particular the 6U type.

NASA's Advanced Exploration Systems Division, Jason Crusan said significantly:

“The advancements of the cubesat community are enabling an acceleration of flight-qualified technology that will ripple through the aerospace industry, our future missions will be standing on the developments the cubesat community has enabled.”

4. How to get in Space

§ 4.1 So close so far away

Once the nanosatellite has been developed, tested and is ready for operations, it must be placed in orbit. There are currently multiple launch options for nanosatellites, including the shared use of government agency rockets, private company launchers or logistic links with the International Space Station (ISS).

CubeSats reduce launch costs in two fundamental ways. They don't weigh that much, which means a rocket doesn't need a lot of fuel to bring them along. Furthermore, they can share a rocket with a larger satellite. However, they have some design challenges. As a tiny box of electronics, it has more sensitivity to radiation. Design engineers build them to last a few weeks, but increasingly, they have them lasting months or even years. The low Earth orbit ones often fall back into Earth's atmosphere. Again, this is by design to keep costs low.

Each year new technologies allow companies in the private sector to use CubeSats.

With more and more schools and companies making CubeSats the demand for getting them into space will increase.

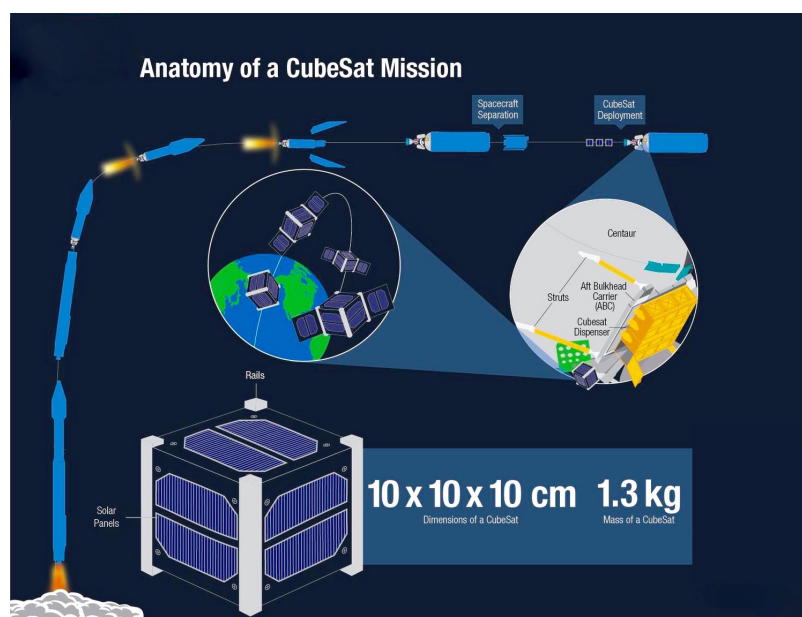


Figure 4.1.1: CubeSat launch

[Figure 4.1.1] schematically represents the logic for placing a CubeSat into orbit, naturally starting from a launcher that acts as a launch vector.

As a general rule, nanosatellites are launched in low circular or elliptical orbits (altitudes of between 400 and 650 km) and travel at around 8 km per second. At this altitude and height, it takes them around 90 minutes to orbit the Earth, completing between 14 and 16 orbits a day. These conditions are ideal for nanosatellites. By orbiting closer to the Earth, they not only guarantee optimum conditions for land observation or communications, but are also better protected from solar and cosmic radiation.

As it has been mentioned, satellites are commonly placed in orbit by launchers, which will release the CubeSat in a LEO (Low Earth Orbit) The choice of a low earth orbit is due to the need to comply with two different needs:

- on the one hand, the need to ensure communication between the satellite and the earth;
- on the other side, to comply with the de-orbiting rule imposed within a time frame of up to 25 years.

This last aspect is particularly important and is increasingly being studied today.

The [Figure 4.1.2] below is a representation of the debris around Earth. The objective of the NASA Orbital Debris Program along with the Inter-Agency Space Debris Coordination Committee (IADC) is to limit the creation of space debris. They have mandated that all spacecraft either deorbit within a given amount of time or be placed into a graveyard orbit for safe storage.

The lifetime requirement is 25 years post-mission, or 30 years after launch if unable to be stored in a graveyard orbit³.

As has been said, for the CubeSats the indication is 25 years - when a nanosatellite comes to the end of its operational life, it re-enters the atmosphere and disintegrates - but only recently a study has been started to try to understand the true impact of these satellites: in particular, different possible future scenarios are simulated to investigate the effects of the size of future CubeSat launches and have fact of post-mission disposal on

the proliferation of catastrophic collisions over the next 200 years. when a nanosatellite comes to the end of its operational life, it re-enters the atmosphere and disintegrates.

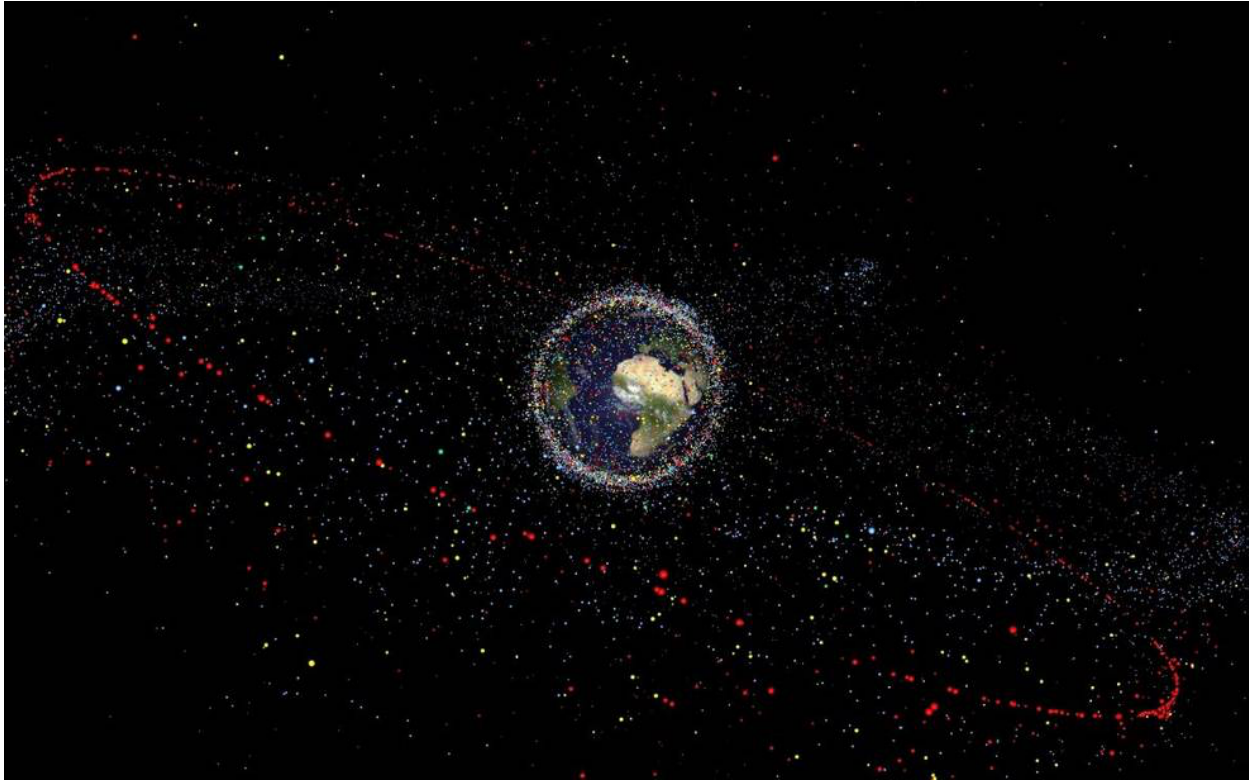


Figure 4.1.2: Distribution of space debris

§ 4.2 Take a european ride

There are different types of launchers that are used as launch vectors for CubeSat. The most common launchers that offer services to bring satellites into the orbit of interest are:

- PSLV



Figure 4.2.1: PSLV from ISRO (India)

The Polar Satellite Launch Vehicle [Figure 4.2.1] commonly known as PSLV, is a launcher developed by ISRO (Indian Space Research Organization).

- Falcon 9



Figure 4.2.2: Falcon 9 from Space X (USA)

Falcon 9 [Figure 4.2.2] is a category of rocket launchers designed and built by the American Space Exploration Technologies (SpaceX), where 9 stands for the number of first stage engines.



Figure 4.2.3: Electron from Rocket Lab (New Zealand)

- Electron

The Electron [Figure 4.2.3] of the New Zealand company Rocket Lab is designed for the launch of small satellites, in particular for the CubeSats.

- **VEGA**



Figure 4.2.4: VEGA from ASI/ESA (Europe)

VEGA [Figure 4.2.4] is the launcher resulting from the collaboration between the Italian Space Agency (ASI) and the European Space Agency (ESA) for the launch of small satellites into orbit. This is the vector with which Sat flies and is therefore the launcher used as a reference for the entire study conducted.

Vega (European Advanced Generation Carrier) is a launcher developed and manufactured by the Italian company Avio and is marketed at Arianespace (the world's leading company in commercial space transport): in fact, the Arianespace commercial launcher family was expanded in 2012 with this addition launcher, a new-generation vehicle for flights with small- to medium-sized satellite payloads.

This European four-stage launcher is tailored to carry the growing number of small scientific spacecraft and other lighter-weight payloads under development or planned worldwide. Vega's target payload lift capability is 1,500 kg. on missions to a 700-km. circular orbit at 90° inclination

Vega has an essential role within the family of European launchers, joining Ariane 5 (which is optimized for large satellites on missions to geostationary transfer orbit, and low-Earth orbits with very heavy payloads), and Soyuz (tailored for medium weight payloads for low-Earth orbit and certain smaller GTO spacecraft).

This launcher Vega is designed, as has just been said, to carry small loads (between 300 and 1500 kg) in orbit in low orbits and is formed by a single four-stage body (without side boosters). It is about 30 meters high, with a maximum diameter of about 3 meters and a take-off weight of 137 tons.

Vega is a 3 m-diameter single-body vehicle, standing 30 m tall with a liftoff mass of 137 tonnes. It has three solid-propellant stages, P80, Zefiro 23, Zefiro 9, and a liquid-propellant upper module for attitude and orbit control as well as satellite release, the AVUM. You can see all this in the [Figure 4.2.5].

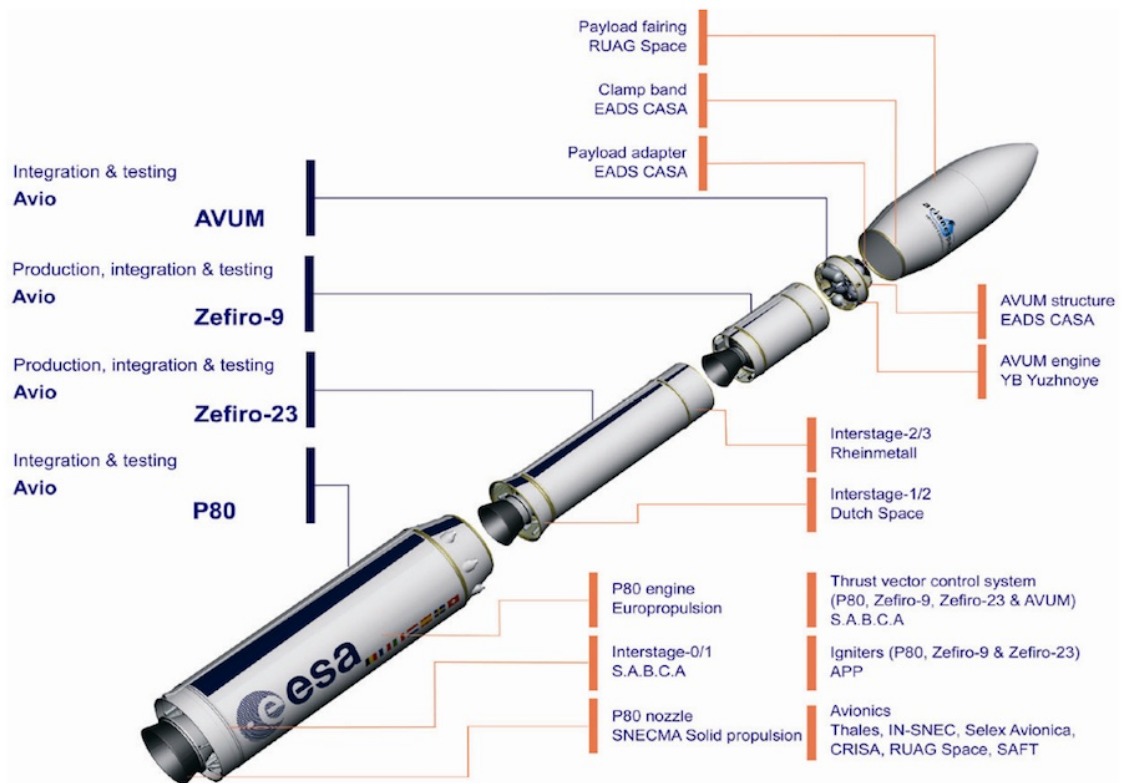


Figure 4.2.5: VEGA stages

A particular and much appreciated feature of this launcher is the ability to carry two or three small loads at the same time and position them correctly on different orbits, a capability not common in such small launchers.

In [Figure 4.2.6] you can see a description of Vega-C launcher, a more powerful version of Vega with a larger fairing is set to debut in 2020.

It shares the same P120C motor with Ariane 6 reducing recurring costs and allowing launches to remain at a similar cost to Vega. It will use a range of payload carriers for different shapes and sizes of payloads from 1 kg to 2300 kg.

Future evolutions of the Vega launch system will further increase competitiveness beyond 2025 offering a family of configurations based on common building blocks. These activities run in parallel with Vega-C developments.

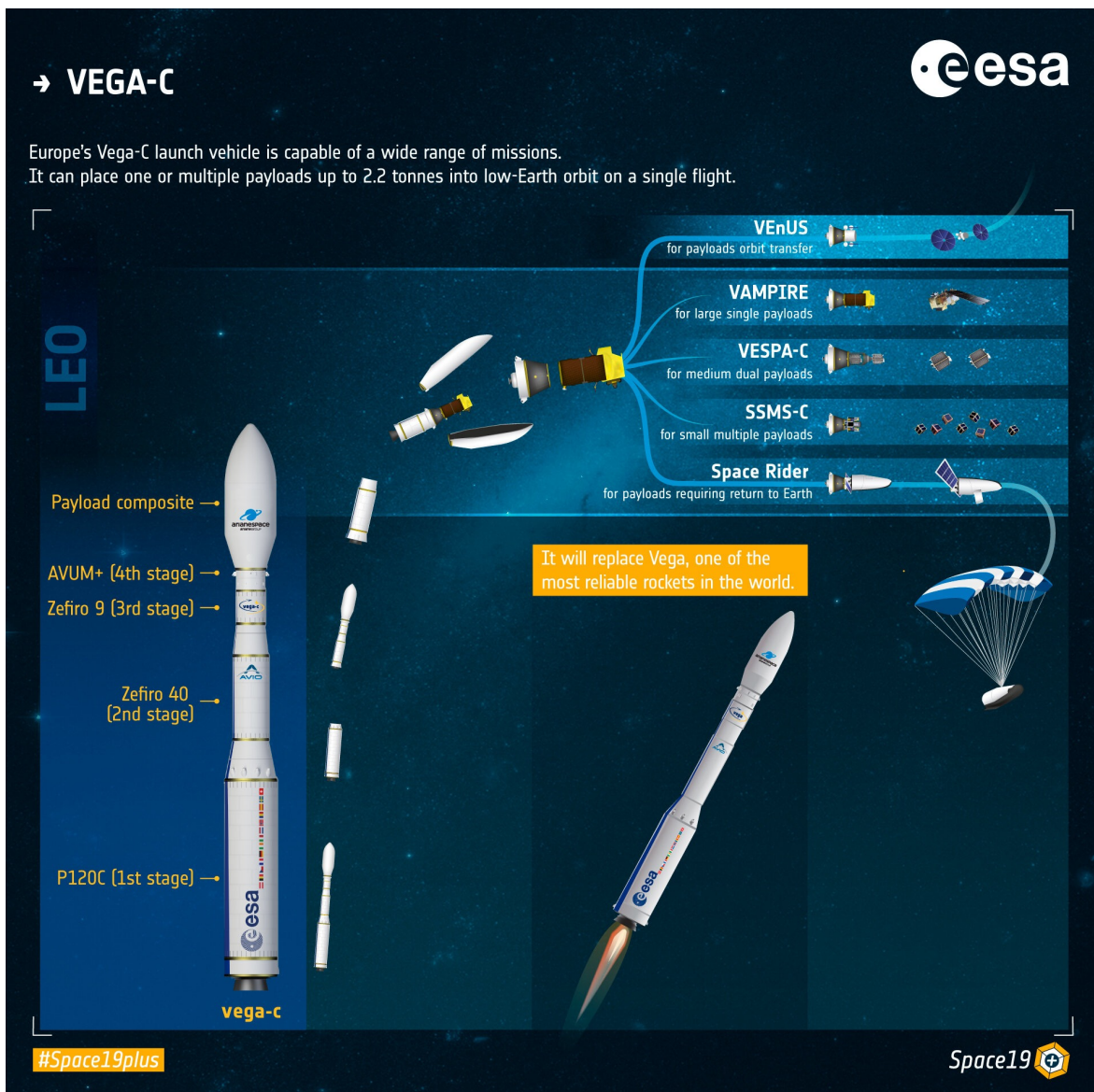


Figure 4.2.6: VEGA-C

§ 4.3 Dispenser

A series of adapters have been developed to enable multiple launch missions. VESPA and SSMS already flown, while an additional system called Vampire is currently being developed and is expected to fly by the 2021. On top of that ESA is also developing a re-entry vehicle to enable microgravity mission with the possibility to analyze once on earth the samples.

VESPA

VESPA is the acronym of Vega Secondary Payload Adapter. The VESPA (Vega Secondary Payload Adapter) has been developed to offer launch opportunities to mini satellites. It has successfully flown on the second Vega flight in 2013.

The VESPA carrying structure allows to embark:

- passenger in upper position (1000 kg max);
- passenger(s) inside the VESPA cavity (600 kg max in total).

The VESPA consists of a load bearing carbon structure, comprising a cylindrical part enclosing the lower passenger(s) with their adapter, and an upper conical shell supporting the main passenger.

The separation of the VESPA upper part is achieved by means of a clamp band and the distancing is ensured by a series of springs.



Figure 4.3.1: VESPA dispenser

SSMS

The SSMS Dispenser is the hardware developed to optimize multiple small satellite missions on VEGA and VEGA-C. The SSMS Dispenser is a modular structure which can be flexibly configured in order to be adapted to the specific satellite aggregate. The SSMS dispenser coupled with the VEGA AVUM (Attitude Vernier Upper Module) provides maximum flexibility for rideshare missions, allowing multiple satellite releases in different orbits with different altitudes and/or some inclination change.

The dispenser were developed under ESA leadership by the launcher Vega Prime AVIO, the dispenser design authority being SAB Aerospace and it is conceived as a fully modular system, enabling finalisation of mission architecture at the latest possible time before flight date and provide unprecedented flexibility on the mission preparation process.

Infact, the dispenser system is composed essentially by two major elements; Lower Part and Upper part, eventually suitable for independent accommodation on the launcher. The Upper part provides a number of possible configurations described in more detail in the following sections.

The mass of the dispenser varies between 160 to 360 Kg, depending on the configuration complexity; the system maximum load capabilities by design are depending on the chosen configuration; maximum mass for a single microsat is 500 Kg., maximum number of spacecrafts 9 microsats and 24 12U deployers.

The majority of avionic services to the spacecrafts are provided by the launcher avionics system, separation commands, monitoring, telemetry and Spacecraft services are centralised using the existing or upgraded launcher avionics; autonomous additional separation commanding functions are implemented directly on the dispenser by means of 2 dedicated sequencers.

The SSMS is a modular concept, allowing to interface small satellites in several configurations based on the same structural elements:

- *Piggy back configuration*, based on one our two hexagonal modules:

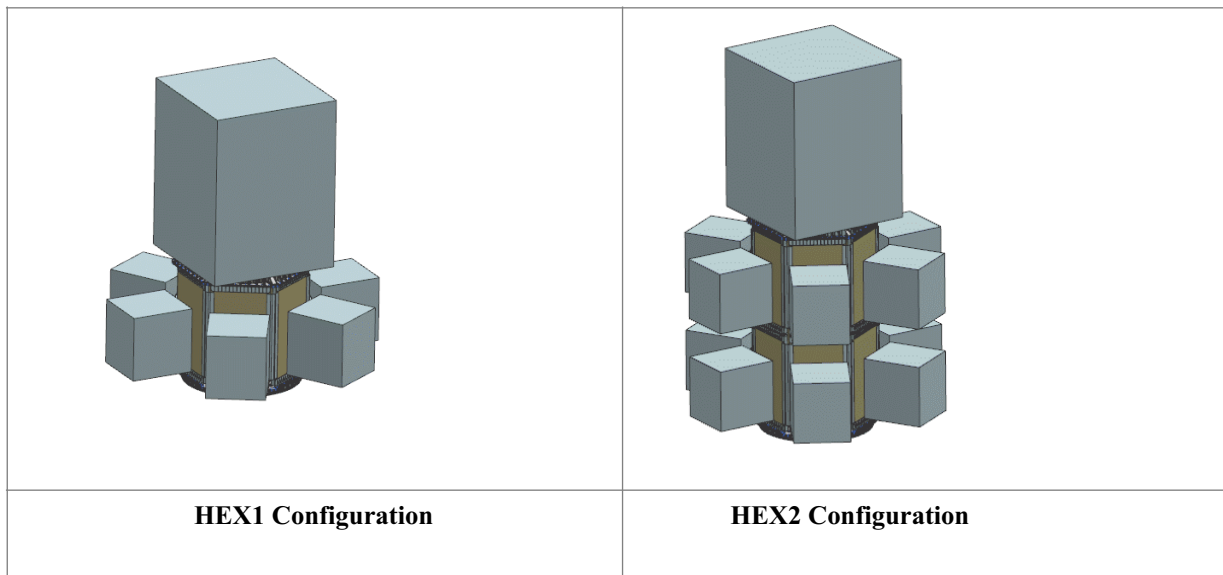
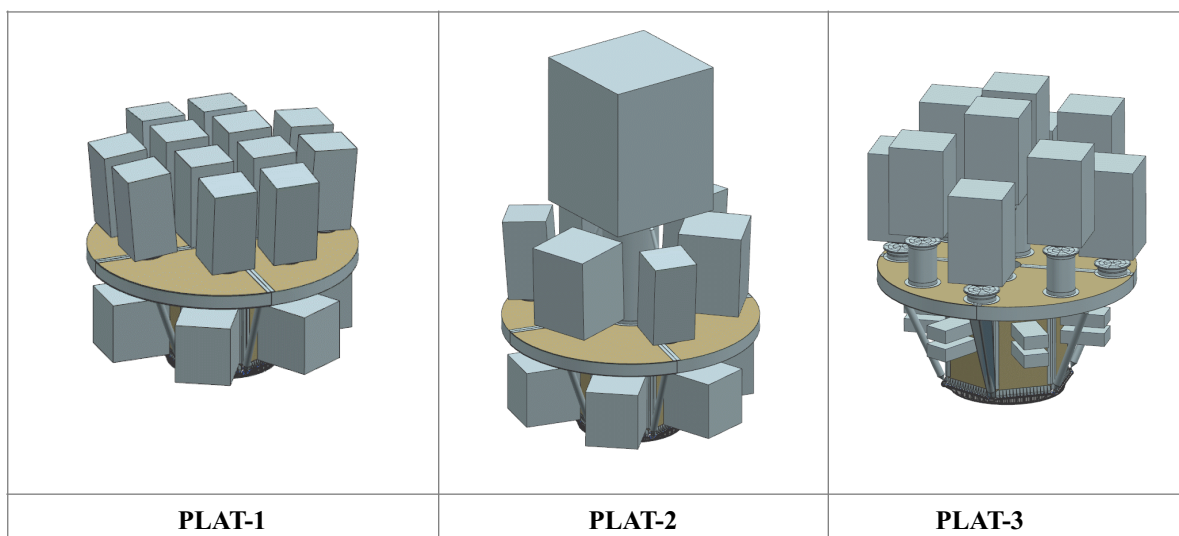


Figure 4.3.2: SSMS dispenser, piggy back configuration

- *Ride Share configurations*, based on one hexagonal module and a platform, equipped with or without spacers, a central column, and/or tower module.



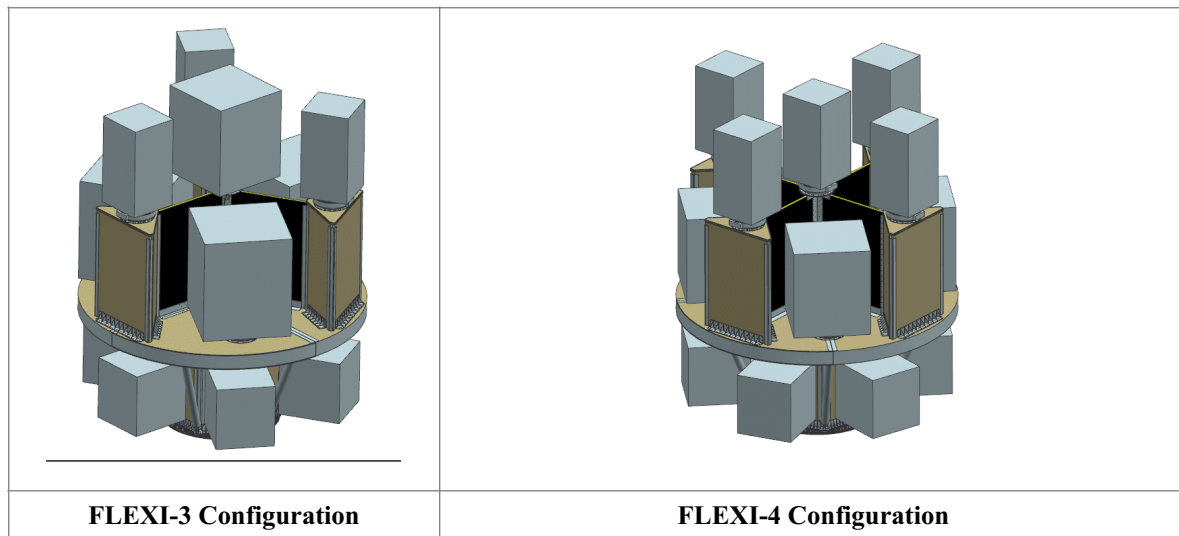


Figure 4.3.3: SSMS dispenser, Ride Share configurations

The SSMS hardware is consisting of a dispenser structure accommodating the P/Ls to be deployed, the related separation systems and avionics.

The structure is made of sandwich panels with aluminum honeycomb core and CFRP skins. In addition to these composites parts, it is made up of an aluminum machined I/F ring towards the VEGA launcher 1194 PL adapter and aluminum machined brackets.

In September 2020 the POC model of the SSMS flown in a FLEXI-3 configuration featuring:

- 1 Lower Module:
 - Lower IF Ring
 - Hexagonal Module Assy
 - Main Deck Assy (OD ø2300mm)
 - External Rod Assy
- 3 Tower Modules
- 1 Shear Web Module

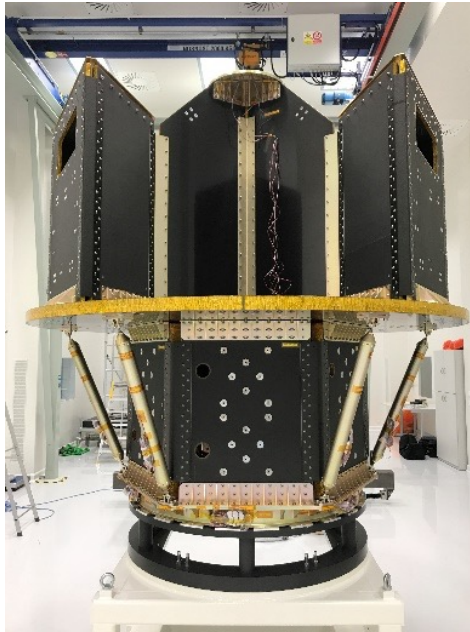


Figure 4.3.4: Flexi-3 Configuration (PoC)

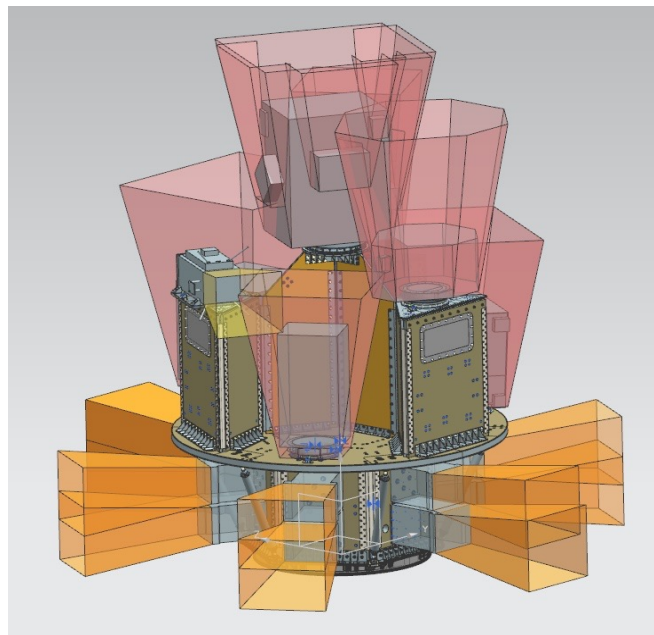
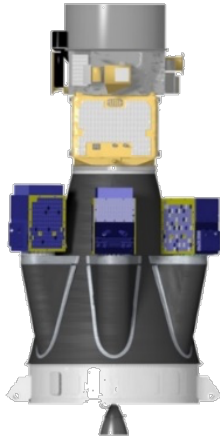


Figure 4.3.5: Flexi-3 PoC Separation angles study

VAMPIRE

Vampire is the last Dispenser being developed to offer Piggy back specific solutions where the secondary passengers are Microsatellites with mass up to 120kg.



The structure, made up of Carbon Fiber is not as flexible as SSMS, but it allows axial separations for all the satellites. The system is still under development and the maiden flight is expected by the second half of 2021.

Figure 4.3.6: Vampire dispenser

5. Deployer for CubeSat

§ 5.1 Sharing is caring

Typically satellites are launched and released by separation system: this mechanism represents the interface between the satellite and the launch vehicle. His job is to keep the satellite tethered and release it under the correct conditions.

The most used system is called MLB [Figure 5.1.1], produced by PSC, which, like all separation systems, is equipped with two rings, one integral with the satellite and one with the launch vehicle.

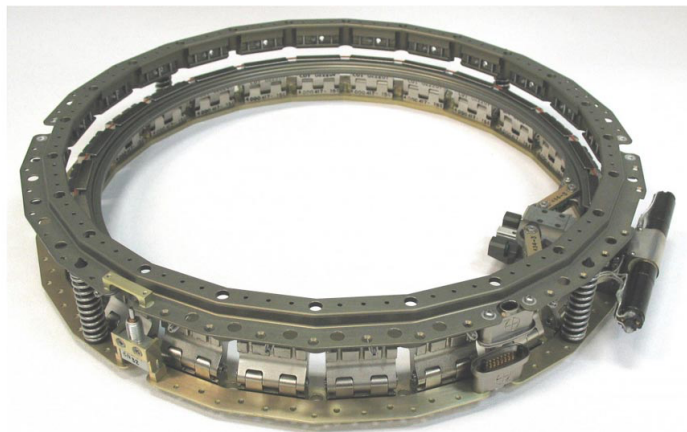


Figure 5.1.1: MLB from PSC

Unlike satellites, which are launched and released by separation system as has just been said, CubeSat are packed inside deployers [Figure 5.5.2]

In fact a deployer exploits the concept of packing the CubeSats in canisters enclosed by doors that push the CubeSat onto the pusher plates.

Once in orbit, the actuator opens the door and the pusher plate is free to push the CubeSat out.

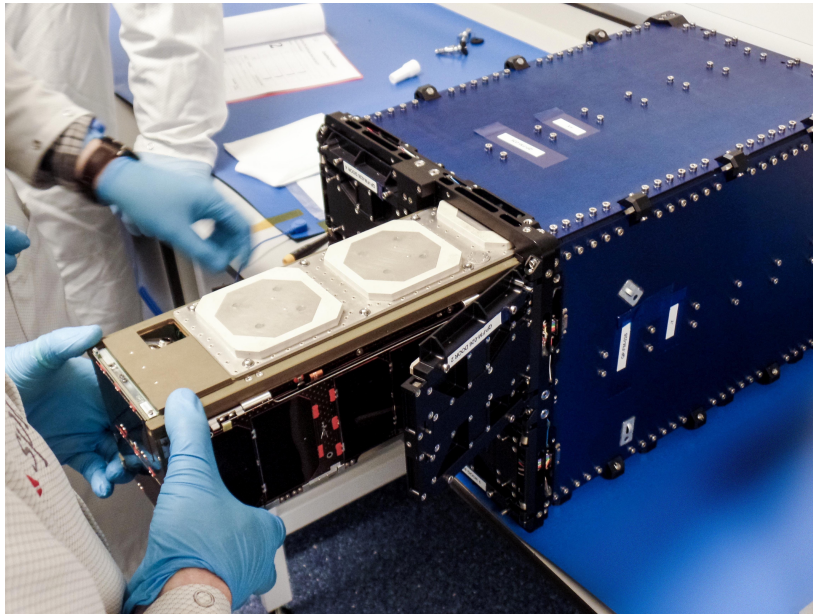


Figure 5.1.2: Deployer for CubeSat

The philosophy that we tend to adopt today for the launch of CubeSats is to provide for the sharing of a single deployer between multiple satellites, in order to obviously benefit from space optimization and consequent sharing and therefore cost reduction.

§ 5.2 Deployment system

The pico-nano satellites to be launched are stowed in one of the slots or a combined slot into the payload dispenser, in order to reduce launch campaign complexity and associated costs. Hence, the device is able to deploy different kind of configurations of the housing of cubesates: one 1U CubeSat, one 2U CubeSat, one 3U CubeSat from each of the four slots or one 6U CubeSat from a combined slot or one 12 U Cubesat from four combined slots. The main task of deployer is to allow the ejection of the cubesats according to the mission requirements ensuring the safety of the contained and protecting the launch vehicle, the primary payload and the other satellites to be launched during the transport in orbit. The pack is designed to ensure the safety of the contained CubeSats and to protect the launch vehicle (LV), the primary payload and other satellites to be launched

during the transport into orbit. After the safe transportation of the CubeSats into the orbit, a deployment with a high reliability and a low spin rate is achieved by patented design principles. After a successful deployment, a telemetry signal is available for the launch provider. The launch slots of the pack usually can be commanded independently.

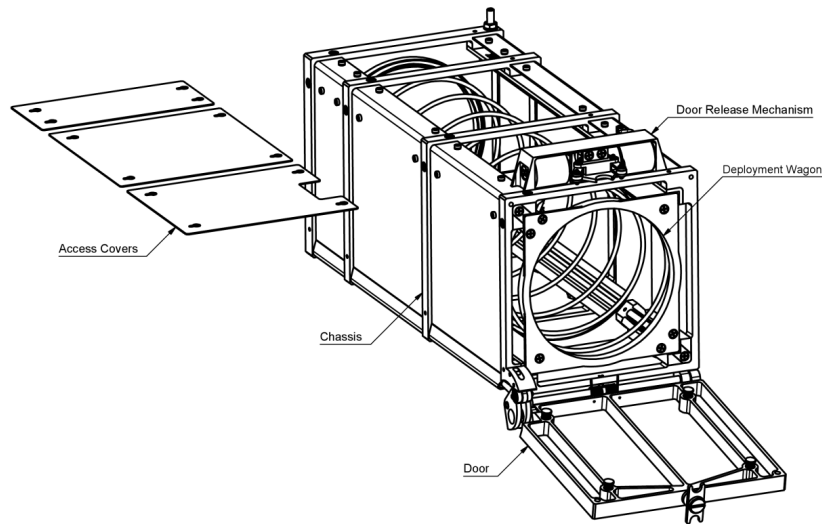


Figure 5.2.1: Deployer description

The main components of a deployer are: chassis; the doors with its individual release mechanisms; access cover. All those components are mounted onto the container and the sidewall can be configured on demand.

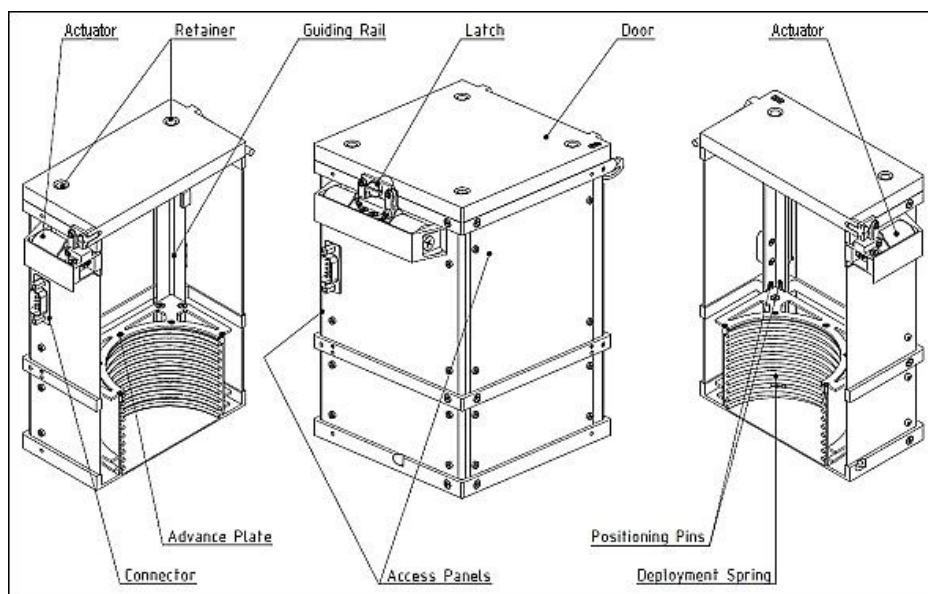


Figure 5.2.2: Deployer elements

The Chassis is the rigid framework of pack that serves as structure, mounting interface and guide of the deployment wagons in each slot. The rails of the chassis guide the deployment wagons in such way that no canting and twisting of these wagons is possible. The chassis is closed on all sides during launch to prevent any parts from leaving to the deployment process of the CubeSats.

The Doors open upon the initiation of the deployment process for the corresponding slot typical until 110° and are locked in this position immediately after reaching the end stop. As soon as the door has opened completely the deployment wagon of the appropriate slot is immediately released. Besides the opening function, the doors are also used to hold the CubeSats in place during transportation and launch. Therefore the doors are equipped with spring loaded retainers, which are in contact to the contact faces of the guide rails of the CubeSat at any specified environmental conditions. The spring forces of the retainers also contribute to the opening energy of the door.

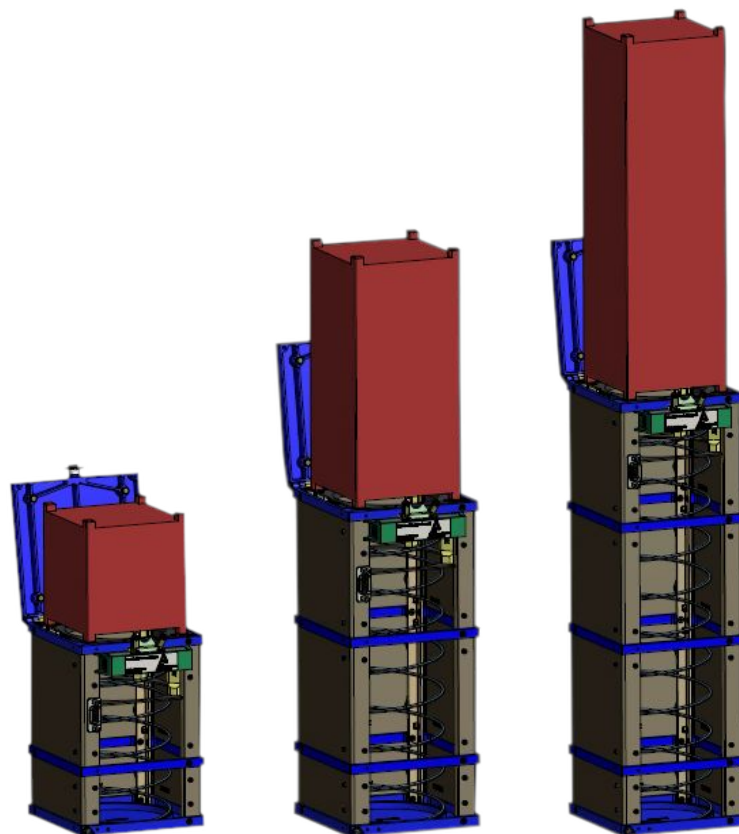


Figure 5.2.3: Deployment process schematization

The Door Release Mechanisms are mounted on the doors of the pack. The mechanisms keep the doors closed during any transportation and launch operation. Once the electrical signal for the deployment is given the deployment process is initiated. Two redundant electric permanent magnets are located at each door. The magnets are employed as actuators to release the door using a lever mechanism. The Deployment Wagon ejects the CubeSat into the open space, once the door is completely opened and locked. The wagon is guided in the chassis with roller bearings. Hence a smooth and continuous motion with predictable deployment energy is accomplished. The deployment spring provides the force to accelerate the CubeSat and the deployment wagon during deployment.

The following functional tests are recommended and should be performed prior to launch:

- Satellite fit check
- Door release test
- Test of the deployment indicator switches
- Electrical end to end function test of the release mechanism
- Electrical end to end test of the deployment indicator switches

§ 5.3 Deployers market survey

Nowadays there are different kind of deployers which use a particular technology for the ejection of cubesats. The main companies are PSC, ISIS, Astrofrein, Tyvak and D-Orbit.

● PSC's deployer

PSC technology is based on a Canisterized Satellite Dispenser (CSD). It is an aluminum box that encapsulates small payloads during launch. A pair of tabs on the payload are preloaded to the CSD. Closing the CSD's door automatically preloads the tabs and prevents movement of the payload during launch. The door initiator is a DC brush motor. There are no consumables and no items to reset

between operations. There are two CSD operations: A) Stowing: Installing the payload (satellite) in the CSD and closing the Door. B) Deploying: Powering the

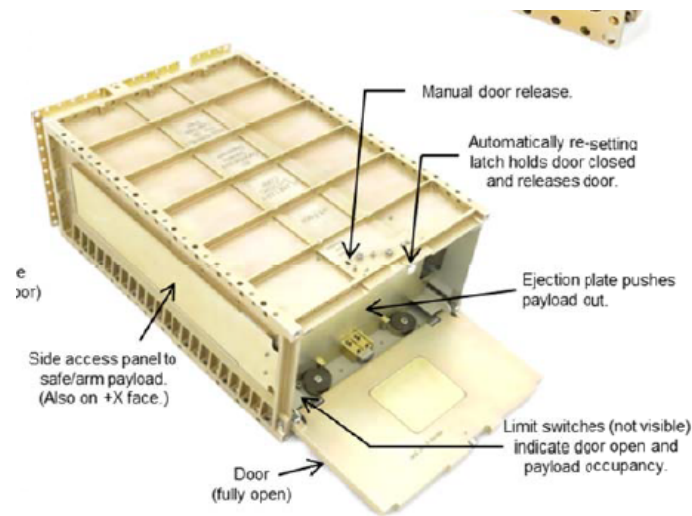


Figure 5.3.1: Deployer from PSC

CSD initiator (motor) which opens the door and allows the payload to eject.

A canisterized satellite dispenser includes one or more of: a pair of guide rails that eliminate the requirement of a rectangular profile for the satellite; a preload system that secures the canisterized satellite during transport and launch, and releases to deploy the canisterized satellite; a constant-force spring to provide a uniform and predictable dispensing force; an external rectangular profile in each dimension; and internal support surfaces that simplify the design of canisterized satellites, particularly those with deployable components. Each canisterized satellite includes a pair of opposing flanges on a lower portion of the satellite that ride in a channel formed by the dispenser's guide rails and restraining flanges; no other support constraints are imposed. During travel and launch, the satellite flanges are held against the restraining flanges, rigidly fixing the satellite to the dispenser until the satellite is deployed.

● ISIS's deployer

In spite of Psc's system deployment, cubesat deployers of ISIS Company can be considered modulars. In fact Isis uses different kind of lunch adapters like the Quadpack, Duopack and Isipod deployers



Figure 5.3.2: Deployer from ISIS

The QuadPack, DuoPack and ISIPOD deployers are the most flown CubeSat launch adapters, developed by ISIS - Innovative Solutions In Space to accommodate CubeSats onboard a large variety of launch vehicles, through ISIS' turn-key ISILaunch Services, or with tailored integration support. The QuadPack and ISIPOD deployer product lines can accommodate any type of CubeSat or nanosatellite, from 1U, 2U, 3U, 6U up to 12U and 16U, while custom formats and volumes can be quickly realized. Each ISIS deployer provides simple, well defined interfaces towards the CubeSats internally and the launch vehicle externally, with an optimized balance between internal versus external volume and payload versus deployer mass. All ISIS deployers are fully qualified with flight heritage on 6 different launch vehicles so far.

● Astrofein's deployer

This type of deployment is based on “PSL-P Concept” which is designed to accommodate different CubeSat size. Therefore the four deployment slots can be

used separately or can be combined. Figure 8 depicts the possible configurations. Each slot number is engraved at the bottom plate for defined assignment. The configurations are tagged according the number of loadable satellites. Each slot is separated by a divider-plate to avoid interferences.



Figure 5.3.3: Deployer from Astrofein

This type of deployer has been chosen as model of main inspiration for development of the new deployer concept in SAB Aerospace. This choice was made because of the affidability of model but also because it answers the demands of the market (variable requirements, possibility to change easily the types of cubesats stowed into the deployer; possibility of increase the number of cubesats into the deployer; cost and time reduced; reduce the weight of deployer in spite of payload; structural requirements and vibration).

● Tyvak's deployer

The Tyvak NLAS design was derived from the NASA Ames Research Center NLAS Mk.I and incorporated lessons learned from the Poly Picosatellite Orbital

5. DEPLOYER FOR CUBESAT

Deployer (P-POD), which has carried over 100 U-Class satellites with a 100% success rate.

Let's see instead how Tyvak is studying a new category of deployer based on the construction of a frame (which should support the panels protecting the CubeSat).

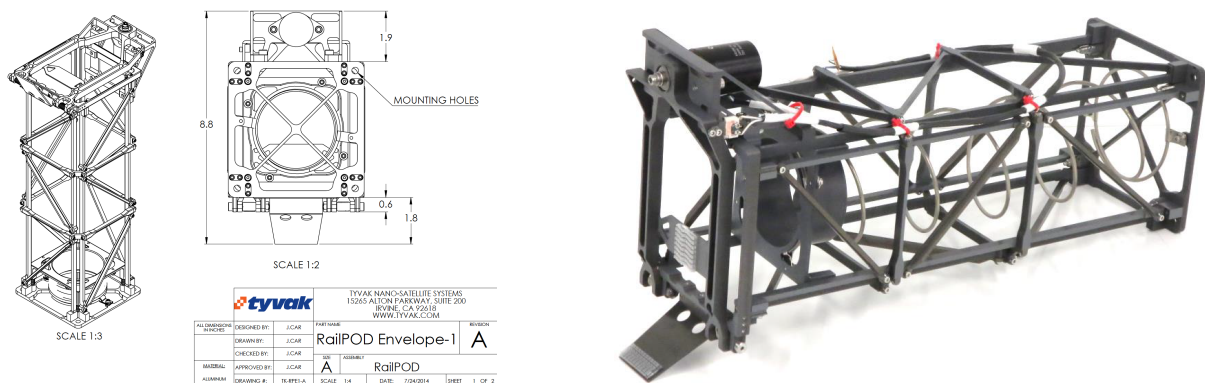


Figure 5.3.4: Deployer from Tyvak

● D-Orbit's deployer

“ION-mk01” is equipped with an autonomous fault-tolerant mechanism for CubeSat release. An on-board timer is used to monitor elapsed time from last ground contact. Should a failure results in the platform inoperability from ground, all the CubeSats would be autonomously released consecutively, a few minutes apart. This emergency protocol is triple-fault tolerant, completely autonomous and independent of most spacecraft subsystems.

Such a provision guarantees CubeSats deployment at most within one month from launch, in “Minimum Mission” condition (i.e. without Precise Deployment and Fast Dispersion), even in the very unlikely case of total loss of the satellite. This Minimum Mission is, in fact, the current state-of-the-market of all other

5. DEPLOYER FOR CUBESAT

CubeSat dispensers, giving an unprecedented mission assurance to Customers for their CubeSat deployment phase.

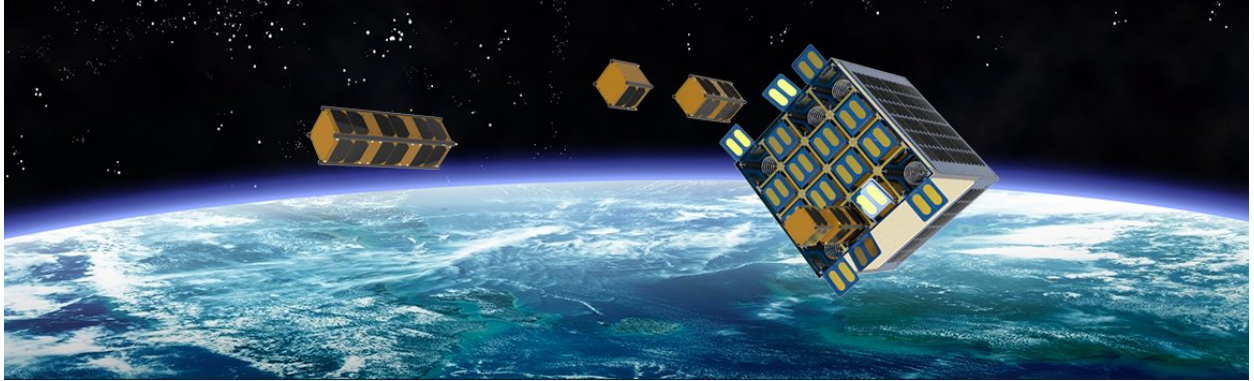


Figure 5.3.4: Deployer from D-Orbit

6. Deployer design

The design and verification of the deployer is performed following the standard normally adopted for spatial systems and subsystems, which is described in the ECSS standard guide.

The phases that follow one another in the development of a subsystem intended for space applications are defined as reported in [Table 6.1].

Phase 0	Feasibility Study
Phase A	Requirement Definition
Phase B	Preliminary design leading to a Preliminary Design review
Phase C	Detailed design leading to a Critical Design Review
Phase D	Qualification model to reach qualification of the deployer and flight model for in orbit validation

Table 6.1: ECSS space project guide

Entering into the specifics of the various phases indicated by ECSS:

Phase 0 (Feasibility):

This is mainly an activity conducted by the top level customer and one or several first level suppliers with the outcome being reported to the project initiator, and representatives of the end users for consideration.

Major tasks will be:

- Establish the preliminary management plan, system engineering plan and product assurance plan for the project.
- Elaborate possible system and operations concepts and system architectures and compare these against the identified needs, to determine levels of uncertainty and risks.
- Establish the function tree.

- Assess the technical and programmatic feasibility of the possible concepts by identifying constraints relating to implementation, costs, schedules, organization, operations, maintenance, production and disposal.
- Identify critical technologies and propose pre-development activities.
- Quantify and characterize critical elements for technical and economic feasibility.
- Propose the system and operations concept(s) and technical solutions, including model philosophy and verification approach, to be further elaborated during Phase B.
- Elaborate the risk assessment.

Phase A (Requirement definition):

The preliminary requirements definition is held at the end of Phase 0. The outcome of this review is used to judge the readiness of the project to move into Phase B. The primary objectives of this phase are:

- Release of preliminary management, engineering and product assurance plans.
- Release of the technical requirements specification.
- Confirmation of the technical and programmatic feasibility of the system concept.
- Selection of system and operations concept(s) and technical solutions, including model philosophy and verification approach, to be carried forward into Phase B.

Phase B (Preliminary definition):

Major tasks of this phase:

- Finalize the project management, engineering and product assurance plans.
- Establish the baseline master schedule.
- Elaborate the baseline cost at completion.

- Elaborate the preliminary organizational breakdown structure (OBS).
- Confirm technical solution(s) for the system and operations concept(s) and their feasibility with respect to programmatic constraints.
- Conduct “trade-off” studies and select the preferred system concept, together with the preferred technical solution(s) for this concept.
- Establish a preliminary design definition for the selected system concept and retained technical solution(s).
- Determine the verification program including model philosophy.
- Identify and define external interfaces.
- Prepare the next level specification and related business agreement documents.
- Initiate pre-development work on critical technologies or system design areas when it is necessary to reduce the development risks.
- Initiate any long-lead item procurement required to meet project schedule needs.
- Prepare the space debris mitigation plan and the disposal plan.
- Conduct reliability and safety assessment.
- Finalize the product tree, the work breakdown structure and the specification tree.
- Update the risk assessment.

There are 2 project reviews associated with Phase B: The system requirements review (SRR) held during the course of Phase B; the preliminary design review (PDR) held at the end of Phase B. The outcome of this review is used to judge the readiness of the project to move into Phase C.

Phase C (Detailed definition):

The scope and type of tasks undertaken during this phase are driven by the model philosophy selected for the project, as well as the verification approach adopted.

- Completion of the detailed design definition of the system at all levels in the customer– supplier chain.
- Production, development testing and pre– qualification of selected critical elements and components.
- Production and development testing of engineering models, as required by the selected model philosophy and verification approach.
- Completion of assembly, integration and test planning for the system and its constituent parts.
- Detailed definition of internal and external interfaces.
- Issue of preliminary user manual.
- Update of the risk assessment.

The critical design review (CDR) is held at the end of phase C. The outcome of this review is used to judge the readiness of the project to move into phase D.

Phase D (Qualification and production):

Major tasks of phase D are:

- Complete qualification testing and associated verification activities.
- Complete manufacturing, assembly and testing of flight hardware/software and associated ground support hardware/software.
- Complete the interoperability testing between the space and ground segment.
- Prepare acceptance data package.

The activity present here focused on phases A and B.

§ 6.1 Requirement definition

The activity started with the definition of the requirements. Since this is an internal project (no external customer), the requirements have been defined based on the needs of the market and the launcher to be used (Vega).

The requirements for our object can be classified as requirements:

- **Functional**
- **Physical properties**
- **Interfaces**
- **Environmental loads**

§ 6.1.1 Functional requirements

The functional requirements, being an internal project of Sab, have had a particular weight:

The goal is to identify a deployer architecture capable of providing modularity and flexibility, both in order to allow the arrangement of different types of CubeSat (1U, 2U, 3U, 6U and 12U) within the same deployer and in order to obtain an easily reconfigurable deployer (with minimal changes) to vary the type of satellites to be adopted: this to meet the very different requests that occur from launch to launch and during the phases preceding it (CubeSat which are suddenly withdrawn from the mission and CubeSat who ask for "a ride" at short notice).

For the same reason, the deployer should guarantee the possibility of "last minute" aggregation, that is, to somehow increase its capacity at the last moment.

Obviously, the minimization of costs is one of the binding aspects.

§ 6.1.2 Physical properties requirements

Another requirement concerns the physicality of our system.

In [Figure 6.1.2.1] the red area is the so-called "door" of the HM which is currently used to host a single 12 U deployer. The green area is any space available (without interfaces).

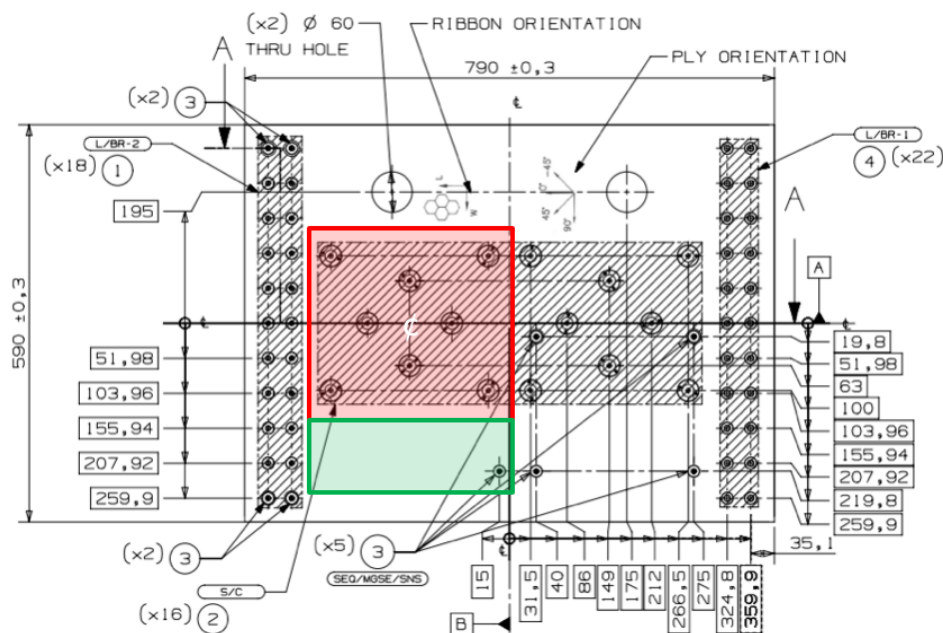


Figure 6.1.2.1: Available space on SSMS door

While on the right and left the volumes are limited by the presence of the SSMS Main Deck on one side and the presence of the second door on the other side

The single door of SSMS is sized to bring a mass of 35 kg and with CoG 250 mm from the surface of the door itself (N.B. in our case it will be more important to lower the CoG than the kilos as this is the most dimensioning aspect)

We also estimate that the weight of a CubeSat 3U is 6.1 kg (the exact weight is unknown).

§ 6.1.3 Interfaces requirements

Of course it is necessary to take into account interface constraints. There are 2 types of interfaces on the deployer.

An interface will be the one between the deployer and the SSMS (hexagonal module): in particular, the door of the hexagonal module has a pattern like the one we see highlighted by the red points in the [Figure 6.1.4.1].

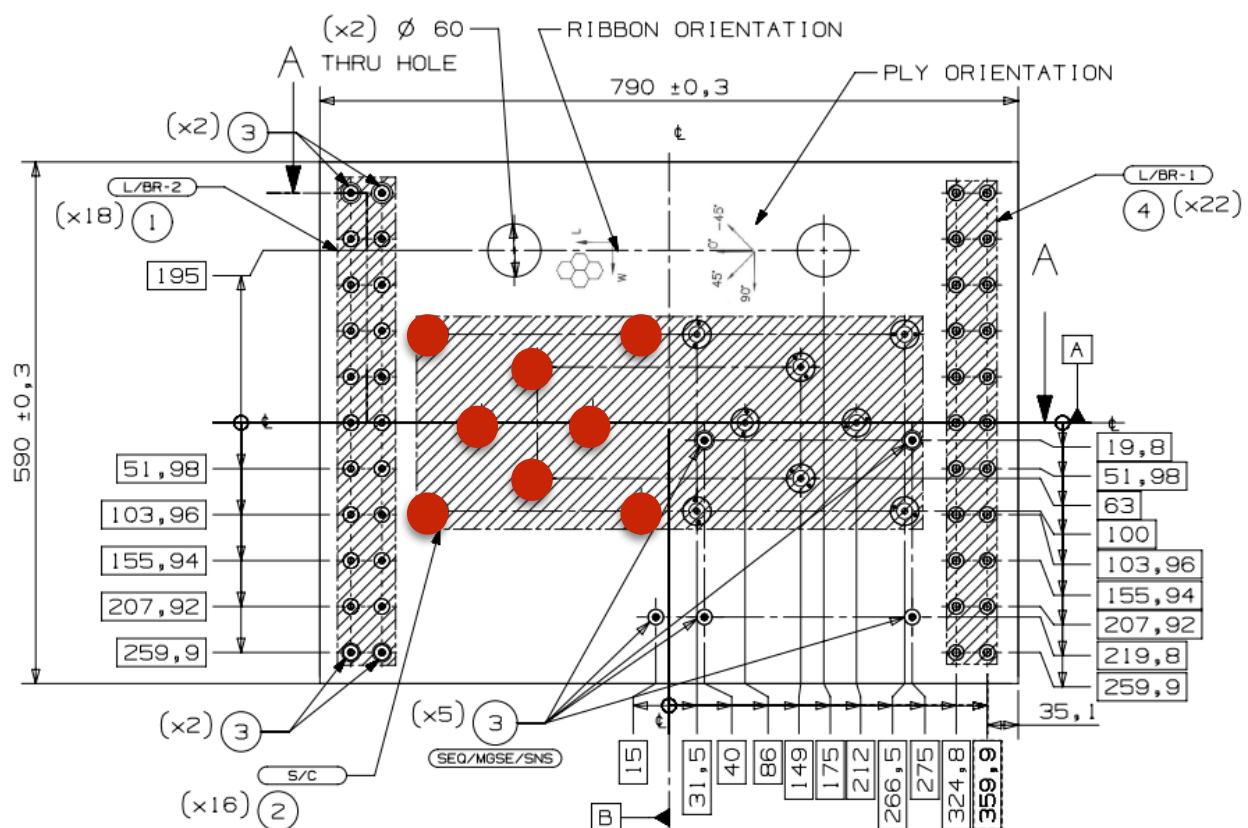


Figure 6.1.3.1: Deployer - SSMS HM interface

The other interface is the one existing between the deployer and Cubesat: on the CubeSat we find a rail at each corner, as shown in the [Figure 6.1.3.2], the satellite that is released crawls with these rails in the deployer.

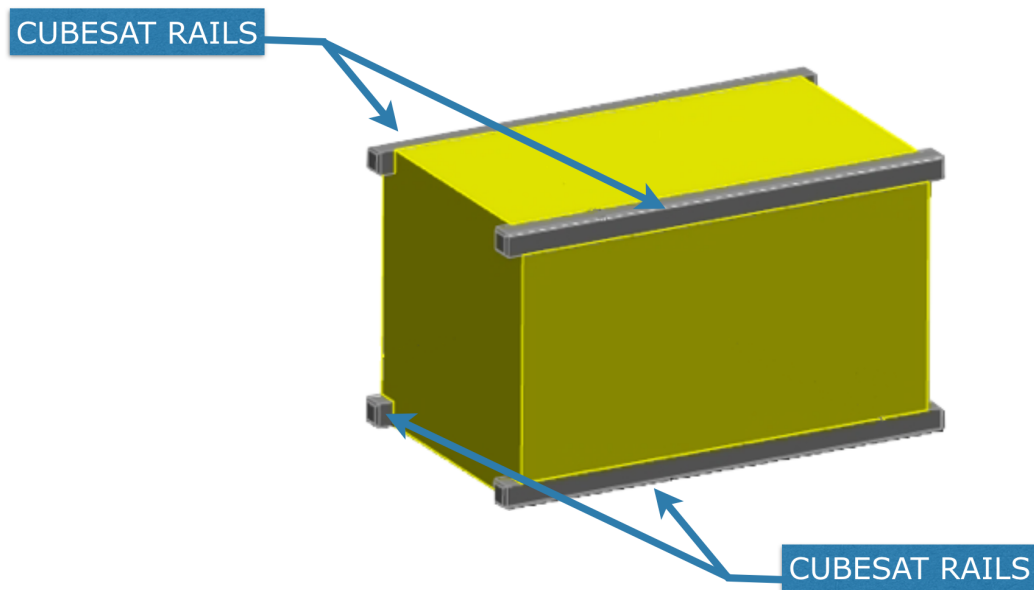


Figure 6.1.3.2: Deployer - CubeSat interface

§ 6.1.4 Environmental loads requirements

The most commonly used parameter (in industry) to “define the motion of a mechanical system” is acceleration, g.

The choice to express the loads acting on the spacecraft is motivated by two very good reasons: on the one hand the accelerations are directly related to forces / stresses, on the other hand they are "easy" to specify and measure.

The mechanical loads to which all the objects that are placed in a launcher are subjected are due to:

- Transportation
- Rocket Motor Ignition Overpressure
- Lift-off Loads
- Engine/Motor Generated Acoustic Loads

- Engine/Motor Generated Structure-borne Vibration Loads
- Engine/Motor Thrust Transients
- Pogo Instability, Solid Motor Pressure Oscillations
- Wind and Turbulence, Aerodynamic Sources
- Liquid Sloshing in Tanks
- Stage and Fairing Separation Loads
- Pyrotechnic Induced Loads
- Maneuvering Loads
- Flight Operations, Onboard Equipment Operation

In particular we can go and see a qualitative graph of the accelerations that the payload undergoes by the launcher, [Figure 6.1.4.1]. The three great peaks that I see correspond to the moment of switching off and separation of each of the 3 stages of Vega; we also notice how there is overlap between static and dynamic.

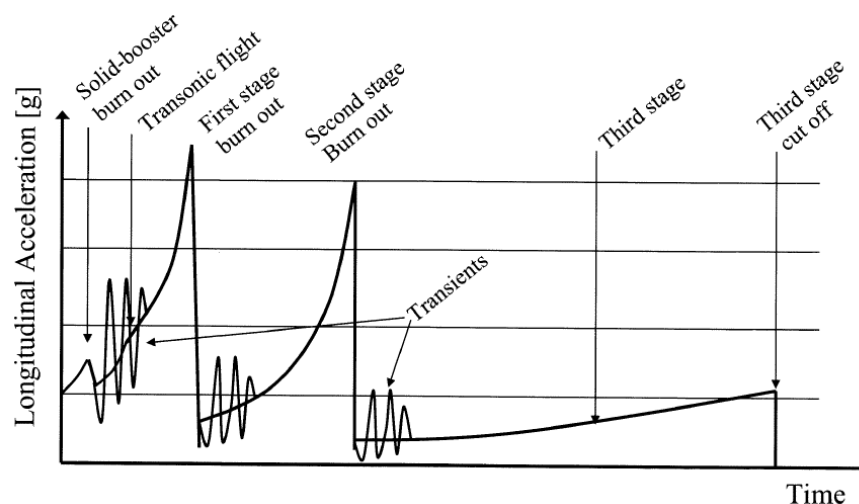


Figure 6.1.4.1: Acceleration from launcher to payload

Moving on from the description of mechanical loads in terms of time that we have just seen to the same loads translated in terms of frequency, we see how these can be classified into three main categories, [Figure 6.1.4.2].

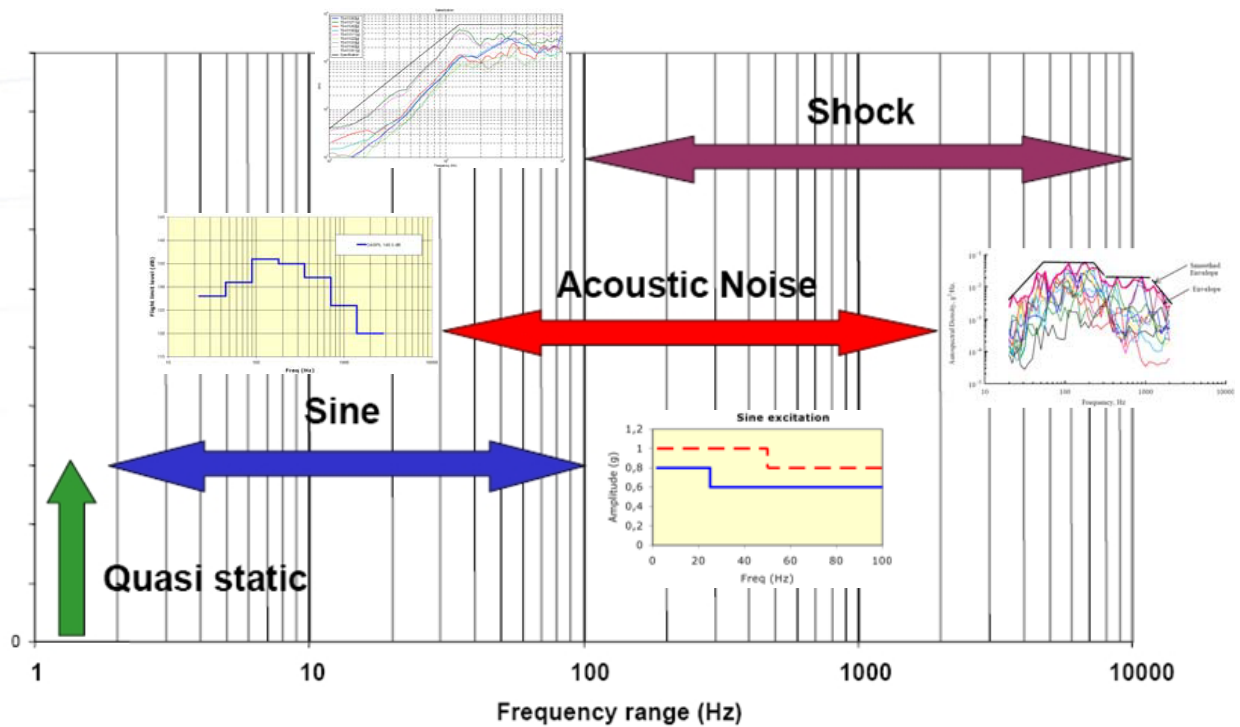


Figure 6.1.4.2: Acceleration in terms of frequency

- QSL (Quasi-Static Loads), which cover very low frequencies;
- Sine excitations, which cover frequencies up to about 100 Hz;
- Acoustic loads that give rise to random excitations on the payload (up to about 2000 Hz);
- Shocks (we are at very high frequency).

	Acoustics	Random Vibration	Sine Vibration	Shock
Lift-off	x	x		
Aerodynamics/ Buffet	x	x		
Separation (stage, fairing, spacecraft)				x
Motor burn/ Combustion/ POGO		x	x	

Table 6.1.4.1: Sources of launch environments

Note that while the quasi-static loads and the sine are transmitted to the payload via the mechanical interface, in the case of the acoustic load it excites all the surfaces of the payload.

§ 6.1.4.1 Quasi-Static Loads

The ECSS-E-ST-32 guide defines them as: “Loads independent of time or which vary slowly, so that the dynamic response of the structure is not significant”.

In the [Figure 6.1.4.1.1] we can find some examples of static loads (axial and lateral) that are given as a design specification by some types of launchers.

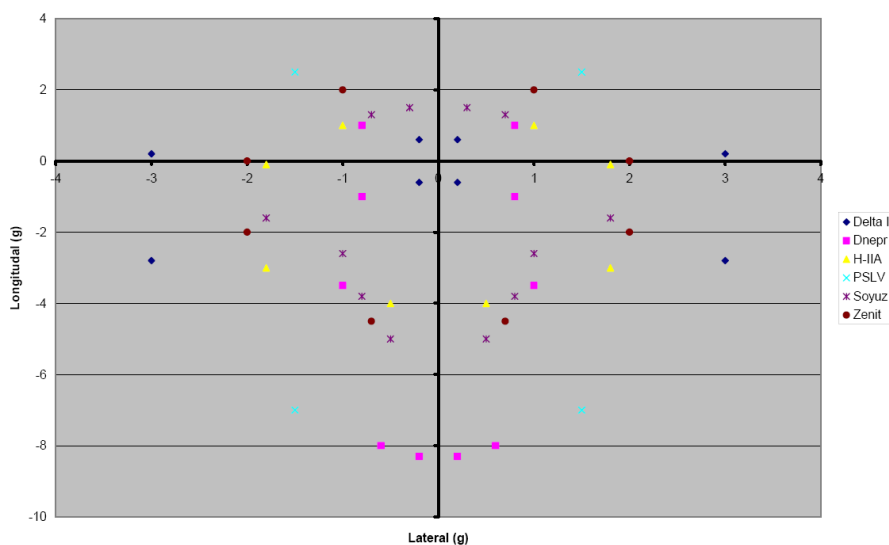


Figure 6.1.4.1.1: QSL for some launcher

For design purposes (e.g. derivation of design limit loads, selection of the fasteners, etc.), the quasi-static loads are normally calculated by combining both static and dynamic load contributions. In this context the quasi static loads are equivalent to (or interpreted by the designer as) static loads, typically expressed as equivalent accelerations at the C.o.G.

§ 6.1.4.2 Sine excitation

With Sine vibration, we are in the presence of an excitation that covers low frequencies up to about 100 Hz and the load profile is what we can see by way of example in [Figure 6.1.4.2.1].

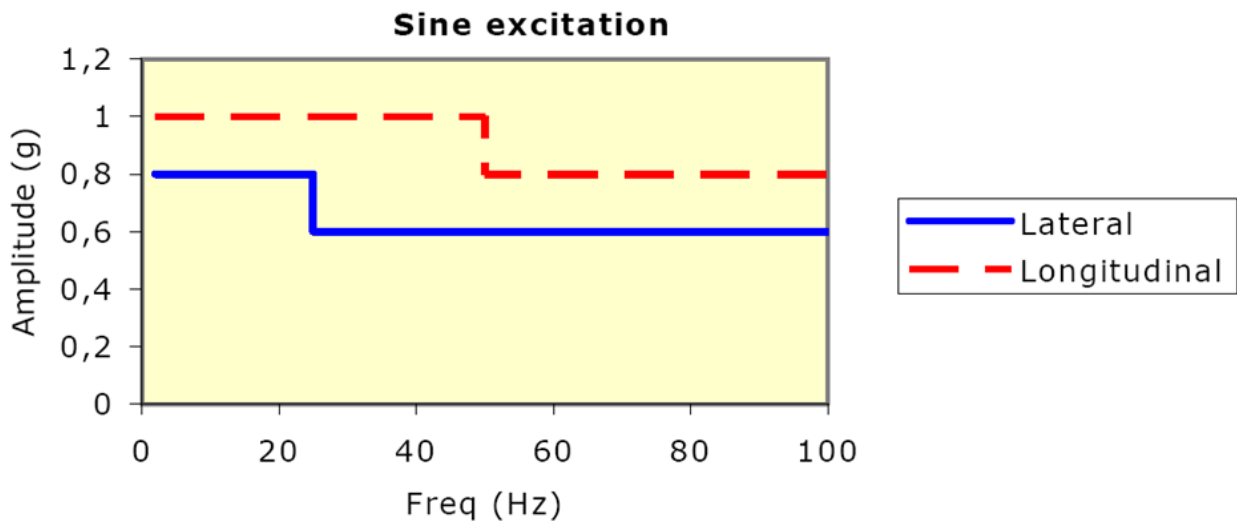


Figure 6.1.4.2.1: Sine excitation

In practice, this is a constant load over a certain frequency range.

This type of excitation is deterministic and is transmitted through and to interfaces. It is generally caused by the launcher engine vibrations.

In [Figure 6.1.4.2.2] and In [Figure 6.1.4.2.3] we can see some examples of sine loads provided by different types of launchers.

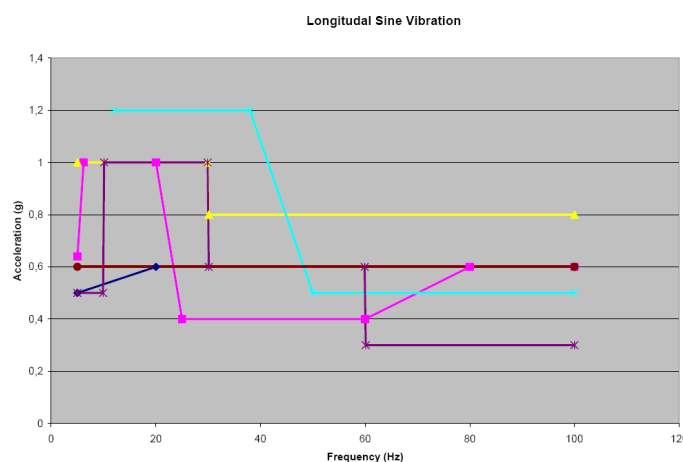


Figure 6.1.4.2.2: Sine loads examples

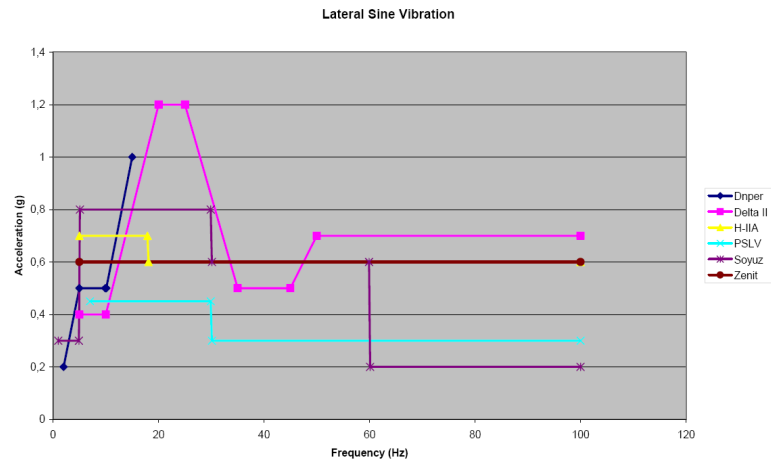


Figure 6.1.4.2.3: Sine loads examples

§ 6.1.4.3 Acoustic Loads

During the lift off and the early phases of the launch an extremely high level of acoustic noise surrounds the payload.

The principal sources of noise are:

- Engine functioning
- Aerodynamic turbulence

Acoustic noise (as pressure waves) impinging on light weight panel-like structures produce high response



Figure 6.1.4.3.1: Launcher lift off

§ 6.1.4.4 Random excitation

The acoustic load takes us directly to random excitation: the random input is based on the acoustic analyzes carried out on the dispenser.

Random vibration is a kind of vibration that can be described only in a statistical sense.

The instantaneous magnitude is not known at any given time: rather, the magnitude is expressed in terms of its statistical properties (such as mean value, standard deviation, and probability of exceeding a certain value).

Examples of random vibration include earthquake ground motion, wind pressure fluctuations on aircraft, and acoustic excitation due to rocket and jet engine noise.

Note: in structural dynamics of spacecraft, the random vibration analysis is often performed with simplified techniques (e.g. based on “Miles’ equation” + effective modal mass models)

These random excitations are usually described in terms of a power spectral density (PSD) function.

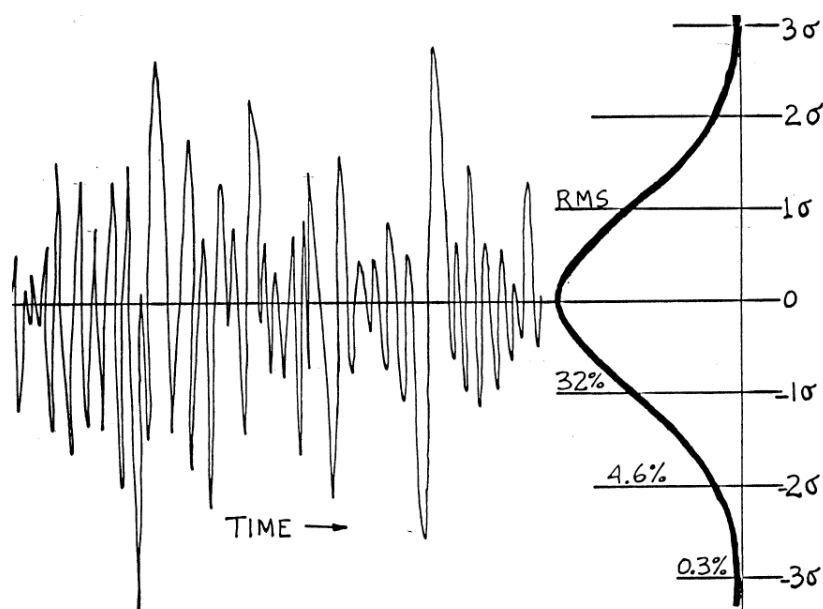


Figure 6.1.4.4.1: Random noise with normal amplitude distribution

The random signal over time [Figure 6.1.4.4.2] is, in fact, processed through the Power Spectral Density thus obtaining a curve expressed in terms of frequency like the one we see in [Figure 6.1.4.4.3]: these curves have a statistical value: they are created assuming a normal distribution of the spectrum vibration (Gaussian) and are given with standard deviation equal to 1. So we are statistically covering 68% of the peaks.

It is for this reason that when the checks are carried out with the random, the equivalent loads will be multiplied by 3 (to be conservative from this point of view and cover 99.75% of cases).

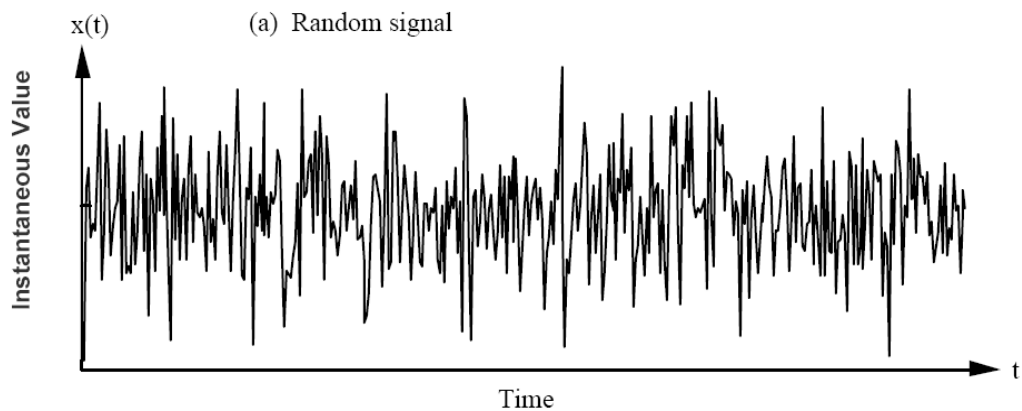


Figure 6.1.4.4.1: Random signal over time

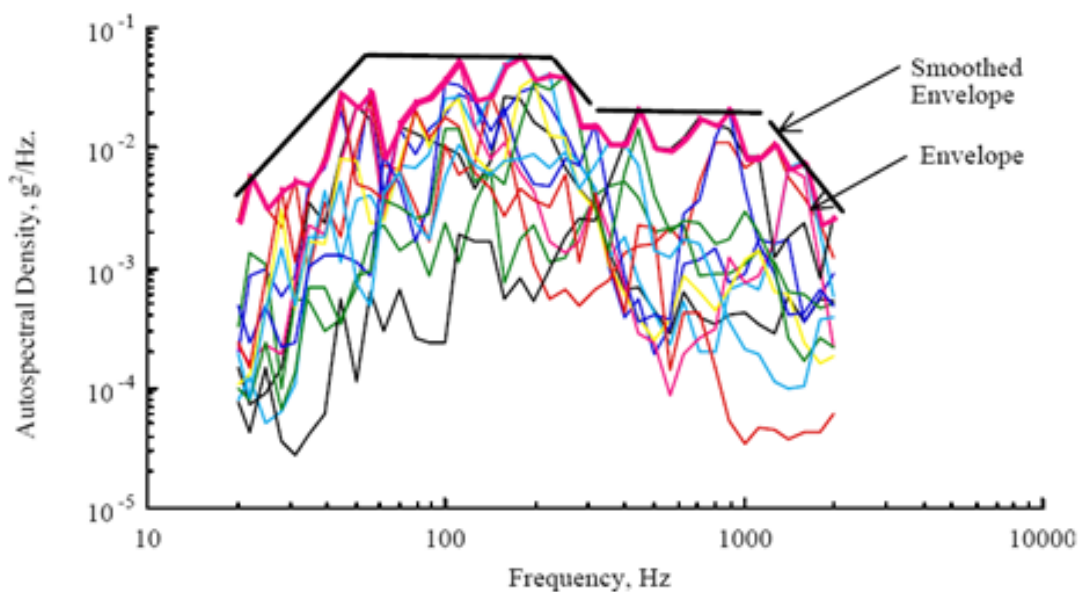


Figure 6.1.4.4.2: Random signal in terms of frequency

§ 6.1.4.5 Shock excitation

Finally, we have the shocks: in this case we are at very high frequencies and these are loads that develop in a very short period of time, a few hundredths of a second. The shocks can be caused by events such as the release of satellites or by the functioning of mechanisms for the deployment of solar panels on the satellite, so in general are mainly caused by the actuation of pyrotechnic devices.

This type of excitation is dimensioning for mechanisms and fragile materials (therefore not for our deployer).

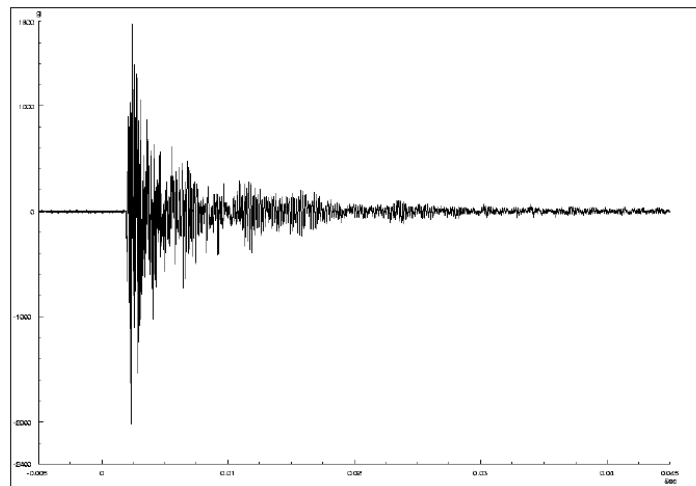


Figure 6.1.4.5.1: Shock signal over time

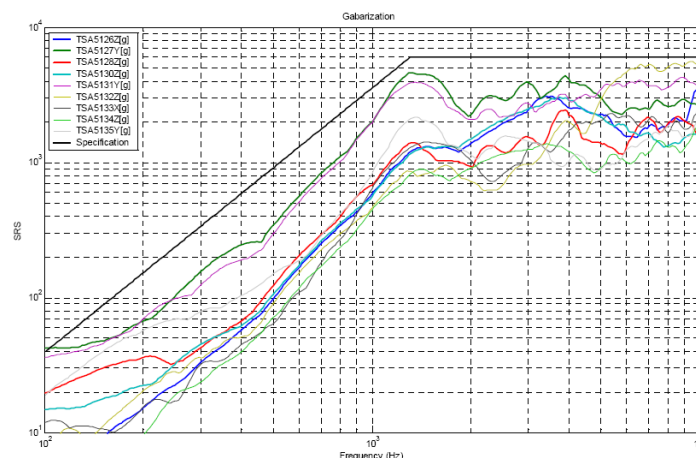


Figure 6.1.4.5.2: Shock in terms of frequency

§ 6.2 Preliminary design

To move from the concept to a preliminary design, a loop is created aimed at optimizing the design and iterative check in which occurs if it falls within the project specifications.

As showed in [Figure 6.2.1] we then start from the concept, make the fem model, verify the dynamics of the object, optimize the from the point of view of frequency and mass and repeat the process until a satisfactory design is reached and that falls within the dynamic requirements and stress.

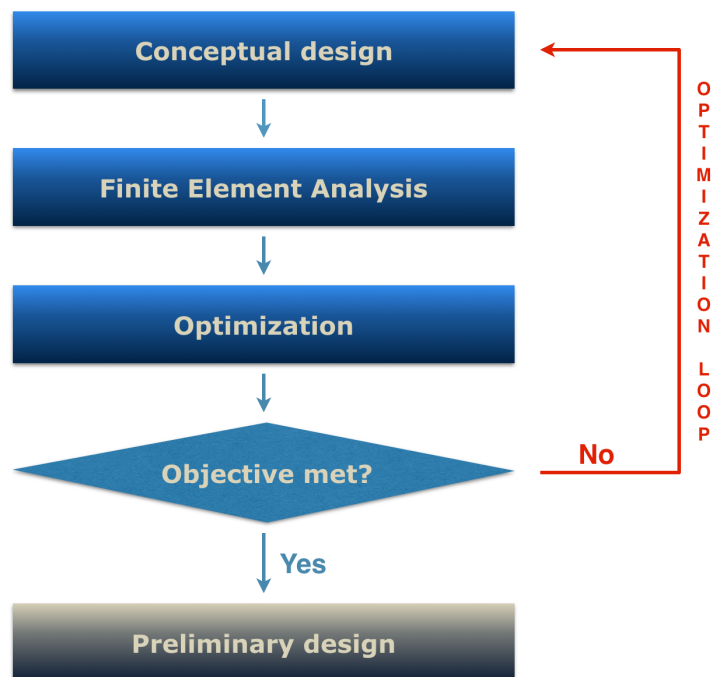


Figure 6.2.1: Iterative action for preliminary design

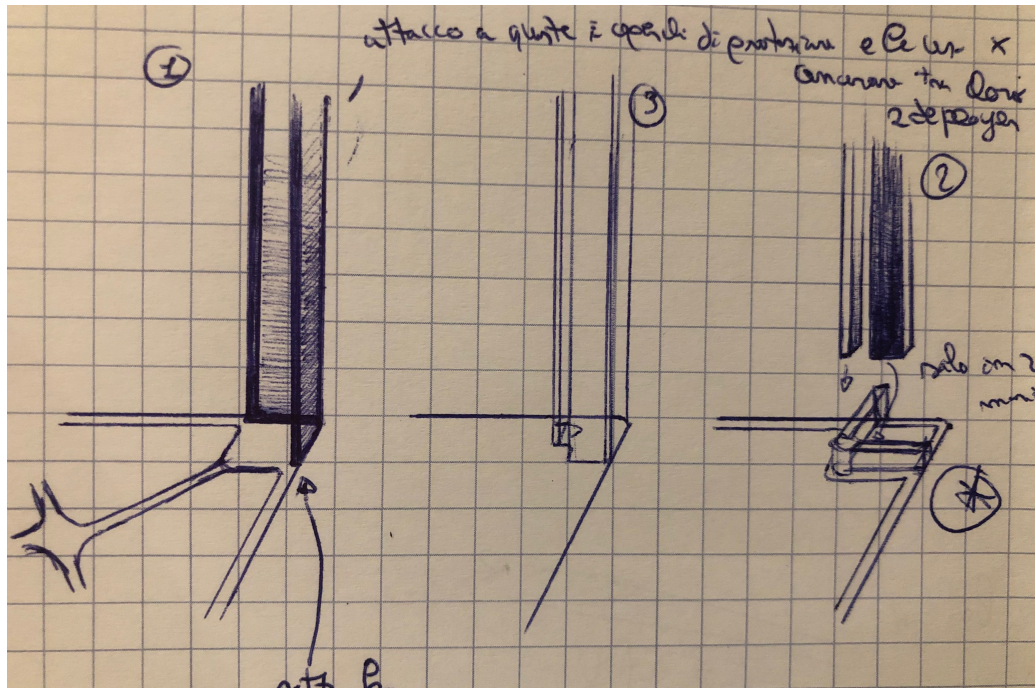


Figure 6.2.1.2 Sketches (b)

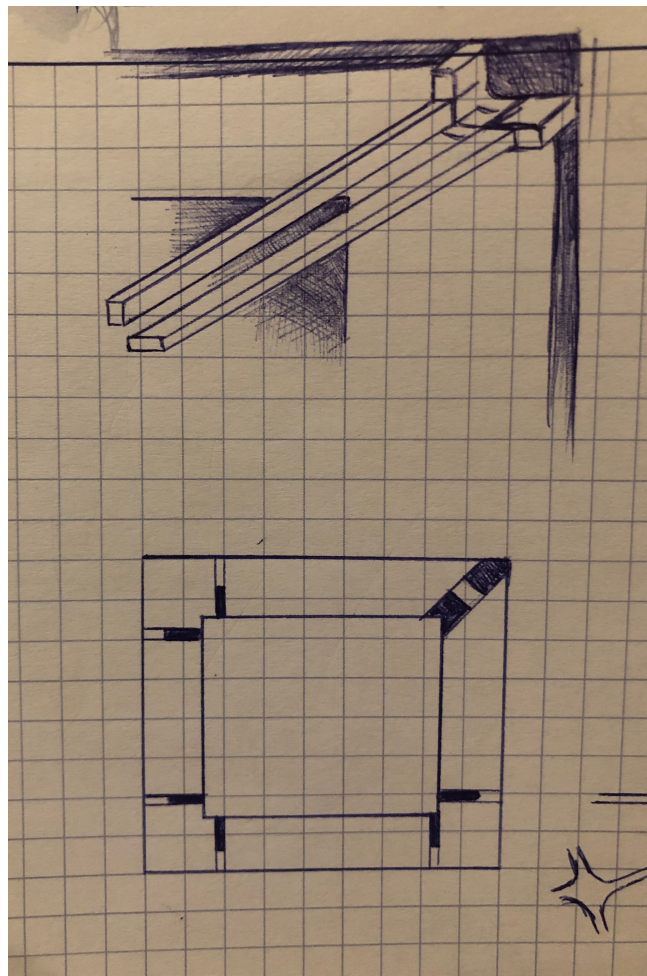
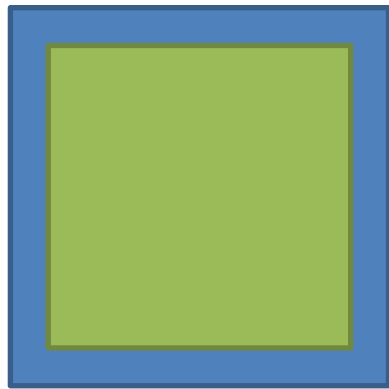
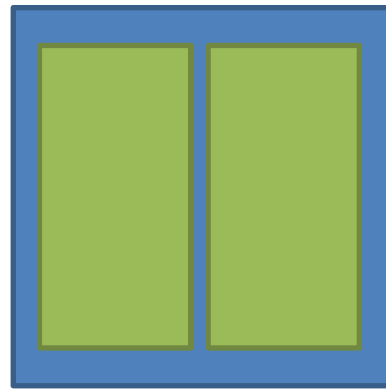


Figure 6.2.1.1: Sketches (c)

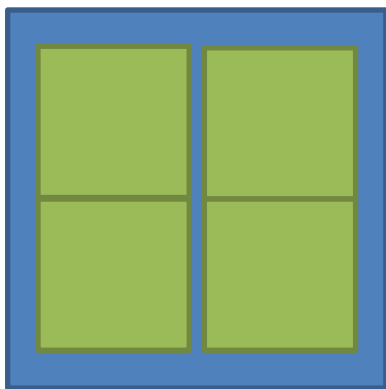
Looking for the right trade off between flexibility and cost minimization, we arrive at the conception of a more compact design. The result is shown in the [Figure 6.2.1.2].



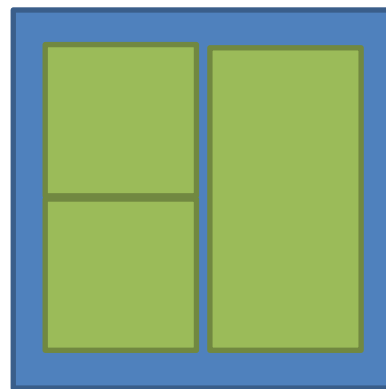
v.1: n°1 12U CubeSat



v.2: n°2 6U CubeSat



v.3: n°4 3U CubeSat



v.4: n°1 6U CubeSat + n°2 3U CubeSat

Figure 6.2.1.2: Core module configurations

As has already been said, the goal is to identify an architecture capable to provide modularity and flexibility in order to allow accommodation of different type of CubeSats (1U, 2U, 3U, 6U and 12U) plus guarantee the possibility for “last minute” aggregation.

According to that, a compromise is to develop a fully family of deployers (1U, 2U, 3U, 6U and 12U) where basic design is essentially common but only scaled to different dimensions.

Additionally, to cope, with SSMS HM features and limitations the following scheme is proposed:

One core module with 4 possible basic versions:

- n°1 12U CubeSat
- n°2 6U CubeSat
- n°4 3U CubeSat
- n°1 6U CubeSat + n°2 3U CubeSat

Note: there are 8 main interfaces between the core module and SSMS HM.

The core module is designed so that “slaves” (side modules) can be attached to it: in particular, we have provisions for lateral accommodation of 6U, 3U, 2U, 1U deployers, as showed in [Figure 6.2.1.3].

The side modules are designed to allow obtaining 4 versions foreseen:

- 6U [Figure 6.2.1.3, (a)]
- 3U [Figure 6.2.1.3, (b)]
- 2U [Figure 6.2.1.3, (c)]
- 1U [Figure 6.2.1.3, (c)]

Note : interfaces with Core module and (also) directly with SSMS HM.

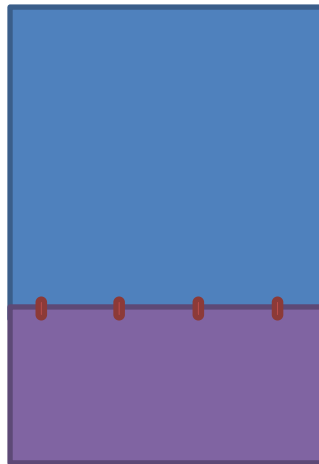


Figure 6.2.1.3: Slave modules configurations (a)

v.x.1: Core + n°1 6U Slave

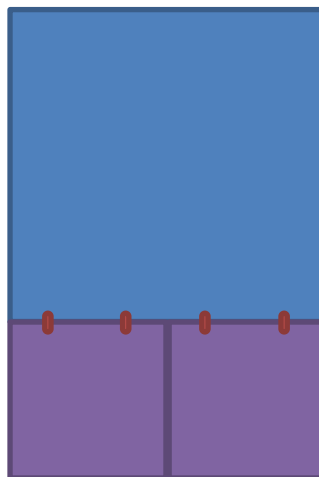


Figure 6.2.1.3: Slave modules configurations (b)

v.x.2: Core + n°2 3U (or 2U or 1U) Slave

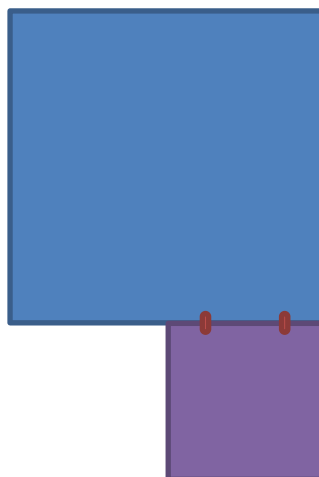


Figure 6.2.1.3: Slave modules configurations (c)

v.x.3: Core + n°1 3U (or 2U or 1U) Slave

§ 6.2.2 Looking for a new concept: Cad model

This study focuses on the development of the core module. A first Cad model was therefore conceived of this, which we find in the following figures.

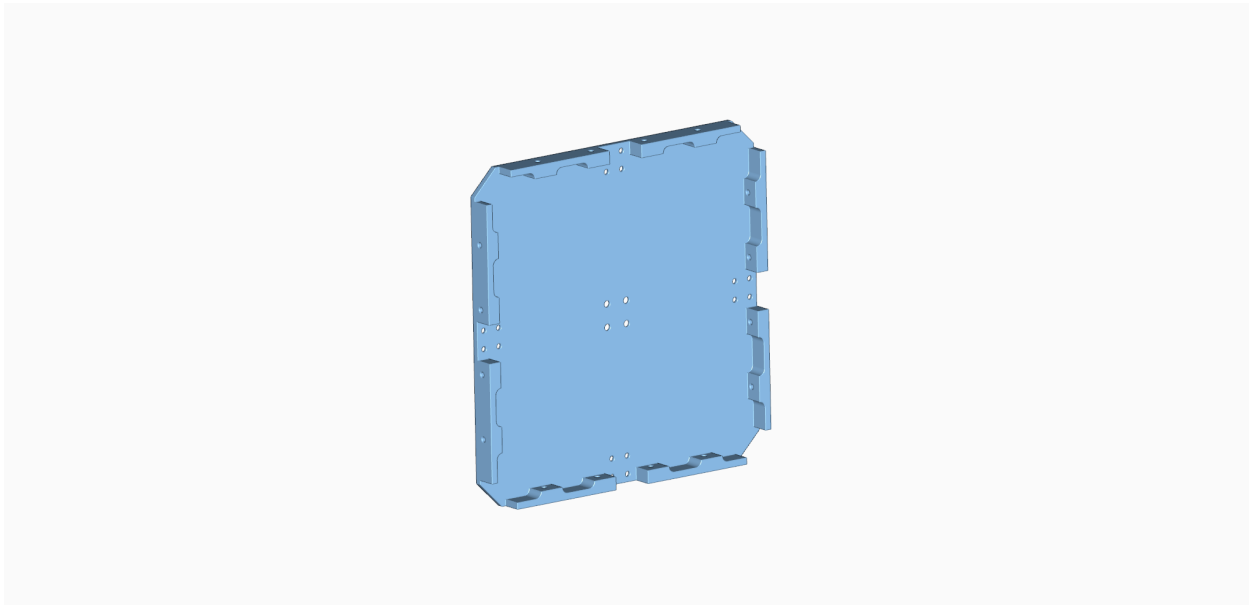


Figure 6.2.2.1: Core module. Base plate

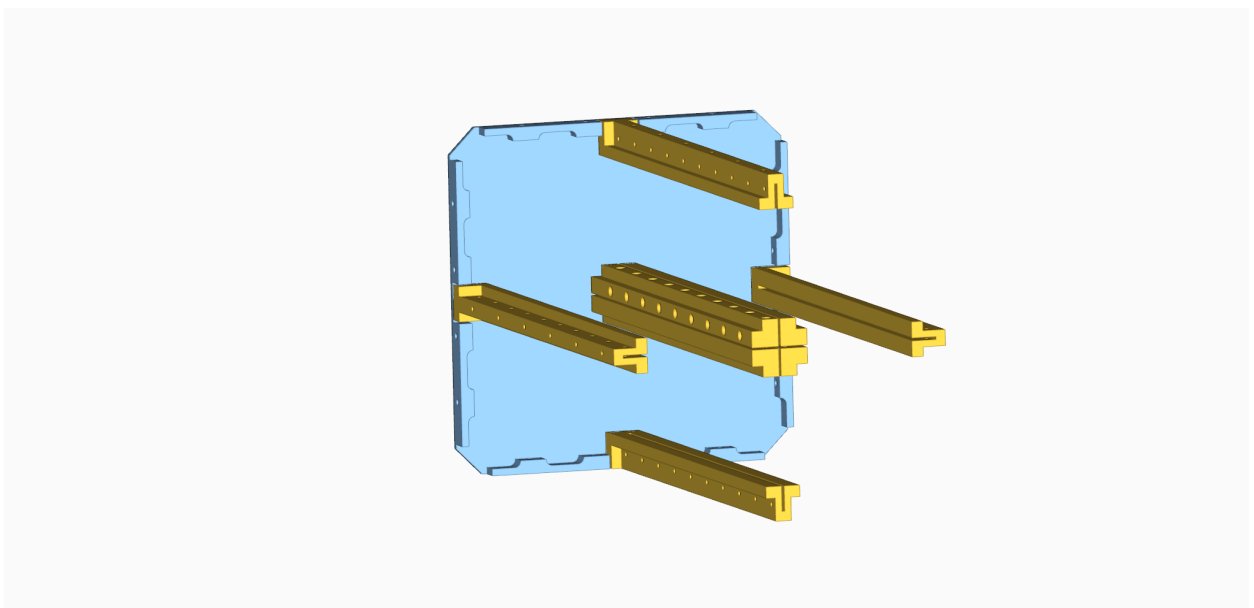


Figure 6.2.2.2: Core module. Base plate and rails

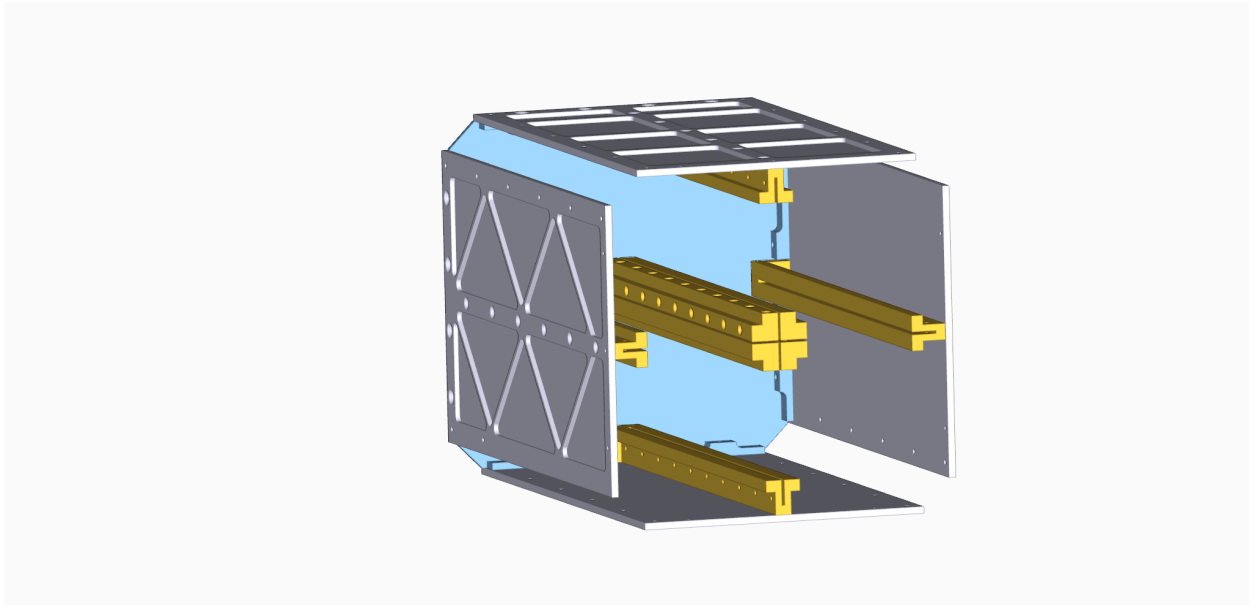


Figure 6.2.2.3: Core module. Base plate, rails and side plates

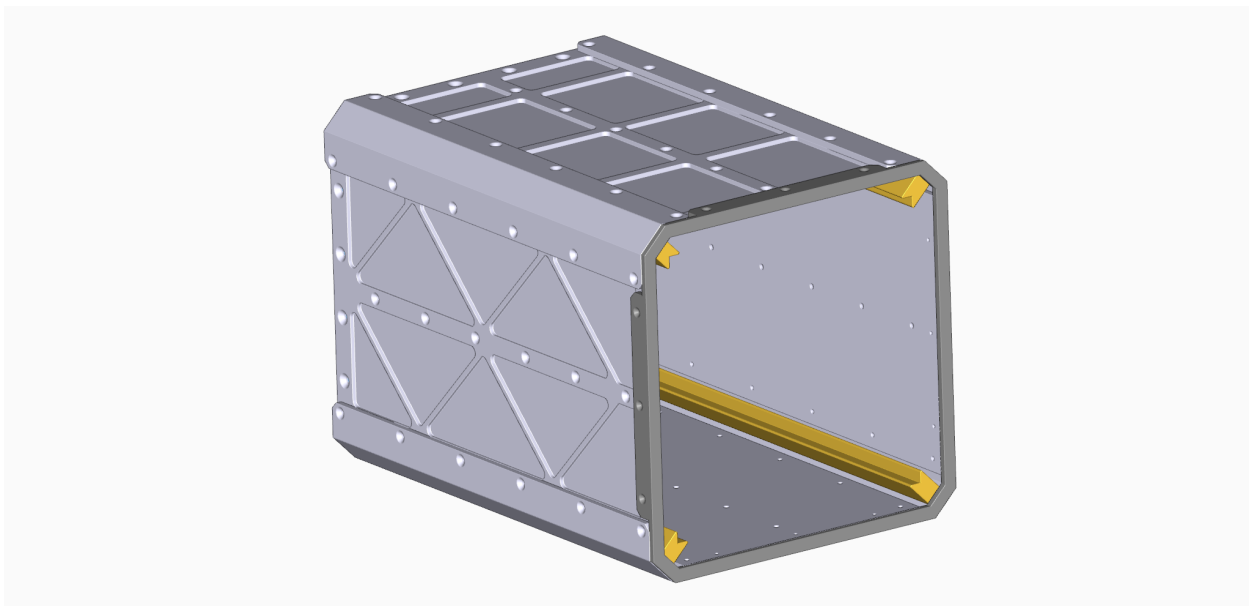


Figure 6.2.2.4: Core module configuration for 12U CubeSat

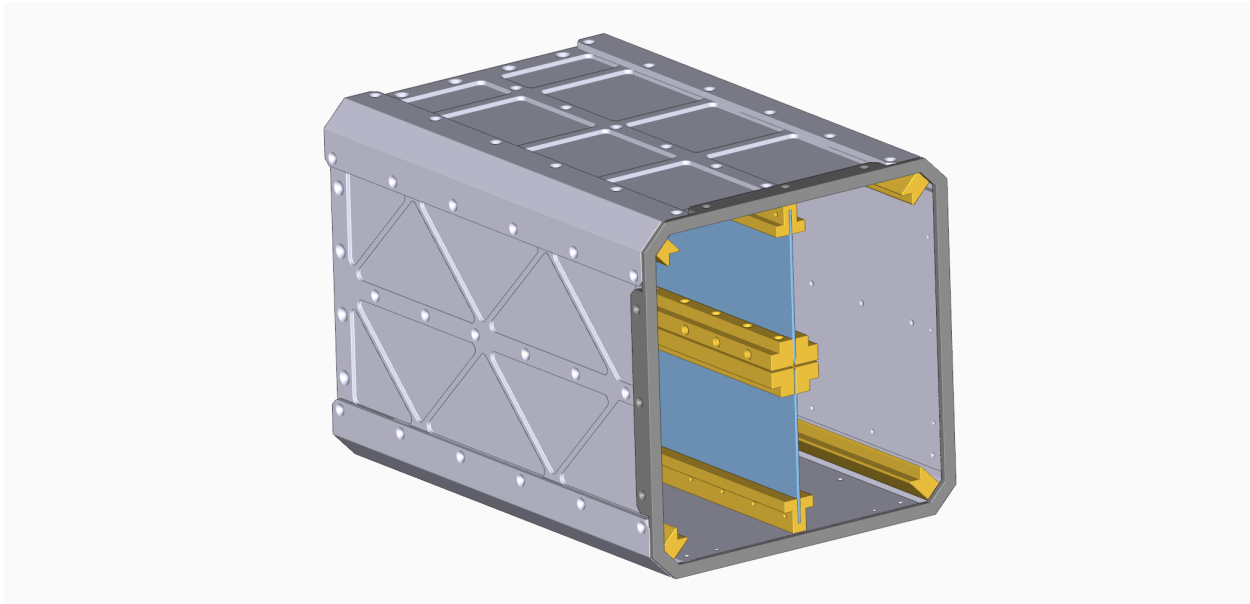


Figure 6.2.2.4: Core module configuration for 2 x 6U CubeSat

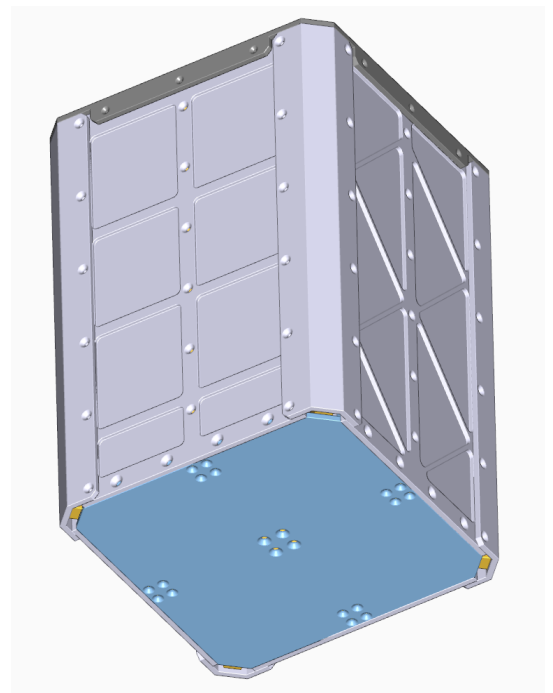
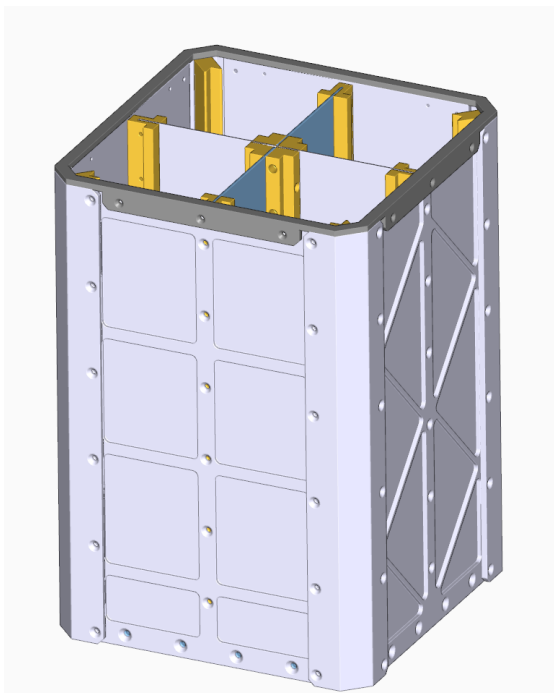


Figure 6.2.2.5: Core module configuration for 4 x 3U CubeSat

From the proposed depiction, we can see how the core module is made up of a base plate on which four central rails and four side rails are fixed, suitably removable according to the chosen configuration, see [Figure 6.2.2.2]. The rails have the function of allowing the CubeSat to go to the stop and therefore ensure the operation of the clamping rails. Beyond this, the central rails serve to fix the bulkheads that separate the CubeSats contained in the deployer, as showed in [Figure 6.2.2.4] and [Figure 6.2.2.5]. The peripheral rails instead also serve as a support for a better fixing the side faces of the deployer.

The four dynamic rails showed in [Figure 6.2.2.4] at this stage of the design are shaped only in their overall dimensions, because the mechanism will be studied in the subsequent phases of detail design. The dynamic rails are designed to always be present in any deployer configuration and are intended to ensure the immobility of the CubeSats contained in the deployer in the various phases (transport of the deployer, fixing the deployer to the SSMS HM).

Note how the side plates are shaped differently, in fact, of the four, two are designed for the installation of inspection windows, see the side plate in the foreground of the [Figure 6.2.2.5].

7. FE Model

The Cad model is converted into a fem model with the Hypermesh program.

Hypermesh interface is showed in [Figure 6.1.3.1].

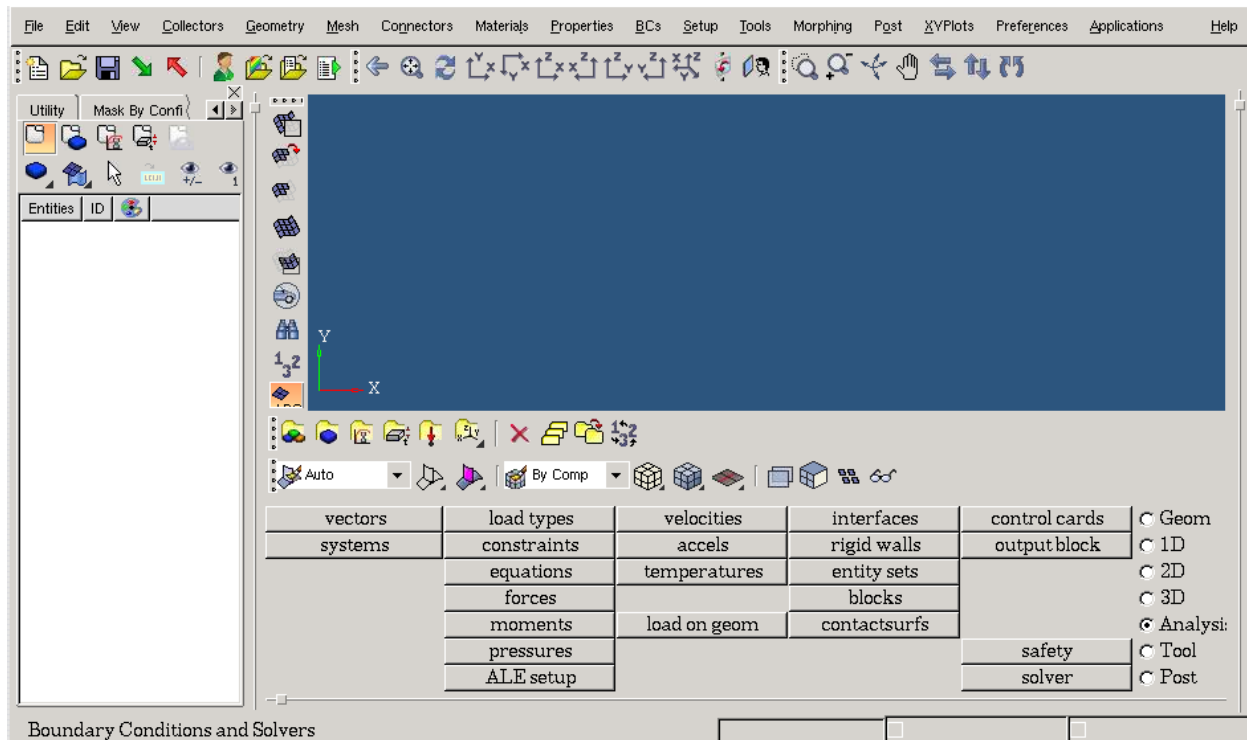


Figure 6.1.3.1: Hypermesh interface

The Cad model is converted into a fem model with the Hypermesh program: in creating meshes that give a plausible result, the principle of simplification of the geometry is followed. In particular, the elements are modeled as 1D 2D elements (remember that the elements have their own shape function that increases in complexity with the increase of the element nodes (I have one per corner) and the shape function of the element 3D has great limitations so I avoid 3D elements as much as possible (among other things, Nasco manages only 2D elements so to give the stiffness I still have to model a shell around them). Also in 2D meshes I try to create quadrilateral elements and avoid triangles, because the latter give unrealistic rigidity.

In the following images we find some examples of components and the assembly modeled with fem.

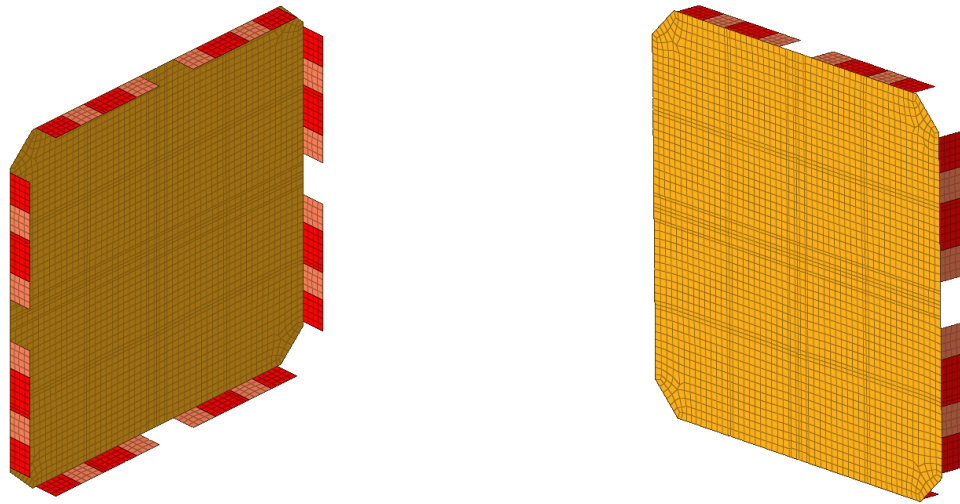


Figure 6.1.3.2: Base plate

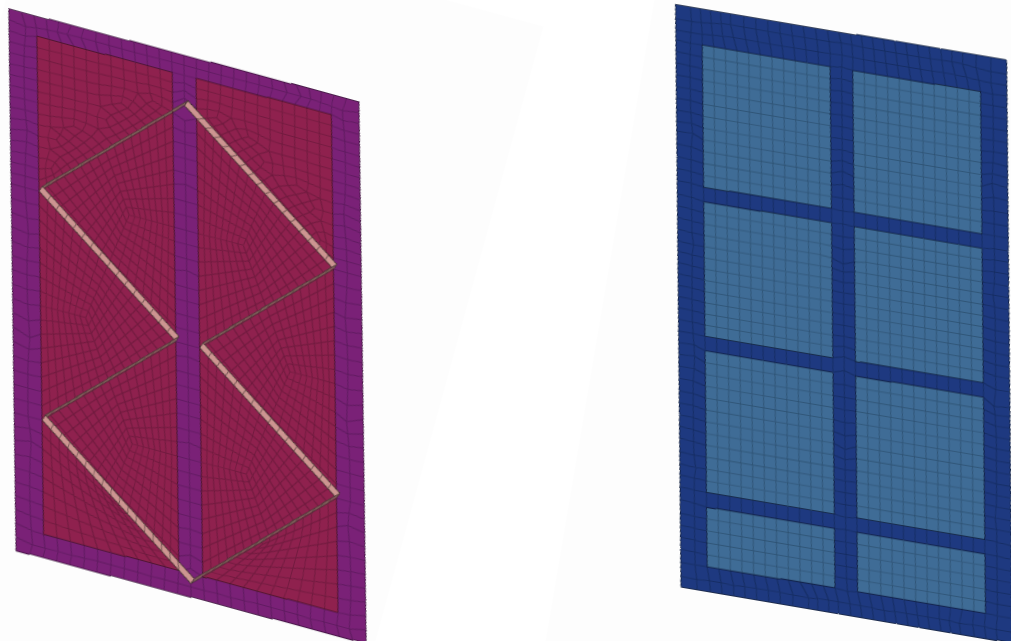


Figure 6.1.3.3: Side plates

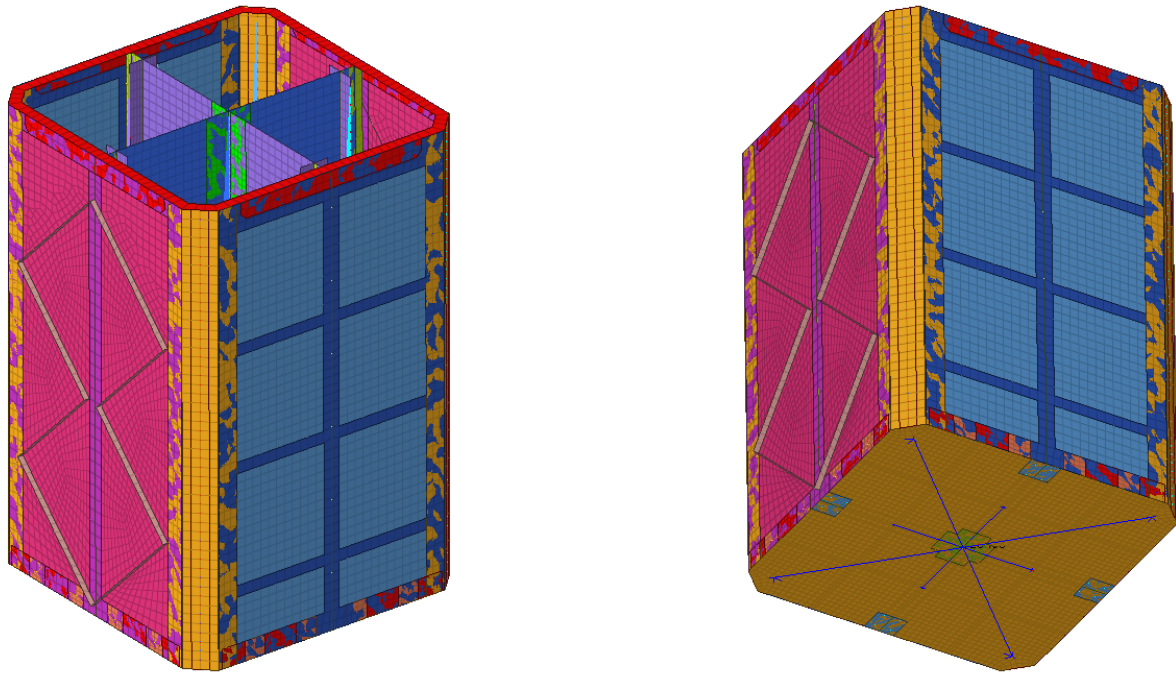


Figure 6.1.3.3: Assembly

The step file has been the starting point for the FEM model creation. The software used for this process has been Altair Hypermesh as per company standard. In order to represent the structural element by 2D elements (SHELL elements) and the connections (e.g. screws) by 1D elements (RBE2) simplifications of the geometry has been done. The strategy foreseen to represent the walls and rib of the deployer case with mid surface mesh. Thus surfaces have been preliminary created by means of the specific command in Hypermesh. Pshell elements have been then created on those mid surfaces avoiding the use of triangles and maximizing the quad elements. Particular care has been put by placing specific nodes where interface elements like screws were present. As mentioned before rbe2 have been used to represent such structural parts. To prevent from unrealistic moments, the modelling strategy foreseen 0length 1D element.

During the modelling, constant control on the element quality has been performed. Parameters like (Jacobians, warpage XYZ) have been checked for 2D elements while XYZ have been checked for 1D element.

The FEM model has been finalized by including thicknesses on the specific elements and material properties. No material density has been assigned while mass has been assigned as “non structural mass”.

§ 7.1 Model check

The FE Model created has been subjected to model checks before being used for the analyses. The performed checks were:

- Ug – one g check
- Ff – free free check

One g check

This check is performed by constraining in all 6 degree of freedom the nodes representing the external interfaces with the launcher structure and applying 1g in all three directions separately.

The analysis is performed by Nastran solver and the results as f06 (text file) and .op2 (animation) are then checked. The first check is the presence of the so called “fatal message” which indicates that the job has been interrupted before arriving to the end. One of the main reason is usually an uncorrect definition of the constraints or more in general a big difference in term of stiffness on adjacent elements. Once the job ends without fatal the check of the warning messages is performed to ensure that no issue has been identified during the run.

The first aspect to be checked is the “weight grid point generator” where the mass and the inertia of the system is extracted. In case the mass is not in line with the total one an issue

occured. After that it has to be checked the O load. First of all the table has to give results just on the nodes where constraints have been applied. This indicates that no free nodes are present and that the load is correctly applied on the model.

Last check consist in ensuring that the O load corresponds to the SPC load (they should have same value and opposite sign).

Free-Free check

This check is performed by running SOL 103 on the un-constrained model. The main purpose of this check is to review the strain energy. As prescribed by the ECSS the value for f-set, g-set and n-set shall be below $1e-3$. Failure on this is usually an indication on the quality of the mesh (e.g. unconnected nodes, duplicated elements and so on).

The free free check is also performed to check that the first 6 modes are “rigid-body modes”. If this is confirmed the first 6 modes are extracted at frequencies on the order of magnitude of $1e-2 / 1e-3$ Hz. In case that more than 6 rigid bodes modes are extracted it is possible that parts of the model are not well connected.

After all the checks are successfully passed, the modal analysis and the verification of the stiffness requirement is performed.

Once the checks have been carried out, we move on to modal analysis.

8. Modal Analysis

The modal analysis is performed to study the dynamic behavior of the structure and to verify the structure stiffness against the requirement.

The deployer is considered as an equipment and for such reason the requirement of 140Hz as first mode has been identified. Such an high value is chosen to prevent from coupling with launcher modes preventing from high amplification possible at lower frequencies.

The analysis is done running the NASTRAN SOL103.

The common checks described above in term of fatal and warning messages are done also in this case and in general for all the NASTRAN jobs performed.

The results from the analysis are checked from the f06 file (text files) and .op2. The op2 file is managed by the tool for post processing ALTAIR Hyperview which allows to look at the deformed shapes showed as animation.

The animations are useful to understand the shapes of each modes and the area where the structure is stiff or not. In order to deeply investigate the dynamic behavior the data from the f06 file has to be post processed. In this case it is important to extract the matrix reporting the frequencies and the associated mass for each direction. By the creation of a simple excel table it is possible to calculate the percentage of mass associated to each mode in each direction. Of course in each column the total mass shall be 100%.

The stiffness requirement is verified for those mode with mass associated above 5%. The other can be considered local modes not relevant at system level.

It is important also to distinguish between lateral and longitudinal modes. Usually requirements are different in the two directions and most of the times the requirement for longitudinal stiffness is higher than the lateral one.

[Table 8.1] reports the results:

Mode	Cycles	kg			kgm ²		
No.		mx	my	mz	Ixx	Iyy	Izz
1	9.53E+01	2.41E+01	3.75E-04	5.28E+00	4.60E-03	1.36E-01	2.20E-02
2	9.55E+01	5.28E+00	2.82E-03	2.41E+01	2.10E-02	5.25E-01	3.61E-03
3	2.27E+02	1.87E-05	3.70E+01	2.96E-03	1.04E-03	6.49E-05	8.31E-01
4	5.00E+02	3.84E-05	2.08E-07	1.77E-07	2.49E-08	5.83E-02	5.11E-08
5	5.33E+02	6.69E-03	1.28E-07	5.74E-09	4.19E-10	2.38E-07	8.69E-04
6	5.39E+02	2.62E-09	5.55E-05	6.43E-03	6.52E-04	1.72E-04	1.28E-06
7	5.54E+02	2.15E-07	3.73E-04	3.17E-06	3.05E-09	8.89E-08	9.43E-06
8	6.63E+02	1.82E-07	9.52E-09	8.45E-09	1.67E-10	7.03E-03	3.03E-07
9	6.68E+02	1.12E-04	4.79E-09	1.08E-09	1.60E-11	1.21E-05	1.85E-07
10	6.78E+02	8.35E-02	3.58E-11	1.25E-10	3.96E-12	3.86E-04	6.67E-03

Table 8.1: First 10 modes of deployer

In particular, first 3 modes are:

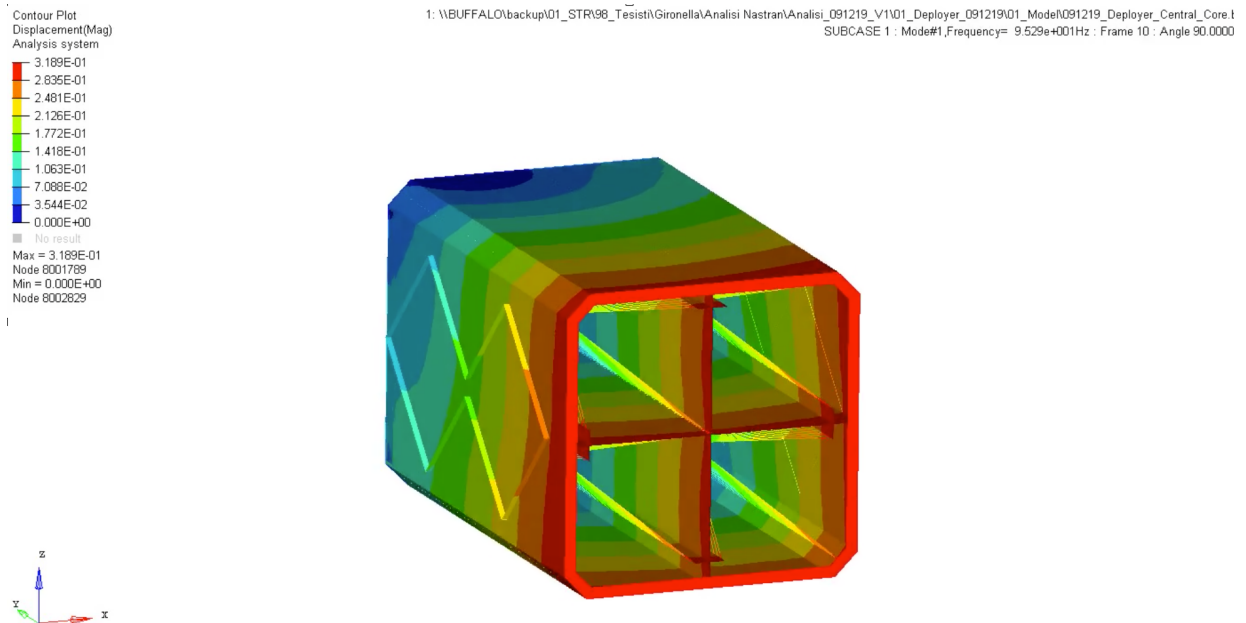
Mode	Frequency [Hz]	Characterization	kg	Effective Mass
1	95.29	1st global mode in X direction (lateral)	24.15	64,5%
2	95.51	1st global mode in Z direction (lateral)	24.14	64,5%
7	227.11	1st global mode in Y direction (axial)	37.00	98,8%

Table 8.2: First 3 modes of deployer, with directions of acceleration

As it can be seen the first lateral mode is at 95,29 Hz while the first axial one is at 227,11 Hz: the frequencies check has not passed! The structure has its first mode just below 140Hz.

8. MODAL ANALYSIS

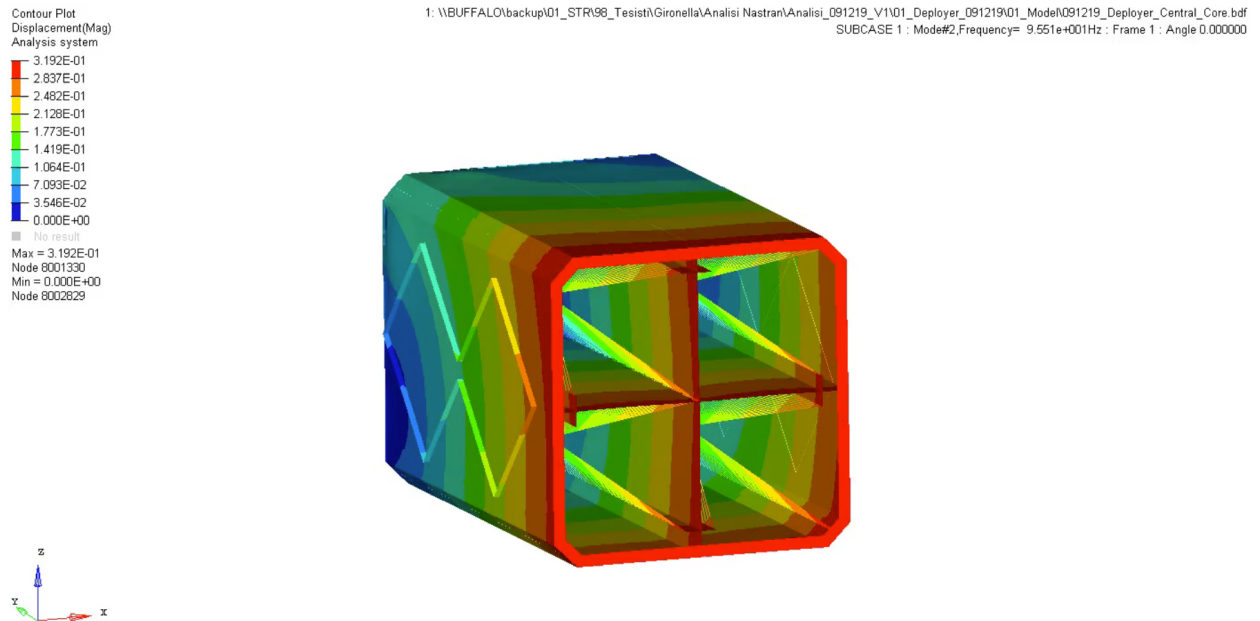
In particular, in the following images we see the eigenfrequency analysis visually translated in Hyperview, for each of the first three modes. Of these the program provides an animation that allows a more accurate understanding of the quality of the structure's own modes.



Mode	Frequency [Hz]	Characterization	kg
1	95.29	1st global mode in X direction (lateral)	24.15

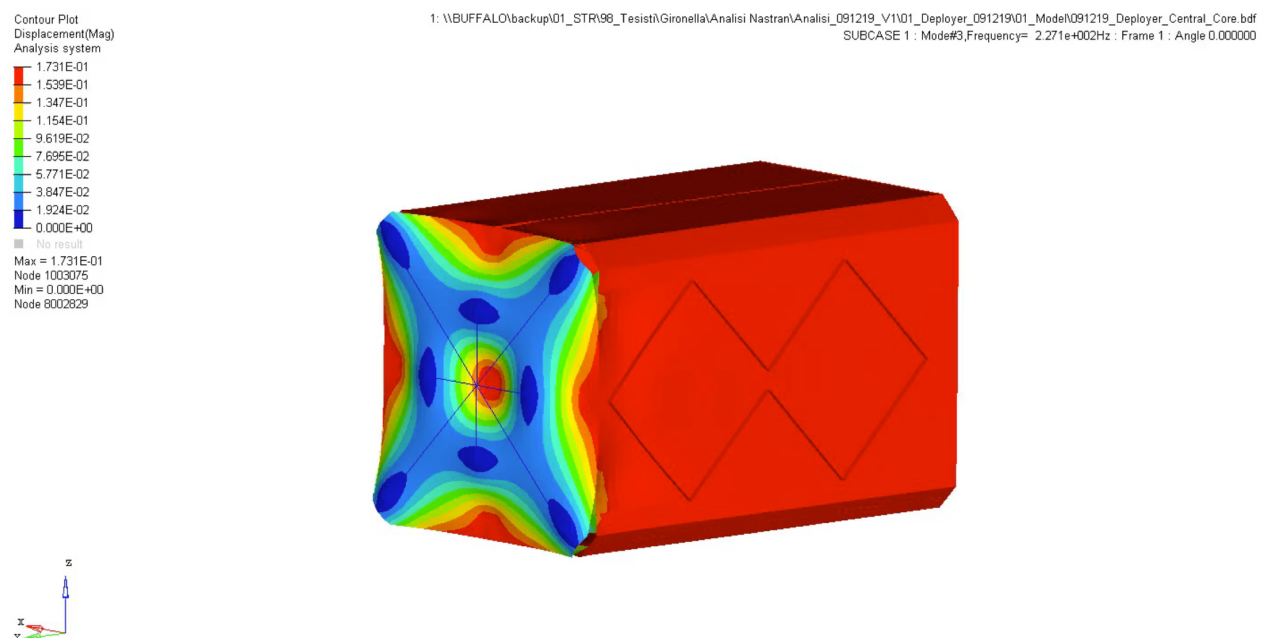
Figure 8.1: First global mode in X direction

8. MODAL ANALYSIS



Mode	Frequency [Hz]	Characterization	kg
2	95.51	1st global mode in Z direction (lateral)	24.14

Figure 8.2: First global mode in Z direction



Mode	Frequency [Hz]	Characterization	kg
3	227.11	1st global mode in Y direction (axial)	37.00

Figure 8.3: First global mode in Y direction

§ 8.1 Stiffness optimization

Having verified that the frequency associated with the first mode of the structure is below 140 Hz, we need to make changes in order to increase the stiffness of the deployer.

In order to increase the frequency of the first way, we operate a series of actions concerning:

- I. the refinement of the fem model (for example, some elements of the base are modeled in solid, spiders are placed around the interfaces etc. etc.);
- II. design changes: we modify the structure of the deployer going for example to put ribs (thickenings) on the base plate to give greater stiffness.

In particular, the following modifications are carried out:

- Ribs on base plate
- Solid modeling of the interface areas between base plate and dispenser
- Spider at the interfaces between baseplate and side plates
- Four screws (1 per corner) to create interface between base plate and corner brackets
- Solid modeling of the base plate thicknesses in the base plate - side plates interface areas
- Side plates modeled in solid
- Spider on base plate - corner brackets interfaces

Once these changes are made, a new modal analysis is performed on the new model. This time the results are satisfactory: the first way is about 194, well above 140, as showed in [Table 8.1.1].

Note: We keep the frequency higher than 140 Hz anyway to avoid any problems with the detailed design (we are still in the concept phase). In addition, large margins are desired because it is planned to attach the slave module in later design stages.

Mode	Frequency [Hz]	Characterization	kg	Effective Mass
1	194,34	1st global mode in X direction (lateral)	26,55	70,6%
2	195,48	1st global mode in Z direction (lateral)	26,55	70,6%
7	407,46	1st global mode in Y direction (axial)	36,59	97,3%

Table 8.1.1: First 3 modes of deployer optimized

9. Stress check

§ 9.1 Quasi static loads check

We can then calculate the stresses due to quasi-static loads.

I look at the specification document that the bus (satellite, adapter, etc. - SSMS for us) has provided for launches with Vega.

The Vega launcher indicates that the SSMS door where the deployer is located must be sized with the loads shown in the [Figure 9.1.1]:

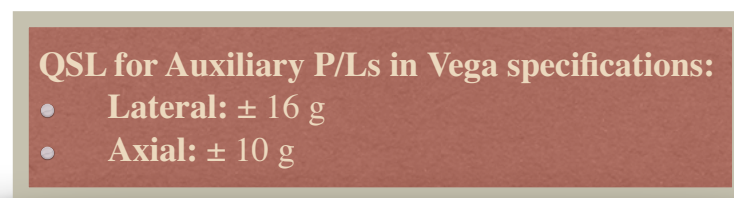


Figure 9.1.1: Vega specification loads

Remember that in our case "lateral" corresponds to the X and Z directions, while "axial" coincides with the Y direction.

The limit loads indicated by Vega must then be multiplied in the design phase by:

- **KQ** (qualification factor) equal to 1.25. Multiplying only by the KQ factor we obtain the qualification loads, that is the loads that the deployer will actually undergo during the qualification phase (for example when it is tested on the shaker);
- **KM** (model factor) equal to 1.2. Multiplying by this factor too, I take into account the various simplifications I make in the modeling phase. I get the DESIGN LOADS (the ones you need in our case).

Consequently, by multiplying the limit loads 10 g and 15 g by the appropriate factors, we obtain the design loads 15 g lateral and 24 g axial. With these two values we make the

possible load cases: we prepare a table on Excel in which we report the possible load combinations, as shown in [Table 9.1.1], (A)

These are obtained by considering axial loads and lateral loads separately.

Of the lateral loads, in particular, we consider all the cases in which these are applied with an angle that varies between 0 and 90 degrees (with steps of 5 degrees).

	Assiale	Laterale-1	Laterale-2	α
Casi carico solo assiale	carico assiale positivo: +15	0	0	
	carico assiale negativo: -15	0	0	
Casi carico solo laterale	0	0,00	24,00	0
	0	2,09	23,91	5
	0	4,17	23,64	10
	0	6,21	23,18	15
	0	8,21	22,55	20
	0	10,14	21,75	25
	0	12,00	20,78	30
	0	13,77	19,66	35
	0	15,43	18,39	40
	0	16,97	16,97	45
	0	18,39	15,43	50
	0	19,66	13,77	55
	0	20,78	12,00	60
	0	21,75	10,14	65
	0	22,55	8,21	70
	0	23,18	6,21	75
	0	23,64	4,17	80

	0	23,91	2,09	85
	0	24,00	0,00	90

Table 9.1.1: Load cases

The specification manual indicates that when there is a lateral static load we must not combine it with the axial. In fact, a sufficient margin is already applied to the lateral load to cover the axial too: margins on the loads have already been applied by Vega to take into account these cross contributions between lateral and axial.

At this point the next step is to perform an analysis with Nastran to calculate stresses and deformations with the nominal load values **(B)**, that is the cases in which I have:

- 1 g in the X direction and 0 g in the other directions;
- 1 g in the Y direction and 0 g elsewhere;
- 1 g in the Z direction and 0 elsewhere

At this point I will give input to the NASCO program:

- the load cases that we have built in Excel **(A)**, after having written them in an appropriate .dat
- the .punch created by Nastran with the strength (stress) analysis made with nominal loads (1 g) **(B)**

In output NASCO provides a .csv file where we can see the stress in all parts of the structure.

By comparing the stresses obtained with the yield strength associated with the chosen material [Table 9.1.2], the MoS (margin of safety) are calculated.

The results are shown in the [Table 9.1.3].

Alluminium 6082 - T651	σ_{Ultimate} [MPa]	σ_{Yield} [MPa]
	310	260

Table 9.1.2: Material mechanical characteristics

Component	σ_{max} [MPa]	MoS_y
01_01_01_BASE_PLATE	83,635	1,826
01_01_02_BASE_PLATE_LATERAL	33,605	6,034
01_01_03_BASE_PLATE_LATERAL	91,308	1,589
01_01_05_BASE_PLATE	84,653	1,792
01_01_06_RIBS	66,458	2,557
01_02_01_CENTRAL_RAIL	1,605	146,310
01_02_02_CENTRAL_RAIL(BASE)	3,237	72,028
01_03_01_SIDE_PLATE_1	42,296	4,588
01_03_02_SIDE_PLATE_1	0,978	240,783
01_04_01_SIDE_PLATE_2	41,297	4,724
01_04_02_SIDE_PLATE_2	33,049	6,152
01_04_03_SIDE_PLATE_2	7,548	30,316
01_05_CORNER_BRACKETS	71,427	2,309
01_06_01_PERIMETRIC_RAIL	6,506	35,330
01_06_02_PERIMETRIC_RAIL	9,864	22,962
01_06_03_PERIMETRIC_RAIL	17,057	12,857
01_07_01_SEPARATOR_1/2	1,669	140,634
01_08_01_SEPARATOR_HORIZONTAL	1,431	164,213
01_09_01_CORNER_UPPER	2,726	85,716

Table 9.1.3: Stress and MoS

The following images are the representation of the stress state on the structure made with Hyperview:

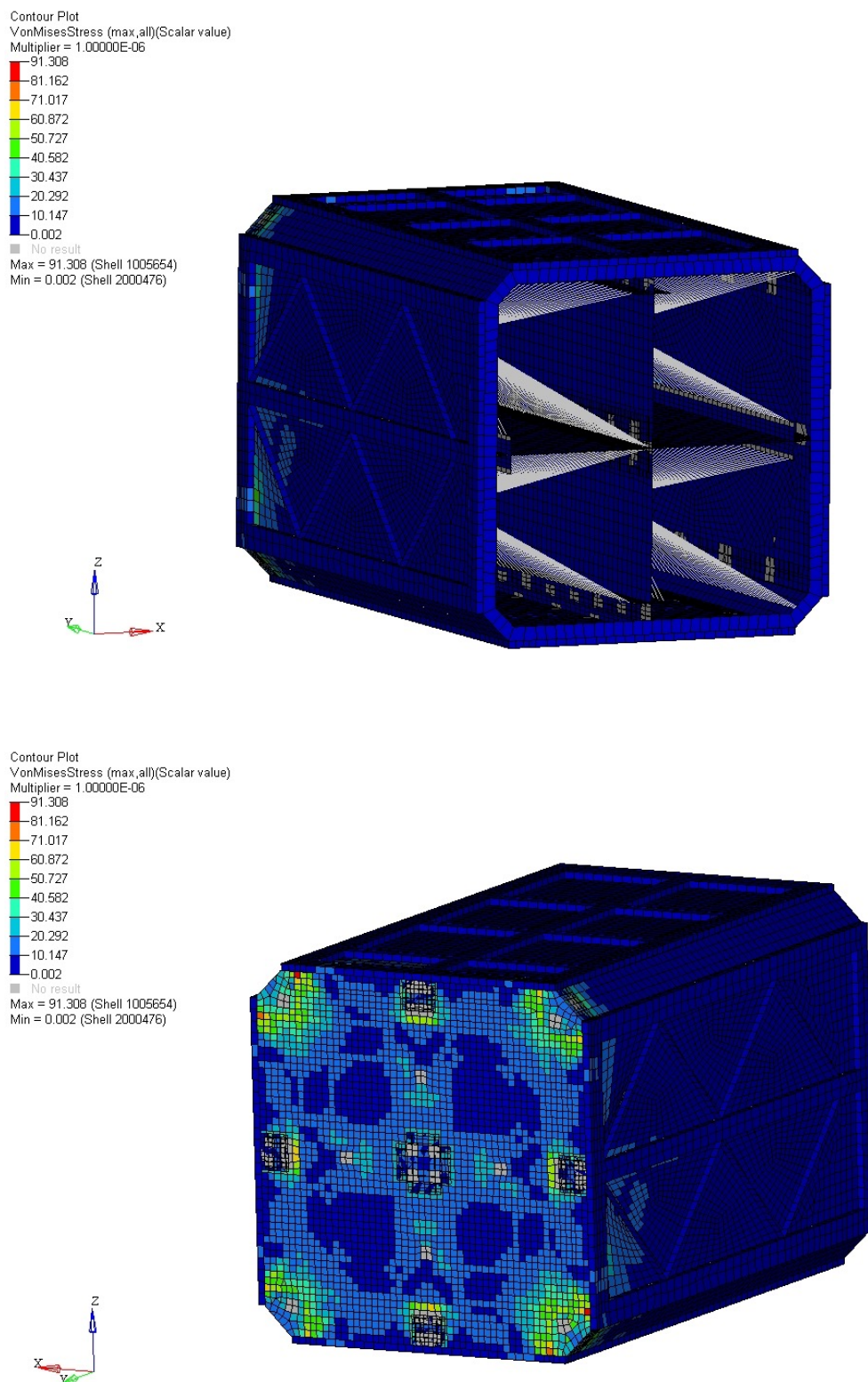
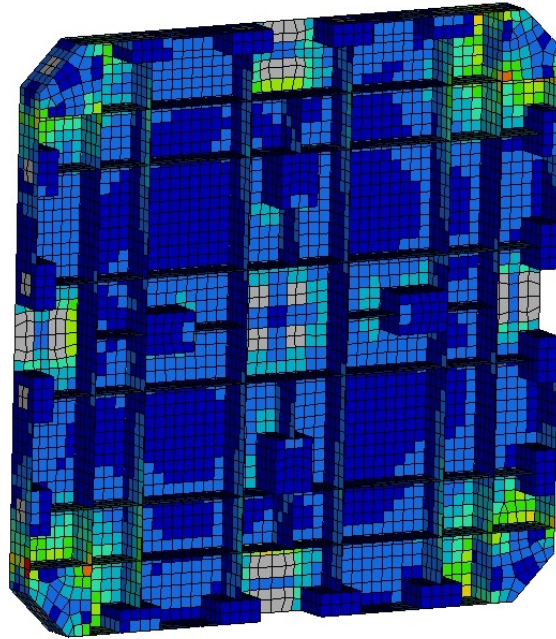
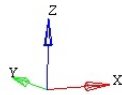


Figure 9.1.2: Stress on assembly

Contour Plot
 VonMisesStress (max,all)(Scalar value)
 Multiplier = 1.00000E-06
 -91.308
 -81.162
 -71.017
 -60.872
 -50.727
 -40.582
 -30.437
 -20.292
 -10.147
 -0.002
 No result
 Max = 91.308 (Shell 1005654)
 Min = 0.002 (Shell 2000476)



Contour Plot
 VonMisesStress (max,all)(Scalar value)
 Multiplier = 1.00000E-06
 -91.308
 -81.162
 -71.017
 -60.872
 -50.727
 -40.582
 -30.437
 -20.292
 -10.147
 -0.002
 No result
 Max = 91.308 (Shell 1005654)
 Min = 0.002 (Shell 2000476)

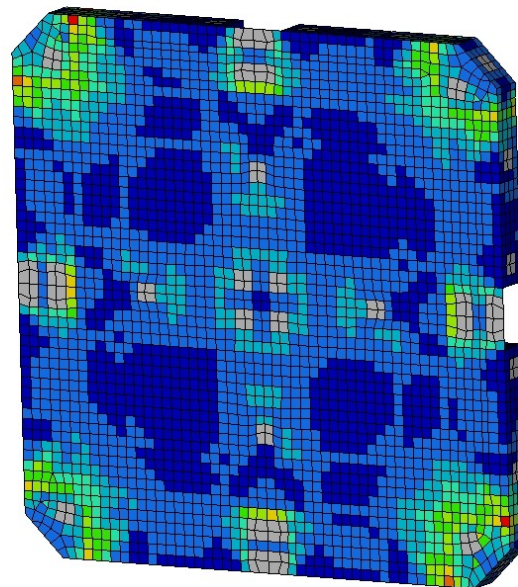


Figure 9.1.2: Detail of stress on assembly

10. Mass Optimization

Observing the values of [Table 9.1.3] we note that the Margin of Safty are all positive, and indeed far above zero.

We can then proceed with a deployer mass optimization loop. In fact, it should be remembered that one of the design goals is to reduce costs and therefore the weight of the deployer. In aerospace, it is estimated that every kg launched from Earth costs 25,000 Euros!

We make a series of changes aimed at lowering the weight of the deployer: mainly we reduce the thickness of the components which, from the stress analysis, have large safety margins.

Changes are always made starting from the initial deployer version, in order to evaluate which changes are more convenient: we will prefer those changes that involve a large decrease in mass compared to a small decrease in frequency of the first mode.

We get 22 different versions of mass-optimized deployer: of each version I know the mass delta (the mass reduction obtained thanks to the modification) and the frequency of the first mode, as shown in [Table 10.1].

Modification step	First Mode [Hz]	mass [kg]	Δ mass [kg]
M1	179.010	37,405	0,211
M2	159.770	37,277	0,339
M3	194.967	37,36	0,256
M4	195.132	37,356	0,26
M5	185.525	36,947	0,669
M6	180.198	37,031	0,585
M7	195.268	37,446	0,17
M8	193.677	37,239	0,377
M9	194.006	37,445	0,171

Modification step	First Mode [Hz]	mass [kg]	Δ mass [kg]
M10	194.016	37,402	0,214
M11	192.895	37,049	0,567
M12	193.484	37,242	0,374
M13	181.836	36,814	0,802
M14	195.342	37,378	0,238
M15	191.883	37,578	0,038
M16	198.403	36,154	1,462
M17	199.727	35,667	1,949
M18	194.265	37,596	0,02
M19	194.211	37,592	0,024
M20	194.226	37,603	0,013
M21	193.629	37,083	0,533
M22	192.490	37,026	0,59

Table 10.1: Modification to optimize mass

Evaluating the most effective changes I combine them together to obtain new versions of the deployer, as reported in [Table 10.2].

Combined Action	First Mode [Hz]	mass [kg]	Δ mass [kg]
M23	195,022	32,777	4,839
M24	173,486	31,523	6,093
M25	186,113	32,108	5,508
M26	181,853	32,191	5,425
M27	163,22	31,353	6,263

Table 10.2: Combined action to optimize mass

I choose the combination of actions corresponding to the M24 version of the deployer, corresponding to the combination of the changes made in the versions:

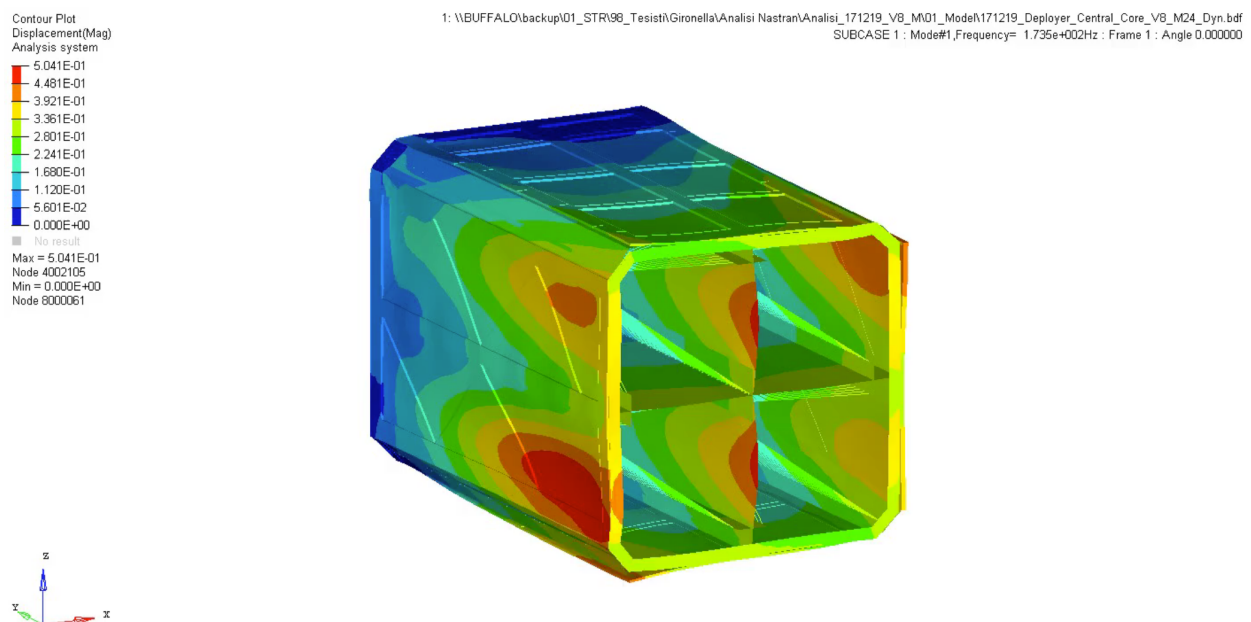
- M3: thickness of 1/2 Separating Plate is reduced from 2 mm to 1 mm
- M4: thickness of Horizontal Separating plate is reduced from 2 mm to 1 mm
- M5: thickness of Side plate 1 and of the Side Plate 2 is reduced from 2 mm to 1 mm
- M6: thickness of Corner Brackets is reduced from 5 mm to 3 mm
- M11: 5 mm thick parts of Side Plate 1 are reduced to 2 mm
- M12: 5 mm thick parts of Side Plate 2 are reduced to 2 mm
- M14: thickness of the Upper Corner is reduced from 5 mm to 0.8 mm
- M15: 1 mm thick parts of the Base Plate are thinned to 0.8 mm
- M17: thickness of Central Rail vertical walls is reduced from 25 mm to 5 mm
- M18: thickness of Central Rail base is reduced from 7.5 mm to 3 mm
- M20: thickness of Perimetric Rail base is reduced from 5 mm to 3 mm
- M21: thickness of Perimetric Rail vertical walls (contact walls with the CubeSat) is reduced from 8,5 mm to 4 mm
- M22: thickness of Perimetric Rail vertical walls (interface walls with Separating Plates) is reduced from 8,5 mm to 4 mm

Thanks to the choices made, we have reduced the total mass of the deployer by 6.09 kg, keeping the frequency of the first mode of the structure well above 140 Hz. In [Table 10.3] we find the first three modes of the structure.

Mode	Frequency [Hz]	Characterization	kg	Effective Mass
1	173,487	1st global mode in X direction (lateral)	24,19	64,8%
2	174,232	1st global mode in Z direction (lateral)	24,28	65,0%
11	357,46	1st global mode in Y direction (axial)	357,46	81,5%

Table 10.3: First three modes of deployer optimized in mass

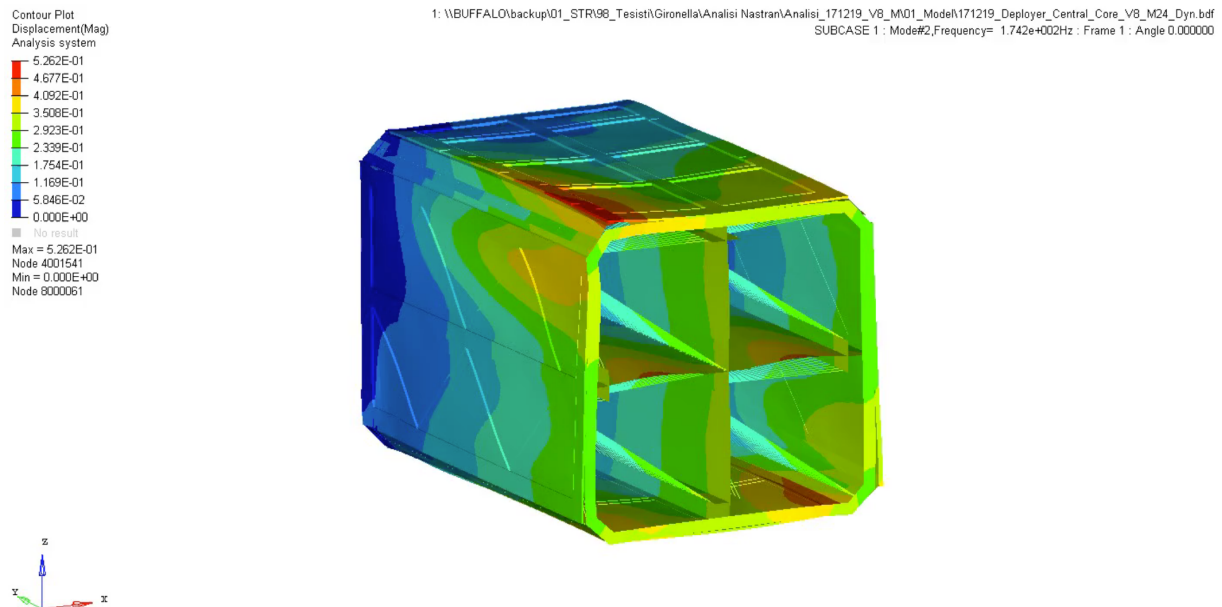
In the images below we find the results of the eigenfrequency analysis represented with Hyperview.



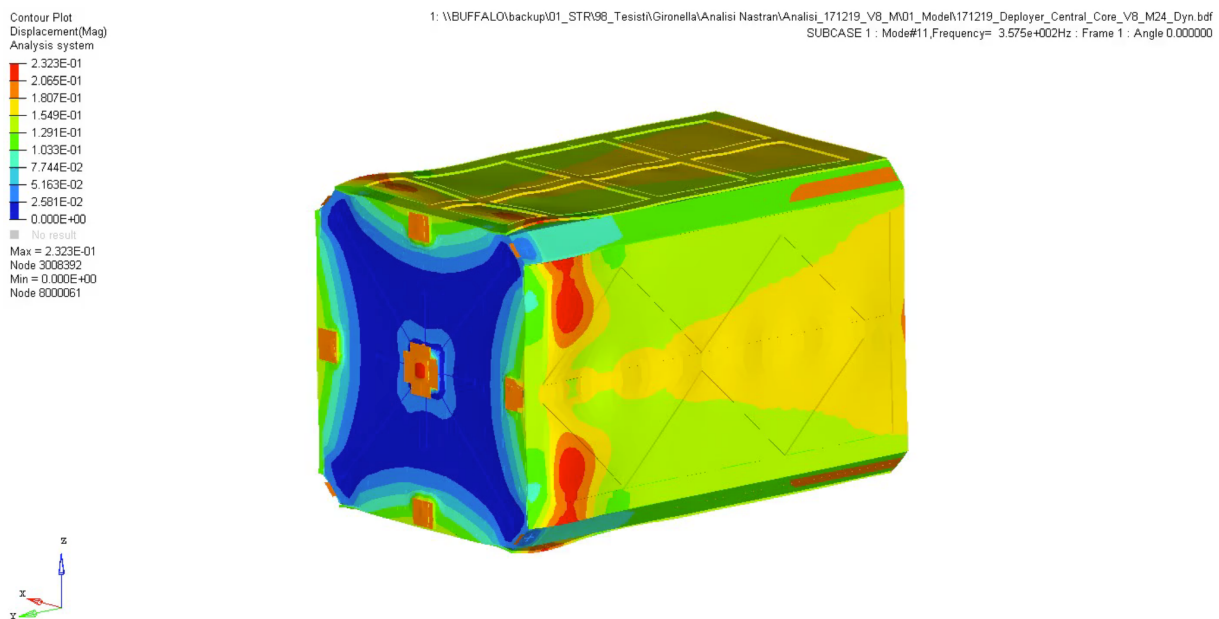
Mode	Frequency [Hz]	Characterization	kg
1	173,487	1st global mode in X direction (lateral)	24,19

Figure 10.1: First global mode in X direction

10. MASS OPTIMIZATION



Mode	Frequency [Hz]	Characterization	kg
2	174,232	1st global mode in Z direction	24,28



Mode	Frequency [Hz]	Characterization	kg
11	357,46	1st global mode in Y direction (axial)	357,46

Figure 10.3: First global mode in Z direction

11. Optimized Deployer: Stress check

Having verified that I have acceptable stiffness values, we can continue with stress checks.

Note.

This time we perform the stress check by considering the equivalent loads acting on the structure due to the random excitation.

This aspect deserves clarification. For example, when designing satellite it is not necessary to consider random excitation, while designing deployer and in general equipment, it is necessary to take this into account.

Our deployer has first mode frequency of 173 Hz: the sine excitation covers a frequency range up to 100 Hz, so we don't risk going into resonance with this type of excitation; on the contrary, if we consider random excitation (high frequencies), dynamic coupling is possible, since we have the dynamic response of our system within the frequency range in which we also have the random load.

Therefore, in the case of random excitation, we repeat it, we have a coupling between the dynamics of the deployer and the loads. So there is necessarily load amplification effects.

There are two approaches that allow to evaluate the equivalent loads due to the random excitation acting on the structure.

The first is the one indicated by Miles and is an approximate method; in the second, a transfer function is sought using Nastran.

Both methods are detailed in the following paragraphs.

§ 11.1 Random response: Miles

Miles is responsible for one of the first studies conducted on the evaluation of the phenomenon of random excitation applied to a structure.

Define ASD (Acceleration Specter Density) as the random load spectrum, expressed in g^2/Hz . The PSD (Power Specter Density) to which the deployer is subject is shown in the [Figure 11.1.1].

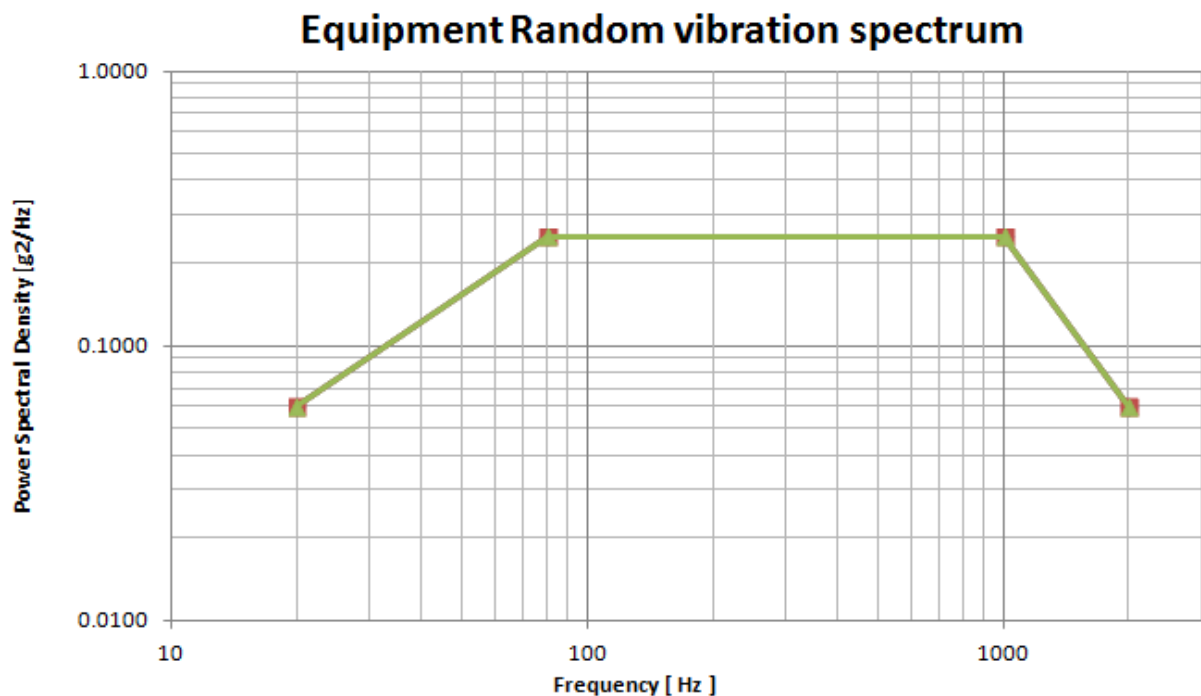


Figure 11.1.1: PSD

Also define G_{RMS} , the acceleration to which the structure is subjected when it is excited with the random excitation. In other word, G_{RMS} is the equivalent load on the structure in terms of acceleration).

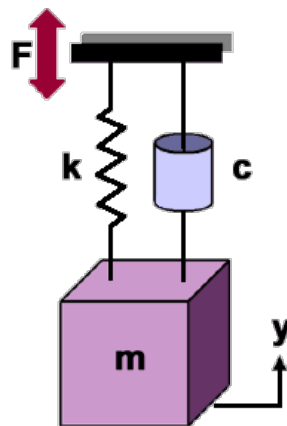
In 1954, Miles developed his version of equation for G_{RMS} as he was researching fatigue failure of aircraft structural components caused by jet engine vibration and gust loading. Miles simplified his research by modeling a system using one degree of freedom only. He also applied statistical advances that had been made at the time. While his goal was to

11. OPTIMIZED DEPLOYER: STRESS CHECK

analyze the stress of a component, the equation can be rearranged and used to determine, among others, displacement, force, and, in our case, acceleration.

Miles' Equation is derived using a single degree of freedom (SDOF) system (lightly damped), consisting of a mass, spring and damper, that is excited by a constant-level "white noise" random vibration input from 0 Hz to infinity. Miles' Equation is thus technically applicable only to a SDOF system.

This [Figure 11.1.2] shows a typical representation of a SDOF oscillator. The mass (m) is attached to the spring (stiffness k) and the damper (damping c). The system is forced by the random vibration function (F) in the y-direction only.



*Figure 11.1.2:
SDOF oscillator*

The logic followed by Miles is: given a mass - spring - damper system, like the one in [Figure 11.1.2], of which we know the natural frequency f_n , assumed the damping (therefore known the Q factor) and knowing the random input in g^2/Hz , the excited mass at the base of this specter ASD is subject to an equivalent acceleration G_{RMS} calculated as:

$$G_{\text{RMS}} = \sqrt{\frac{\pi}{2} f_n Q [ASD_{\text{input}}]}$$

*Figure 11.1.3:
Miles's formula*

where:

G_{RMS} = Root Mean Square Acceleration in G's

f_n = Natural frequency

$Q = 1/(2\zeta)$ = Transmissibility (or amplification factor) at f_n

where ζ is the critical damping ratio

$[ASD_{input}]$ = Input Acceleration Spectral Density at f_n in units of g^2/Hz

In our case, after doing a modal analysis with Nastran to obtain the proper modes of the structure up to the frequency of 2000 Hz and the effective mass associated with each of the proper modes, I create an Excel sheet, as I can see in [Table].

In the Excel I insert for each mode specific to the structure, the corresponding frequency, the actual mass associated with that mode, the calculation of the percentage of mass involved in that way compared to the total mass of the deployer. I enter the value of ASD_{input} (the random input) in the X direction [Table 11.1.1], in the Y direction [Table 11.1.2] and in the Z direction [Table 11.1.3].

In our case the transmissibility Q is equal to 10 (having assumed a damping of 5%).

I must therefore take into account the fact that my system is not at a degree of freedom: I do it considering the percentage of mass associated with each mode with respect to the total mass. That is, for example, in [Table 11.1.1] I see that the first mode has a frequency of 173.49 Hz and that it involves along X 24.194 kg, or 76.75% of the total mass of the deployer: we go to look in the spectrum random to what ASD value corresponds to that frequency.

We then apply Miles to the found values and generate the G_{RMS} column.

We multiply the G_{RMS} values by a factor of 3, in order to be conservative with respect to the Gaussian distribution considered with sigma (i.e. to take into account 99.75% of cases, instead of only 68%).

11. OPTIMIZED DEPLOYER: STRESS CHECK

We scale the values obtained by the percentage of mass associated (in that direction) in that proper way, i.e we multiply $3 \times G_{RMS}$ by the % of total Mass (think that in fact the force that a mode generates is proportional to its associated mass, therefore all acceleration accordingly).

We carry out the procedure just described for all modes and for all directions.

Among all the G_{RMS} mass mediated values found, only those due to modes involving a percentage of associated mass greater than the "trash" value, therefore greater than 5%, are considered.

Of the values left after applying the discriminant of trash, the quadratic sum is made along each axis: as a result, given our random input at the base, depending on the dynamics of the structure, depending on the damping I have assumed, we obtain three values (one long X, one long Y, one long Z) of “equivalent” accelerations at the CoG. We find these results at the bottom right in the following tables.

To roughly take into account the cross loads, we consider 20% of the load found in one direction applied in the remaining two, as shown in the [Figure 11.1.1 (a)], [Figure 11.1.2 (a)], [Figure 11.1.3 (a)].

Mode	Freq [Hz]	Eff. Mass [kg] N _x	% of total Mass N _x	Cumulative mass N _x	ASD _{inp} ut [g ² /Hz]	G _{RMS} [g]	3 x G _{RMS} [g]	G _{RMS} Mass mediated [g]	G _{RMS} Mass mediated (> Tresh)
1	173,49	24,194	76,75%	24,194	0,250	26,101	78,304	60,100	60,100
2	174,23	1,902	6,03%	26,096	0,250	26,157	78,472	4,735	4,735
3	210,68	0,000	0,00%	26,096	0,250	28,764	86,291	0,000	0,000
4	221,60	0,000	0,00%	26,096	0,250	29,500	88,499	0,000	0,000
5	225,25	0,442	1,40%	26,538	0,250	29,741	89,224	1,250	0,000
6	238,38	0,201	0,64%	26,739	0,250	30,596	91,789	0,584	0,000
7	340,16	0,000	0,00%	26,739	0,250	36,549	109,646	0,000	0,000

11. OPTIMIZED DEPLOYER: STRESS CHECK

Mode	Freq [Hz]	Eff. Mass [kg] N _x	% of total Mass N _x	Cumul ative mass N _x	ASD _{inp ut} [g ² /Hz]	G _{RMS} [g]	3 x G _{RMS} [g]	G _{RMS} Mass mediat ed [g]	G _{RMS} Mass mediat ed (> Tresh)
8	341,92	0,048	0,15%	26,787	0,250	36,643	109,929	0,167	0,000
9	347,47	0,018	0,06%	26,805	0,250	36,939	110,818	0,064	0,000
10	347,66	0,010	0,03%	26,815	0,250	36,949	110,848	0,036	0,000
11	357,46	0,003	0,01%	26,819	0,250	37,467	112,400	0,012	0,000
12	364,11	0,000	0,00%	26,819	0,250	37,814	113,441	0,000	0,000
.....
295	1989,06	0,000	0,00%	30,514	0,061	43,542	130,625	0,002	0,000
Equivalent Load X [g]									60,286

Table 11.1.1: Random equivalent load in X direction

Cross Mode		20%
Y	12,06	g
Z	12,06	g

Table 11.1.1 (a): Cross mode in Y and Z, due to random excitation in X

Mode	Freq [Hz]	Eff. Mass [kg] N _y	% of total Mass N _y	Cumul ative mass N _y	ASD _{inp ut} [g ² /Hz]	G _{RMS} [g]	3 x G _{RMS} [g]	G _{RMS} Mass mediat ed [g]	G _{RMS} Mass mediat ed (> Tresh)
1	173,49	0,003	0,01%	0,003	0,250	26,101	78,304	0,006	0,000
2	174,23	0,000	0,00%	0,003	0,250	26,157	78,472	0,000	0,000
3	210,68	0,000	0,00%	0,003	0,250	28,764	86,291	0,000	0,000

11. OPTIMIZED DEPLOYER: STRESS CHECK

Mode	Freq [Hz]	Eff. Mass [kg] Ny	% of total Mass Ny	Cumulative mass Ny	ASD _{imp} ^{ut} [g ² /Hz]	GRMS [g]	3 x GRMS [g]	GRMS Mass mediated [g]	GRMS Mass mediated (> Tresh)
4	221,60	0,000	0,00%	0,003	0,250	29,500	88,499	0,000	0,000
5	225,25	0,000	0,00%	0,003	0,250	29,741	89,224	0,000	0,000
6	238,38	0,000	0,00%	0,003	0,250	30,596	91,789	0,001	0,000
7	340,16	0,000	0,00%	0,003	0,250	36,549	109,646	0,000	0,000
8	341,92	0,002	0,01%	0,005	0,250	36,643	109,929	0,007	0,000
9	347,47	0,001	0,00%	0,006	0,250	36,939	110,818	0,002	0,000
10	347,66	0,000	0,00%	0,006	0,250	36,949	110,848	0,001	0,000
11	357,46	30,439	96,56%	30,445	0,250	37,467	112,400	108,535	108,535
12	364,11	0,000	0,00%	30,445	0,250	37,814	113,441	0,000	0,000
.....
295	1989,06	0,000	0,00%	30,539	0,061	43,542	130,625	0,000	0,000
Equivalent Load Y [g]									108,535

Table 11.1.2: Random equivalent load in Y direction

Cross Mode		20%
X	21,71	g
Z	21,71	g

Table 11.1.2 (a): Cross mode in X and Z, due to random excitation in Y

11. OPTIMIZED DEPLOYER: STRESS CHECK

Mode	Freq [Hz]	Eff. Mass [kg] Nz	% of total Mass Nz	Cumulative mass Nz	ASD _{imp} ^{ut} [g ² /Hz]	GRMS [g]	3 x GRMS [g]	GRMS Mass mediated [g]	GRMS Mass mediated (> Tresh)
1	173,49	1,912	6,06%	1,912	0,250	26,101	78,304	4,749	4,749
2	174,23	24,279	77,02%	26,191	0,250	26,157	78,472	60,441	60,441
3	210,68	0,072	0,23%	26,263	0,250	28,764	86,291	0,198	0,000
4	221,60	0,482	1,53%	26,745	0,250	29,500	88,499	1,352	0,000
5	225,25	0,000	0,00%	26,745	0,250	29,741	89,224	0,000	0,000
6	238,38	0,000	0,00%	26,745	0,250	30,596	91,789	0,000	0,000
7	340,16	0,000	0,00%	26,745	0,250	36,549	109,646	0,000	0,000
8	341,92	0,000	0,00%	26,745	0,250	36,643	109,929	0,000	0,000
9	347,47	0,000	0,00%	26,745	0,250	36,939	110,818	0,000	0,000
10	347,66	0,000	0,00%	26,745	0,250	36,949	110,848	0,000	0,000
11	357,46	0,000	0,00%	26,745	0,250	37,467	112,400	0,000	0,000
12	364,11	0,000	0,00%	26,745	0,250	37,814	113,441	0,000	0,000
.....
295	1989,06	0,000	0,00%	30,513	0,061	43,542	130,625	0,000	0,000
Equivalent Load Z [g]									61,304

Table 11.1.3: Random equivalent load in Z direction

Cross Mode		20%
X	12,06	g
Y	12,06	g

Table 11.1.3 (a): Cross mode in X and Y, due to random excitation in Z

This is the first approach that we can use to study the loads due to a random input.

With these new loads (GRAV) we would go to redo the analysis. With this approach, however, we only get the load equivalent to the cog and it is also a very conservative method.

Furthermore, the Miles method does not give us information on possible cross modes (ie on the phenomenon for which if there is a random excitation, for example in the direction, I also have an answer in the y and z direction). In fact, this approach does not depend in which direction the excitation is, it just looks at the dynamics and the inputs on the separate axes).

So in the first sizing we apply the Miles method and conservatively if for example an equivalent load of 60 g in X direction is considered 20% of that load in the other directions, i.e. we will have 12 g in Y and in Z direction.

§ 11.2 Random response: Nastran SOL 111

The second approach goes through the frequency response via Nastran.

The .dat for the frequency response is SOL 111 (this .dat is used both when we study Sine excitation and when we study the Random one, in fact in both cases it is a frequency response to an input).

In .dat SOL 111 we create three Subcases (since we have three directions of excitation).

The first thing we do in this sheet is the construction of the modal base (eigenvalues and eigenvectors). In fact, the first thing that the Nastran software must do to extract a dynamic response is to build the modal base of the system: we will therefore have, as usual, the eigen card in which we request the natural frequencies up to 2000 Hz and to normalize with respect to the mass and this is recalled in the 3 subcases (exactly as we did for the modal analysis).

After that, to give Nastran the dynamic input to the interface we use an SPC: at point 101 (number of the node where in Hypermesh I placed the SPC) along the X, Y and Z

11. OPTIMIZED DEPLOYER: STRESS CHECK

directions, we assign a scale factor of 9.81 (corresponding to g). We are therefore giving a constant input of 1g between 1 and 2000 Hz.

As for the frequencies, we must communicate to Nastran with which sampling I want the result: with freq1 we instruct Nastran that between 5 and 2000 Hz we want a point for each Hz, i.e. starting from the first frequency equal to 5 Hz, Nastran must proceed at a 1 Hz step for a total of 1995 steps.

In freq4 we ask Nastran that between 5 and 2000 Hz I want a thickening of the sampling in correspondence with the modes of my structure.

Then there is the dumping (the damping): in our case we constantly give a damping of 2% between 0 and 2000 Hz (as with Miles).

I include in the .dat the dynamic model in .bdf (the same as the modal analysis).

What do we want to achieve? The SPC Forces at the SPC (i.e. on the node where we placed the constraint) in order to be able to make a comparison with the results obtained with Miles (in fact, we again have the equivalent cog accelerations).

Then we ask for the acceleration where we want to evaluate it: in addition to the interface, I am interested in knowing the acceleration at the CoGs of the 4 CubeSats. Therefore I insert the number associated with the nodes where we require to know the force.

So far we have therefore made a dynamic analysis, giving 1g between 5 and 2000 Hz with the damping of 2%. And where did random happen?

In this way we calculated the transmissibility, the transfer function: giving 1g in the whole frequency range, we see how our structure responds (in terms of peaks, amplifications).

Now to get the transfer function we should do output divided by input, but our input is unitary: so the output is already the transfer function!

Notes: if we had considered the Sine we would have linearly multiplied the transfer function (the output just found) by the input at the base and we would have obtained the scalar response since it is a linear model.

11. OPTIMIZED DEPLOYER: STRESS CHECK

In random it is like in sine, except that here we have the acceleration density, G_{RMS} : having here g^2/Hz the transfer function must be squared because in the definition of the PSD we have the squared.

Then obtained the transfer function, we square it, we multiply it by the input. In this way we obtain the random response, then the area under the random response curve is calculated: we have the RMS (at the cog or on the nodes that I requested), [Figure 11.2.1] and [Figure 11.2.2].

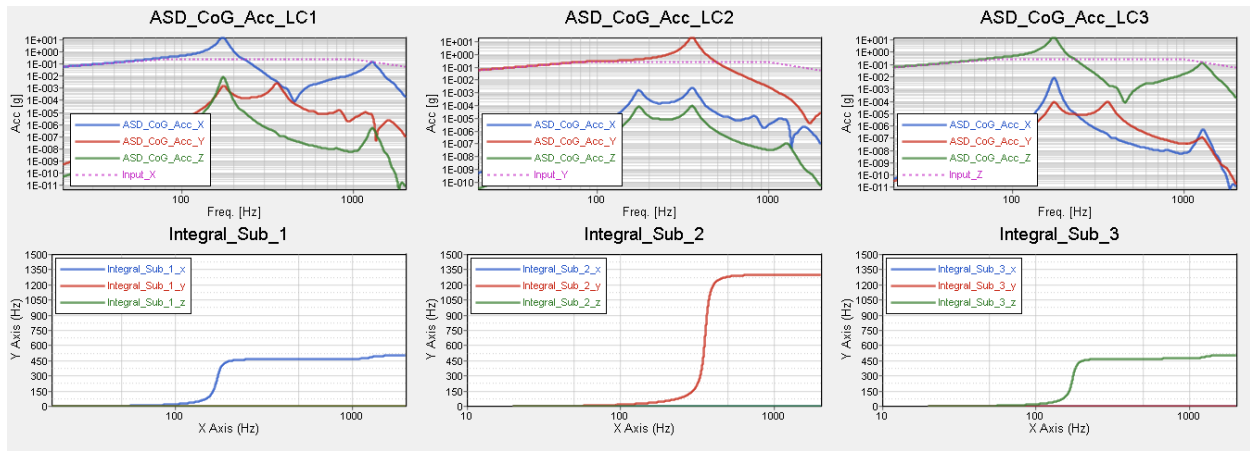


Figure 11.2.1: Random response on SPC

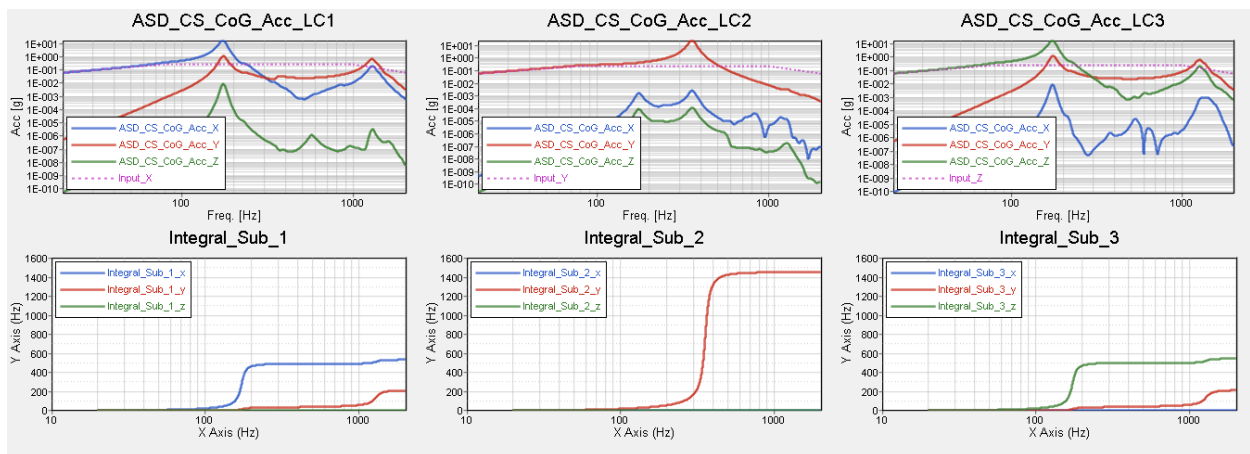


Figure 11.2.2: Random response on CubeSats CoG

11. OPTIMIZED DEPLOYER: STRESS CHECK

Going to see when there is the peak (so the RMS rises) in the response curve that I have obtained: we can take that acceleration to statically re-represent (perhaps always through Nasco) the mode it corresponds.

[Table 11.2.1] shows the equivalent loads obtained at the CubeSats CoG, which are practically identical to those studied at the SPC.

Loads	Equivalent QSL (QL)	
	Axial	108,54 g
	Lateral	61,30 g

Table 11.2.1: Qualification loads

The equivalent static loads we obtained with this second method are very close to those resulting from the Miles method: this is because the deployer structure has a very evident first main mode and the other local modes much lower.

As for the stress verification with quasi-static loads, even with the equivalent static loads due to Random excitation we perform the fatigue verification, using NASCO exactly as it was done in paragraph § 9.1.

The only difference is that the equivalent loads obtained from random excitation are Qualification Loads, so they will have to be multiplied only by the Model Factor (1.20). The Design Loads shown in the [Table 11.2.2] are thus obtained.

Loads	Equivalent QSL (DL)	
	Axial	129,78 g
	Lateral	80,83 g

Table 11.2.2: Design loads

11. OPTIMIZED DEPLOYER: STRESS CHECK

The stresses on the structure are represented by the Hyperview tool in the following images:

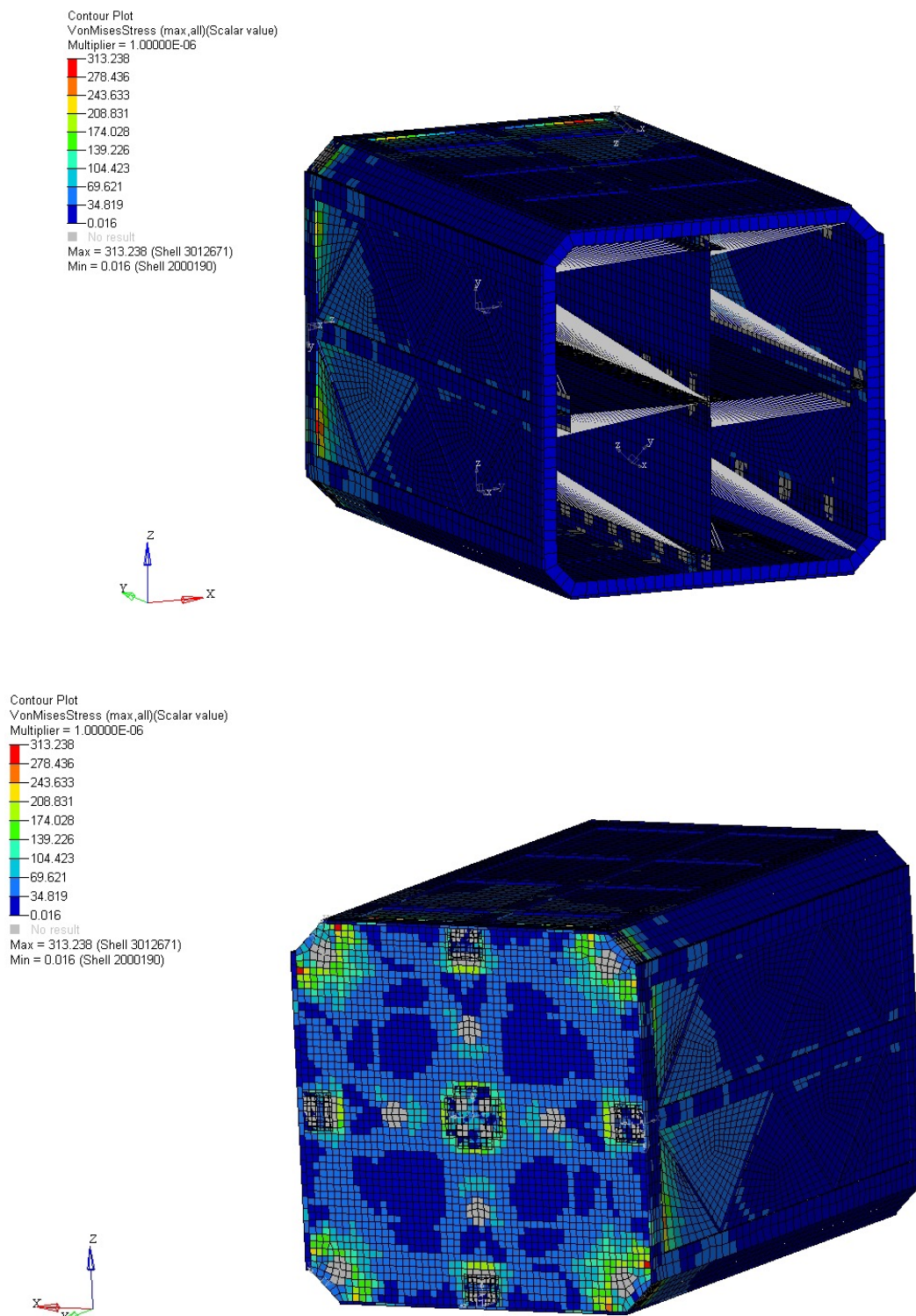
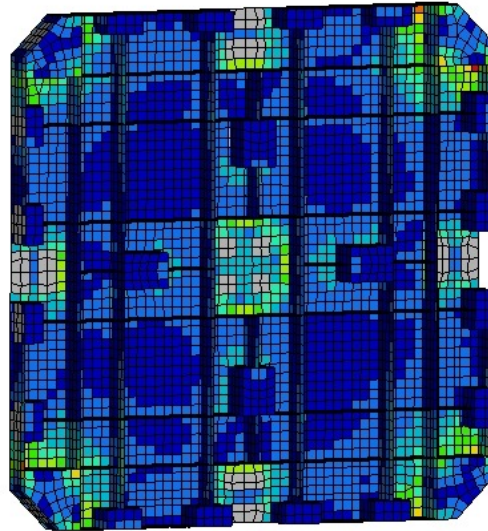


Figure 11.2.3: Stress on assembly

11. OPTIMIZED DEPLOYER: STRESS CHECK

Contour Plot
VonMisesStress (max,all)(Scalar value)
Multiplier = 1.00000E-06
313.238
278.436
243.633
208.831
174.028
139.226
104.423
69.621
34.819
0.016
No result
Max = 313.238 (Shell 3012671)
Min = 0.016 (Shell 2000190)



Contour Plot
VonMisesStress (max,all)(Scalar value)
Multiplier = 1.00000E-06
313.238
278.436
243.633
208.831
174.028
139.226
104.423
69.621
34.819
0.016
No result
Max = 313.238 (Shell 3012671)
Min = 0.016 (Shell 2000190)

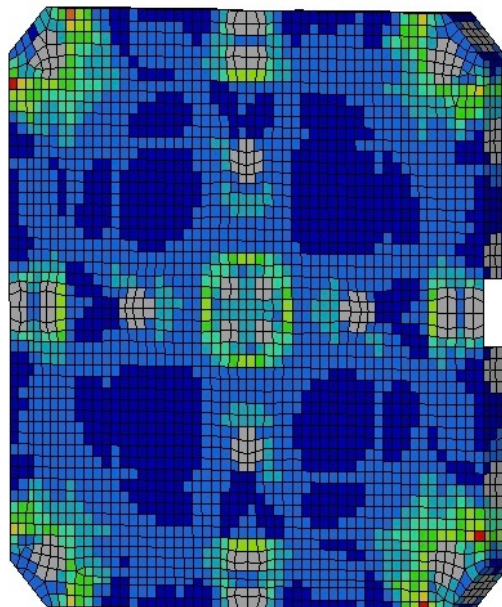


Figure 11.2.4: Stress on base plate

11. OPTIMIZED DEPLOYER: STRESS CHECK

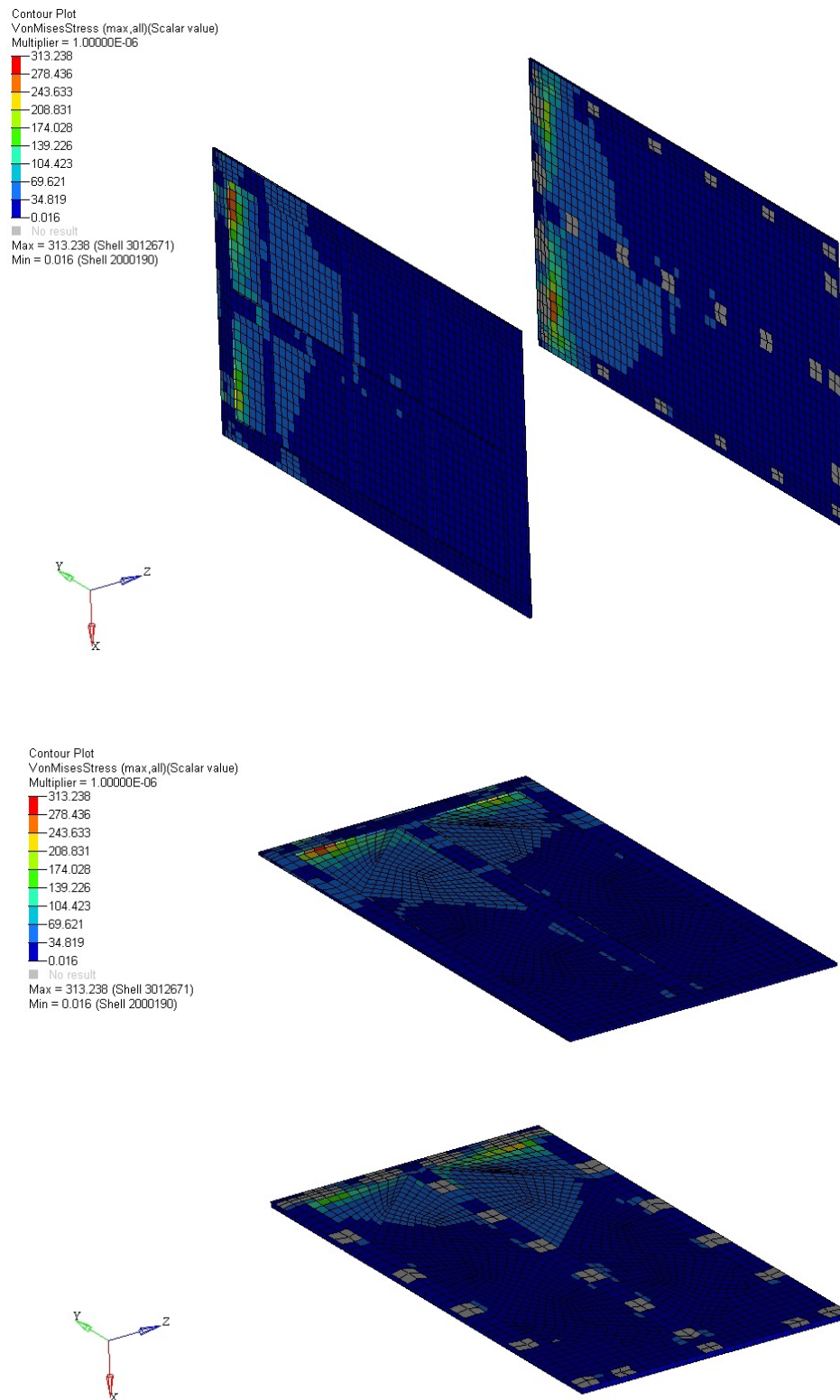


Figure 11.2.5: Stress on base plate

11. OPTIMIZED DEPLOYER: STRESS CHECK

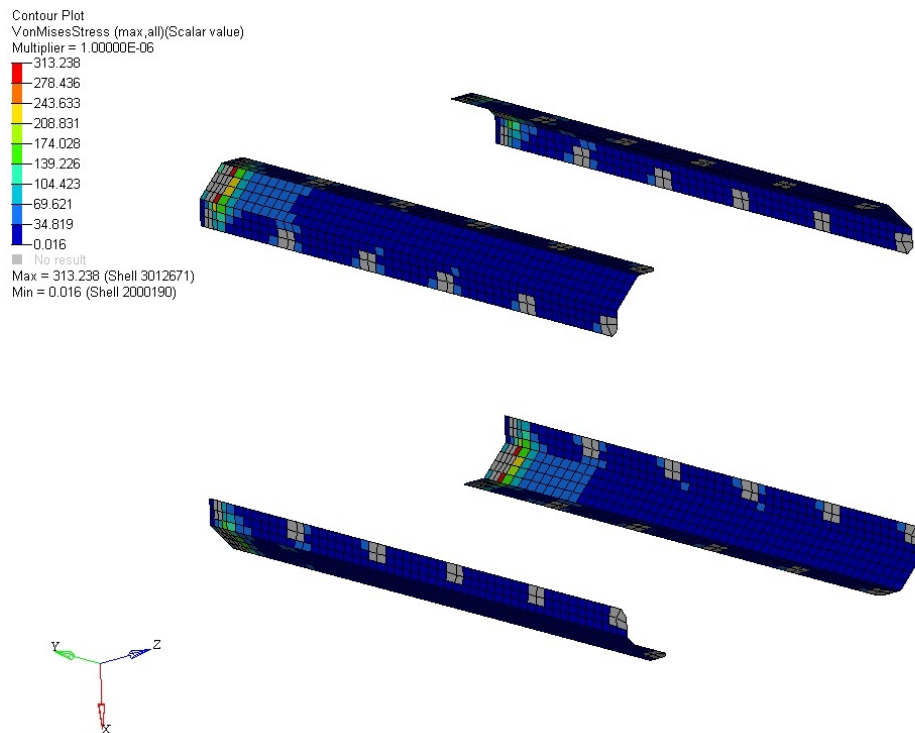


Figure 11.2.6: Stress on corner brackets

By comparing the stresses obtained with the yield strength associated with Alluminium 6082 - T65, the MoS (Margin of Safety) are calculated.

The results are shown in the [Table 11.2.3].

11. OPTIMIZED DEPLOYER: STRESS CHECK

Component	σ_{\max} [MPa]	MoSy
01_01_01_BASE_PLATE	287,063	0,134
01_01_02_BASE_PLATE_LATERAL	308,957	0,053
01_01_03_BASE_PLATE_LATERAL	271,440	0,199
01_01_05_BASE_PLATE	245,121	0,328
01_01_06_RIBS	187,154	0,739
01_02_01_CENTRAL_RAIL	41,438	4,704
01_02_02_CENTRAL_RAIL(BASE)	47,755	3,949
01_03_01_SIDE_PLATE_1	264,420	0,231
01_03_02_SIDE_PLATE_1	12,236	25,598
01_04_01_SIDE_PLATE_2	254,506	0,279
01_04_02_SIDE_PLATE_2	313,238	0,039
01_04_03_SIDE_PLATE_2	41,983	6,752
01_05_CORNER_BRACKETS	309,303	0,052
01_06_01_PERIMETRIC_RAIL	59,058	3,002
01_06_02_PERIMETRIC_RAIL	73,926	2,197
01_06_03_PERIMETRIC_RAIL	125,624	0,882
01_07_01_SEPARATOR_1/2	13,092	17,055
01_08_01_SEPARATOR_HORIZONTAL	9,657	23,477
01_09_01_CORNER_UPPER	22,576	9,470

Table 11.2.3: Stress and MoS

Note that the safety margins are all positive (greater than zero), the optimized structure therefore passes the stress check. If you want to increase the safety margins, you can certainly think of acting on the material, choosing an aluminum with a higher yield strength.

12. Preliminary design

The designed structure respects the parameters of strength and stiffness, is optimized with respect to weight and can therefore be considered the output of this study: we have reached the preliminary design of the deployer for CubeSat. The Cad model is redone and the latter will become the input of phase C described in chapter 6.

Below is a series of images depicting the preliminary design deployer: we can see in particular the modeling of the baseplate and the various configurations that occur when loading a CubeSat 12U to 4 CubeSat 3U.

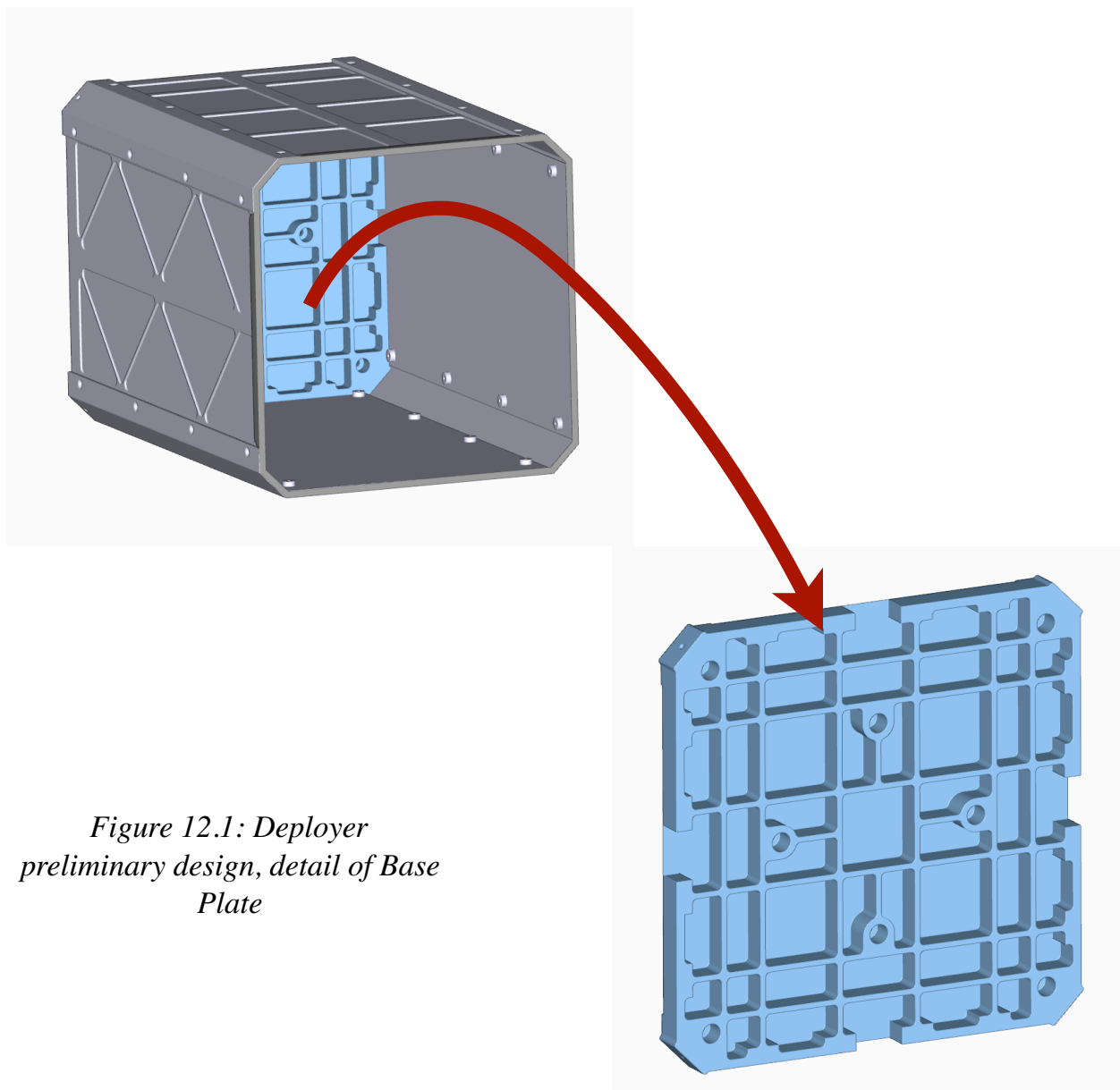


Figure 12.1: Deployer preliminary design, detail of Base Plate

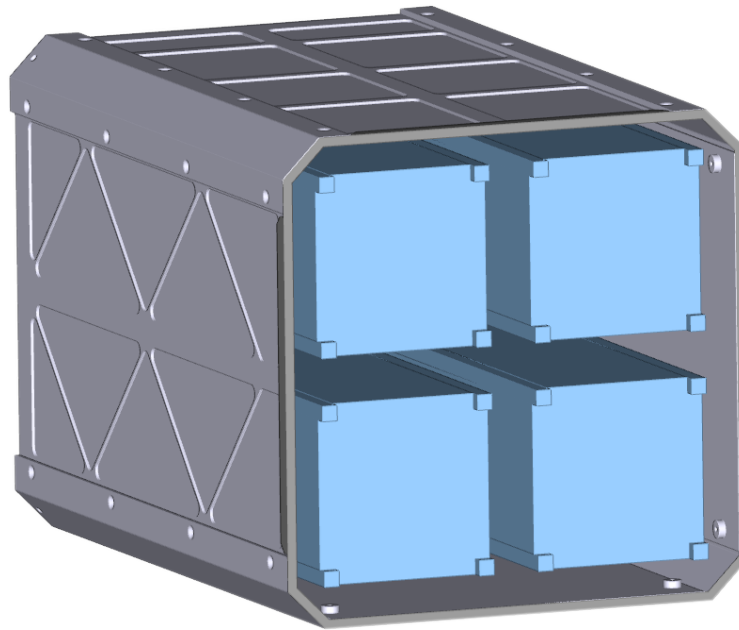


Figure 12.2: Deployer preliminary design, 4 x 3U configuration

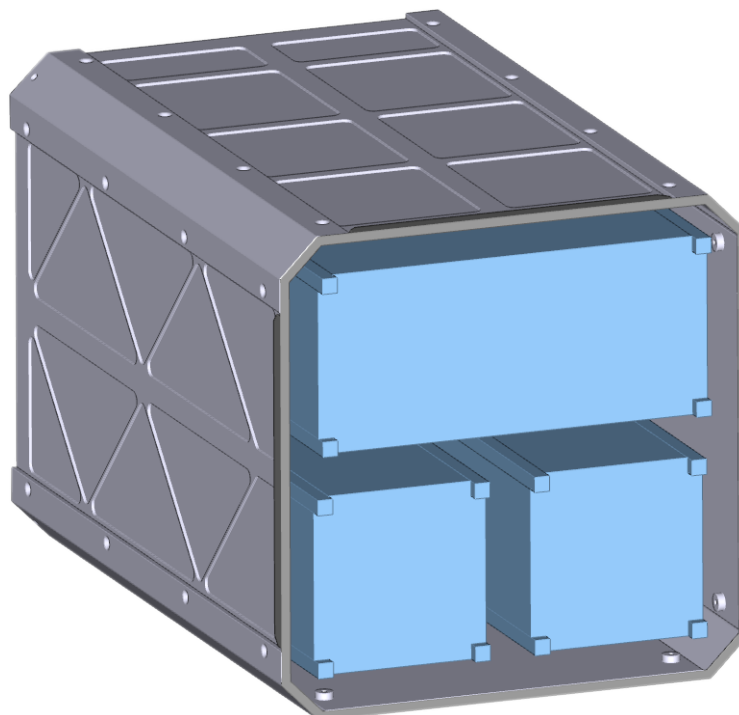


Figure 12.2: Deployer preliminary design, 2 x 3U and 1 x 6U configuration

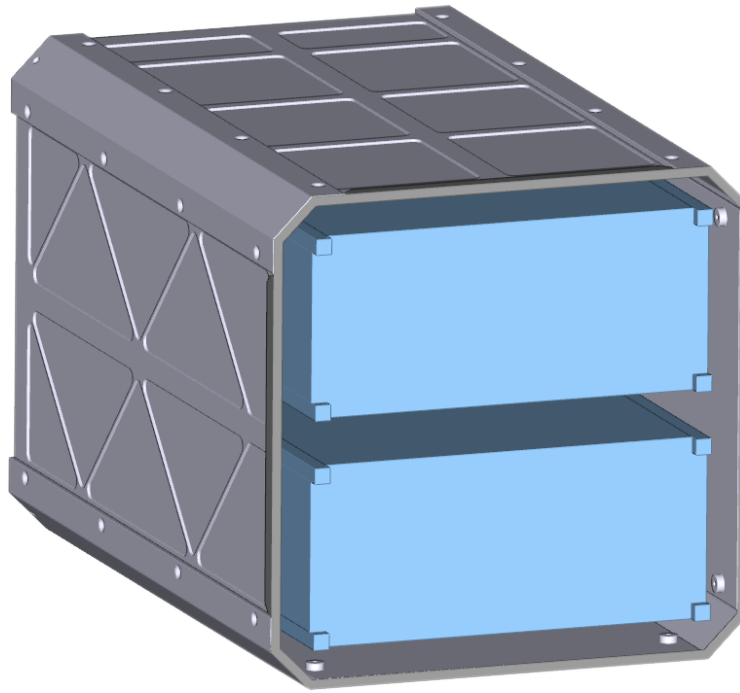


Figure 12.2: Deployer preliminary design, 2 x 6U configuration

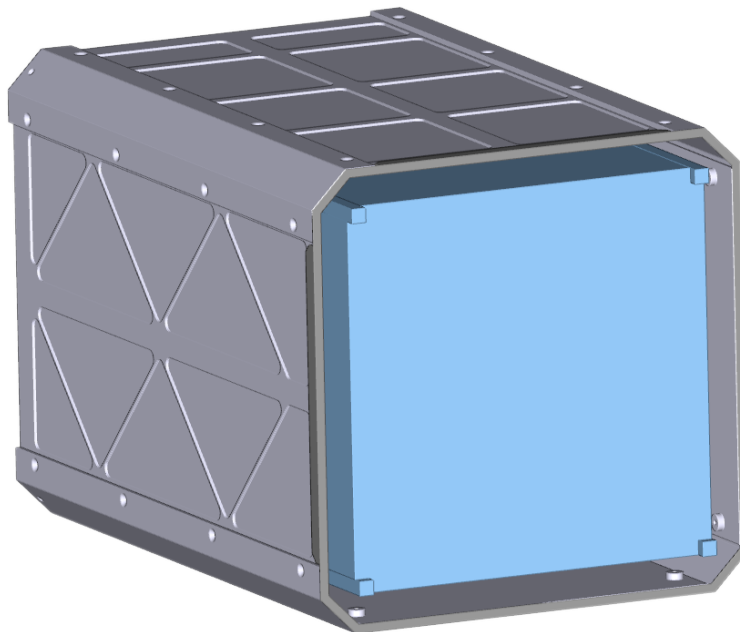


Figure 12.2: Deployer preliminary design, 1 x 12U configuration

13. Conclusion and future developments

A new system to deploy satellites, named cubesat, has been preliminary studied. Starting from the needs driven by European multi mission preliminary concept has been drafted taking into account accommodation as well as flexibility constraints. The study is carried out in collaboration with and on behalf of SAB Aerospace, Italian company working in the field of aerospace for over 20 years and leader on the launch services on VEGA and VEGA-C launching system.

From the preliminary design defined for the mechanical sub-system, the structural verification activity has been performed starting from the creation of a dedicated FEM Model. Checks prescribed by the ECSS has been performed before entering in the analysis loop.

Modal analysis has been performed to verify the stiffness requirement and to optimize the ratio mass/stiffness in order to minimize the structural mass which is an aspect of a paramount importance when talking about hardware for space applications.

Structural Strength has been analyzed by taking into account the load environment derived from the VEGA launcher. Quasi-static load as well as sinusoidal load have been analyzed by directly applying the loads with the specific factors according to ECSS.

Random loads have been applied with a simplified method based on Miles formula and a more accurate methods which start from the transfer functions and applies the specific at each frequency range to check the similarity of the results.

The structural integrity of the designed structure is ensured by the application of safety factors against ultimate and yield.

As future developments the mechanisms to activate the dynamic rail and consequently the pusher plate has to be studied. Some solutions has been already drafted. and are shown in the figures below.

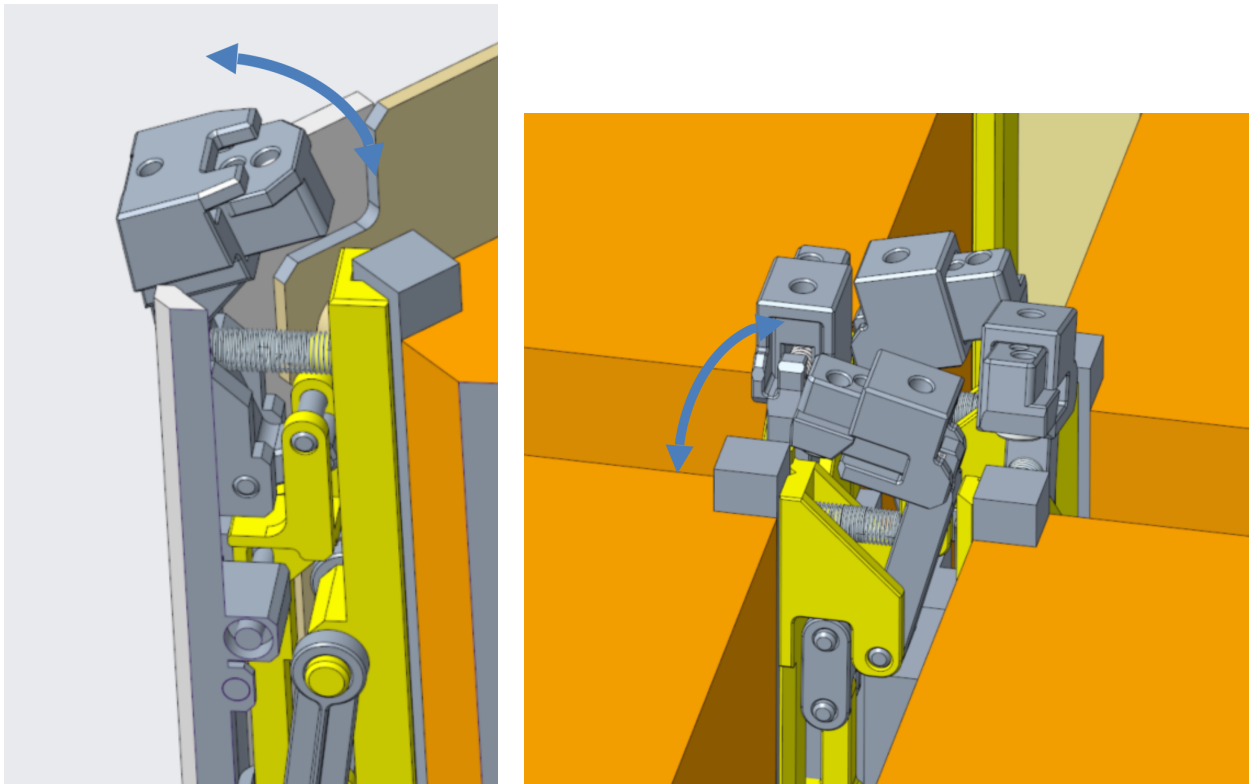


Figure 13.1: Clamping mechanism

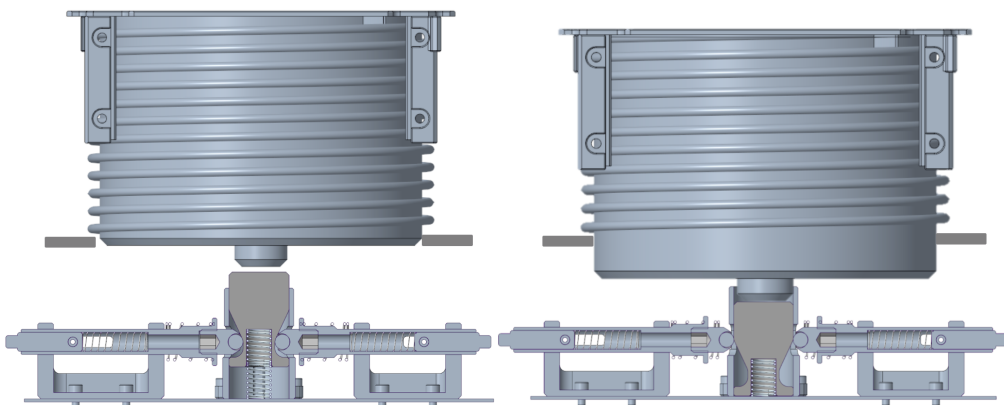


Figure 13.2: Release mechanism

13. CONCLUSION AND FUTURE DEVELOPMENTS

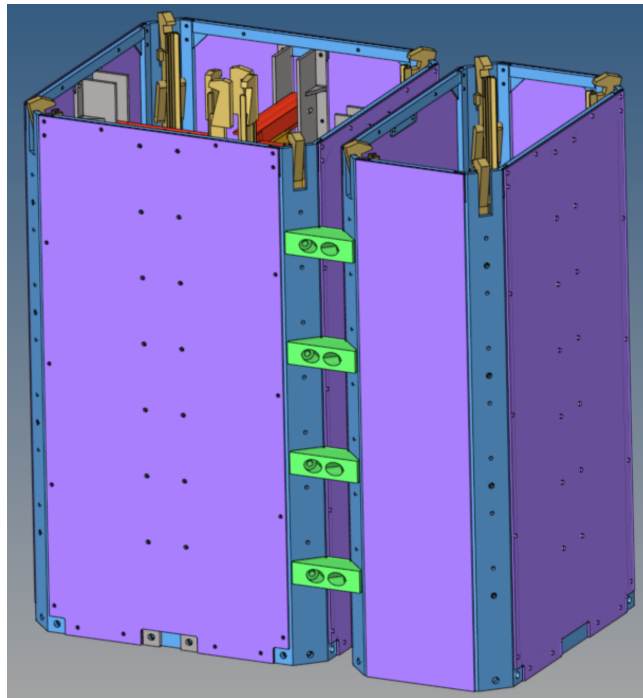


Figure 13.3: Slave module connection

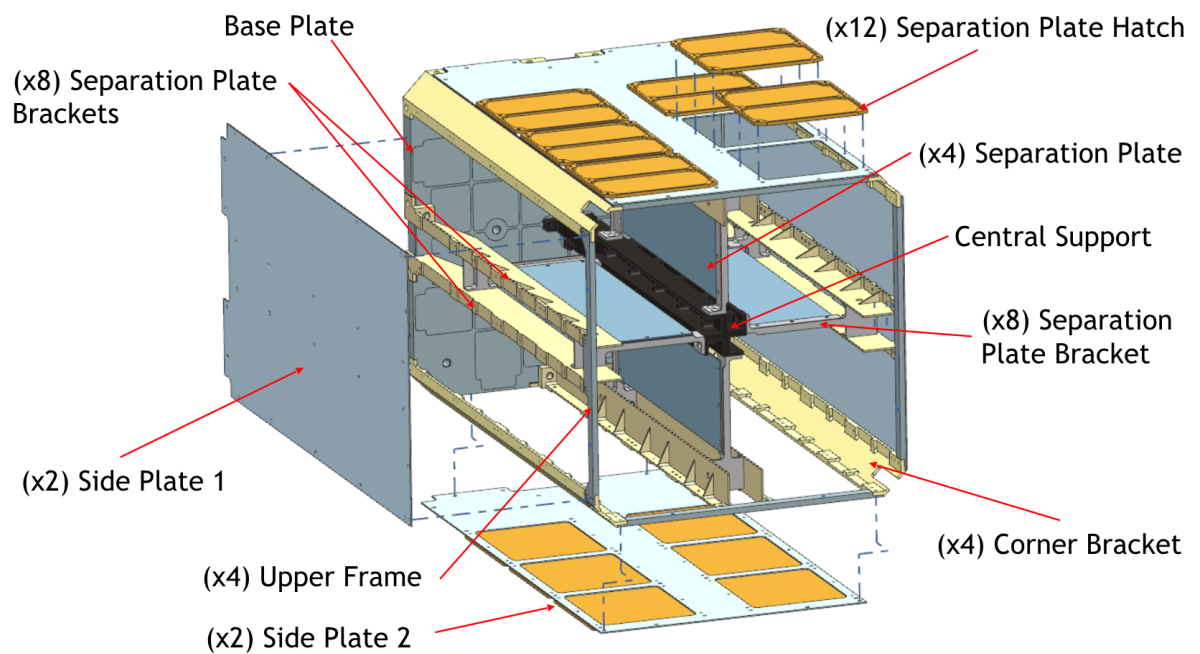


Figure 13.4: Consolidated design

13. CONCLUSION AND FUTURE DEVELOPMENTS

The study can be considered in the frame of the typical Space Project Phase B which ends with a milestone called Preliminary Design Review.

The project Phase C has to be performed in order to arrive to the so called Critical Design Review. During Phase C functional tests will be performed on test models which will be built to verify the separation of dummy cubesats by means of zero-gravity support equipments.

The Critical design review will authorize the procurement and Integration of the development. It is expected that a Qualification model will be built. It will be subjected to all qualification campaign. In the specific case such campaign will encompass vibration testing as well Thermal Vacuum cycling. The successful test campaign will bring to the Qualification review: such milestone gives the authorization to move on with the built of the Flight model which is then subjected to Acceptance Test campaign before flying.

14. Sunto in Lingua Italiana

Questo documento riguarda la progettazione preliminare e l'ottimizzazione strutturale di un deployer per CubeSat.

Il CubeSat è una tipologia di satellite avente dimensioni standard: nel 1999 uno studio congiunto della California Polytechnic State University e la Stanford University dà vita a uno standard per la progettazione di satelliti di piccole dimensioni (pico/nano satelliti) allo scopo di ridurre tempi e costi di sviluppo, per aumentare l'accessibilità allo spazio e consentire lanci frequenti.

Ad oggi il CubeSat sta avendo un largo successo e l'iniziale utilizzo esclusivo da parte di gruppi a scopi di ricerca sta lasciando spazio a progetti commerciali. Esistono differenti tipologie di CubeSat e le più comuni sono:

- 1U CubeSat is $10\text{ cm} \times 10\text{ cm} \times 11.35\text{ cm}$ - poco più grande di un classico cubo di Rubik, per avere un'idea;
- 2U CubeSat is $10\text{ cm} \times 10\text{ cm} \times 22.70\text{ cm}$;
- 6U CubeSat is $20\text{ cm} \times 10\text{ cm} \times 34.05\text{ cm}$;
- 12U CubeSat is $20\text{ cm} \times 20\text{ cm} \times 34.05\text{ cm}$;

Mentre i satelliti classici sono rilasciati attraverso sistemi di separazione, i CubeSat vengono rilasciati attraverso dispositivi chiamati deployer.

Lo studio, svolto in collaborazione e per conto di SAB Aerospace, azienda italiana che opera nel settore aerospaziale da oltre 20 anni, parte dall'esigenza emersa nell'attività aziendale di produrre internamente un deployer adattabile a diversi scenari di utilizzo. L'obiettivo è sviluppare un deployer modulare e facilmente riconfigurabile per contenere CubeSat fino al formato 6U.

Si vanno quindi a individuare i requisiti (funzionali, fisici, di interfaccia, di carico) e, tramite un'attività di brainstorming a ideare un primo concept.

A partire dal concept si effettuano poi le verifiche strutturali e l'ottimizzazione della massa finalizzate ad ottenere un progetto preliminare del deployer: viene eseguita l'attività di verifica strutturale a partire dalla realizzazione di un Modello FEM dedicato.

In particolare, il requisito di rigidezza richiede che la frequenza del primo modo proprio della struttura sia superiore a 140 Hz. Viene quindi fatta un'analisi modale per verificare tale requisito di rigidezza e si prosegue ottimizzando il rapporto massa / rigidezza al fine di minimizzare la massa strutturale, aspetto di fondamentale importanza quando si parla di hardware per applicazioni spaziali.

La resistenza strutturale viene analizzata, tenendo conto dell'ambiente di carico derivato dal lanciatore VEGA: si deve quindi verificare la resistenza ai carichi quasi-statici e all'eccitazione random agente sulla struttura. In entrambi i casi vengono applicati carichi maggiorati con specifici fattori, indicati dalla guida ECSS.

Si precisa che per la valutazione degli effetti sulla struttura dell'eccitazione in alta frequenza (random), si fa uso di due differenti metodi: il metodo semplificato di Miles, basato su una formula che permette di ottenere un valore approssimato di carico statico equivalente, e un secondo metodo più accurato, che permette di ottenere delle funzioni di ottenere il carico statico in qualunque punto di interesse della struttura e consente di valutare anche eventuali modi cross.

L'integrità strutturale del deployer progettato è assicurata dall'applicazione di fattori di sicurezza.

Risultato dello studio è quindi l'ottenimento di un deployer progettato non solo per avere rigidezza e resistenza tali da garantirne il funzionamento nelle varie condizioni nelle quali tale dispositivo si trova ad operare, ma anche per essere leggero (con conseguente riduzione dei costi) e agilmente riconfigurabile, così da poter essere facilmente adattabile a una domanda variabile.

15. Acknowledgments

I would like to thank to my supervisor Prof. Stefano Lenci, for is constant support and the provided indications, and to my contact person at SAB Aerospace, Dr. Riccardo Silvestri for his suggestion in approaching this subject.

Last, but not least, I would like to thank my family and the people who have been there for me on this journey, for all the invaluable support they have always given me, and without which I would not have achieved this result.

16. References

- <https://knowledge.autodesk.com/support/nastran/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/NSTRN-Reference/files/GUID-86B41C9D-41DB-4664-AE0D-B4B55981F183-htm.html>
- https://docs.plm.automation.siemens.com/data_services/resources/nxnastran/10/help/en_US/tdocExt/pdf/User.pdf
- <https://ecss.nl/hbstms/ecss-e-hb-32-26a-spacecraft-mechanical-loads-analysis-handbook/>
- http://everyspec.com/ESA/ECSS-E-HB-32-26A_47695/
- <https://www.dorbit.space/inorbit-now>
- <https://www.isispace.nl/product/isipod-cubesat-deployer/>
- <https://www.astrofein.com/astro-und-feinwerktechnik-adlershof/products/raumfahrt-eng/193/cubsat-deployer-engl/>
- Calvi A., Spacecraft Structural Dynamics & Loads, An Overview, ESA / ESTEC, Noordwijk, The Netherlands
- <https://femci.gsfc.nasa.gov/random/MilesEqn.html>
- <https://www.youtube.com/watch?v=JQy9EwMrILI>
- https://www.youtube.com/watch?v=K_H4WxTiesE
- https://www.researchgate.net/publication/3901492_Development_of_the_standard_CubeSat_deployer_and_a_CubeSat_class_PicoSatellite/link/54381d610cf204cab1d593e7/download
- <https://www.astrofein.com/astro-und-feinwerktechnik-adlershof/products/raumfahrt-eng/193/cubsat-deployer-engl/>
- California Polytechnic State University. Cubesat design specification rev 13. <https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/>

- [56e9b62337013b6c063a655a/1458157095454/cds_rev13_final2.pdf](https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/573fa2fee321400346075f01/1463788288448/6U_CDS_2016-05-19_Provisional.pdf), 2017. consulted on 2017-05-17.
- California Polytechnic State University. Cubesat design specification rev. 13. https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/573fa2fee321400346075f01/1463788288448/6U_CDS_2016-05-19_Provisional.pdf, 2017. consulted on 2017-05-08.
 - Herbert J. Kramer. Cubesat concept. <https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cubesat-concept#top>, 2017. consulted on 2017-04-19.
 - Erik Kulu. World's largest database of nanosatellites more than 1600 nanosats and cubesats. <http://www.nanosats.eu>, March 2017. consulted on 2017-05-29.
 - Gunnar Tibert. Deployable tensegrity structures for space applications. April 2002. PhD thesis, Royal Institute of Technology.
 - Matthew G. McHarg, Brian A. Smith, Timothy H. Russell, Olha Asmolova, Trey S. Quiller, Richard L. Balthazor, Michael E. Dearborn, Brooke M. Isch, Taylor R. Johnson, Angus J. MacDonald, and Eric W. Peek. Falconsat-7 - a deployable solar telescope. 2014. 29th Annual AIAA/USU Conference on Small Satellites.
 - Peter Fortescue, Graham Swinerd, and John Stark. Spacecrafts systems engineering. 2011. Wiley.
 - Adirim H., Scheiding S., Request for Information related to the procurement of Separation Systems for Small Spacecraft to be launched in the frame of the Small Spacecraft Mission Service project, 2017