BFS « BACK FROM SPACE »

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1. ABSTRACT

The paper presents e.NOVA Aerospace's innovative approach to atmospheric re-entry technology through the development of the Back From Space (BFS) project. The BFS aims to provide a low-cost, adaptable means of transporting payloads from orbit to Earth, addressing the growing demand for efficient microgravity environments for scientific and commercial purposes. Drawing on advancements in CubeSat technology and flexible thermal protection systems (F-TPS), the BFS project seeks to overcome limitations in current microgravity research methods by offering autonomous re-entry capabilities for small payloads. The paper discusses the evolution of CubeSat technology and highlights similar projects developed by leading space agencies such as NASA, ESA, and China. It delves into the market demand for microgravity environments and outlines the mission objectives, development process, and challenges faced by the BFS project. Furthermore, it examines the mechanical design, aerodynamics, landing capabilities, electronic unit, and roadmap for future development. Through collaborations with industry partners and research institutions, e.NOVA aims to revolutionize access to space and enable frequent, cost-effective microgravity experiments and payload returns.

2. STATE of the ART

Since the creation of CubeSats in 1999, their technology has evolved and gained in size, weight, and price. The fundamental instruments onboard are now cheaper and much more accessible. At e.NOVA Aerospace, we chose to use said technology alongside our own and create a means of transportation low-cost and accessible to emerging NewSpace actors. Consequently, the BFS was defined as an atmospheric reentry kit, transporting our payload from lower orbit to land safely on Earth.

Several similar projects have already been developed by NASA, ESA, and even China. Here are some examples.

Historically, the IRDT project, based on a Russian inflatable design, was tested in Europe with few successes in early 2000. Later, NASA initiated research on a similar inflatable design which led to a suborbital demonstration (IRVE-2,3). The upgraded design, called HEART [1], was assumed to be able to reenter an entire ISS Module.

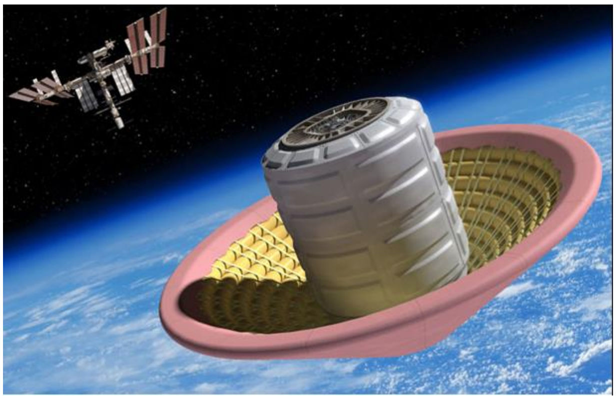


Figure 1: NASA HEART concept

The NASA ADEPT program developed and tested in suborbital, a mechanically deployable re-entry vehicle system for nanosats and spacecraft in 2014. This project uses a very performant F-TPS (Flexible Thermal Protection) allowing high-energetic reentries. More recently, the NASA LOFTID [2] was developed and an orbital demonstration flew successfully in late 2022. This device was foreseen as a reentry decelerator for the ULA’s next Vulcan rocket for the recovery of their propulsion module.

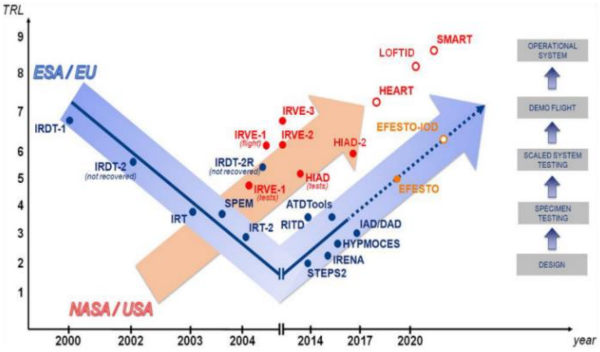


Figure 2: LOFTID Inflatable Heat Shield

In Europe, several projects were developed, but the most advanced project is the mini-IRENE project from the Italian agency ASI. They developed and tested a deployable decelerator. The projects were re-initiated at ESA with the LIED project for a large inflatable device for future Martian landers aiming to land heavy mass or higher Martian altitude. Later, the EU-EFESTO [3] was initiated and achieved in 2022 up to TRL6.

Meanwhile, China made an orbital attempt during the maiden flight of the Long March-5B rocket in 2020.

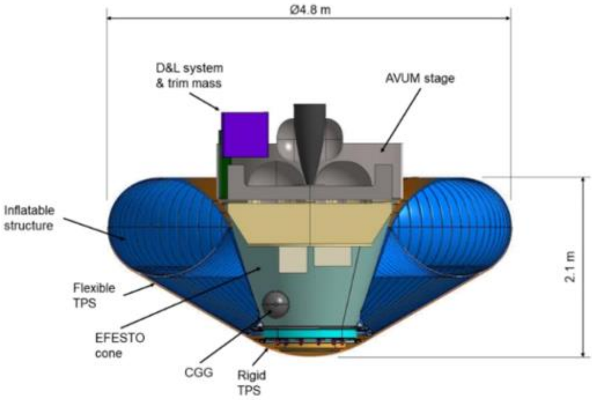


Figure 3: EFESTO system configuration for Earth applications

3. MARKET STUDY

Current means to creating a microgravity environment are limited. On-earth facilities can only produce for a few seconds (drop tube) to discontinuous minutes (parabolic flight). Even a suborbital flight can only produce a few minutes of microgravity at once. Another possibility would be to fly an orbital mission, with the associated difficulty of retrieving the payload.

Currently, the easiest option is to rideshare with multiple experiments on an ISS cargo. Unfortunately, the return volume and mass are very limited, hence expensive. Moreover, the mission schedule is driven by the ISS’s needs and scattered. A typical mission, without considering the waiting queue, is a minimum 6 months between first space exposure and sample return.

The idea behind our BFS project is to have an autonomous re-entry system for small payloads to allow the best possible retrieval delays. The mission duration should be driven by the payload as it could allow customization and new possibilities.

The BFS’s mission will depend on the payload. We can define two types of payloads: scientific and commercial.

- Scientific payloads are experiments requiring microgravity. For some experiments, analysis must be performed by experts back on Earth. The BFS can be mounted as rideshare on launchers making the flight much cheaper than before. The launcher will then bring the BFS and the payload to the orbit needed where it will stay for the specified duration. Finally, the BFS will bring the experiment safely back to Earth without human intervention. For more complex experiments requiring human intervention, the BFS offers the possibility to transport payloads from the ISS to the ground on demand, without waiting on the cargo spacecraft.
- Commercial payloads will happen more often. Our clients estimate the need to fly once a week or more for a period of a couple of weeks. In-orbit manufacturing is still in development but will likely play a major role in the industry of the future for specific, high-quality, and high-added-value products. Some of these products can be 3D-printed organs for medical purposes, high-quality optical fibers, or very sensible crystals.

The pharmaceutical industry is worth billions of dollars every year. Within this budget, a large portion is dedicated to testing. Being able to develop new drugs in space will improve success rates and delays at a fraction of the cost. This is due to accelerated and multidirectional growth offered by microgravity. Space Pharma is a pioneer in in-orbit manufacturing. They are aiming for an orbital deposit in LEO with a need for one payload return every month. Space Pharma flew several experiments on the ISS and in an autonomous way on CubeSats. Alongside several other companies, they intend to democratize in-orbit manufacturing of vaccines, molecules, and much more. The achievement of a low-cost round trip to space may revolutionize this industry.

4. DEVELOPMENT IMPLEMENTATION

Back in 2019, e.NOVA was created with the legacy of ALTRAN Research in space debris, re-entry safety, and design for demise techniques. Therefore, e.NOVA’s first internal project is a software specialized in mission and re-entry analysis called MAGNUS.

Later, e.NOVA developed an F-TPS shield made of ceramic textiles. This shield is flexible, foldable, and can be adapted to any size or weight. Different textiles can be used depending on the energy that the system will endure.

With this Flexible Thermal Protection, e.NOVA decided to tackle their biggest project yet, the BFS project. Hardware combining innovative re-entry techniques for NEWSPACE applications in the CubeSat and NanoSat size and market. The BFS is an atmospheric deployable re-entry kit made to recover payloads from orbit. The F-TPS shield that it uses is the cheapest one e.NOVA has to offer, allowing it to protect a 50kg NanoSat during re-entry.

The company answered a call for proposals related to the French “Plan de Relance” funding but focused on innovative technologies for Nanosat. The technology promoted was the flexible textile aerothermal protection needed to achieve a deployable aero shield. At a second bid, with an enlarged consortium teaming IFTH_FR (textile material and process laboratory), RTech (Hypersonic Computed Fluid Dynamics expert), and CNRS-Icare (Plasma wind tunnel test facility), we were awarded a contract allowing us to kick-of the project.

This comforted e.NOVA in the submission of this project to the 2022-23 BPI Call regarding In-Orbit Servicing. The submission was a success and e.NOVA is now part of the BIC ESA community.

More recently, we have received funding from our region (PIA4) to develop our last technological bricks. These bricks can be separated into four main RFIs. The Electronical Unit (EU) is primordial to the system for it will distribute the power, transmit to ground control, deploy the shield and the parachute, and emit a signal to locate the BFS. The Kinetic module (KIN) oversees the mechanical deployment of the shield. It is also supposed to withstand all the efforts during the re-entry. The Inflatable Atmospheric Deceleration module (IAD) is an alternative solution using inflatable materials to deploy the shield and withstand the efforts. Finally, the landing capabilities (LAND) is a fundamental module in charge of decelerating the BFS once subconical speeds are reached. It is also in charge of guiding the BFS toward the targeted landing point and landing the vehicle safely on Earth.

5. MISSION CHALLENGES

The main objective of the mission is to achieve a controlled reentry of the vehicle and target a landing zone. The scenario considered today is to recover the payload in remote areas such as Woomera or Utah test range with a non-controlled orbital vehicle but a controlled parachute and landing. The first challenge we faced within the project was the study of the re-entry trajectory and the assessment of the reachable landing accuracy. The influence of the different parameters on the final velocity has also been studied, as it is primordial for the touchdown system design. The scenario is based on an unguided descent from the surroundings of the International Space Station (ISS) or NEWSPACE’s usual orbits (<550km) down to the ground. A Keplerian trajectory serves as a first approach. Nevertheless, it is essential to consider the effect of the atmosphere. To this end, the internal e.NOVA software has been used to simulate the atmospheric re-entry. This software allows us to represent our trajectory on Google Earth Pro [4].

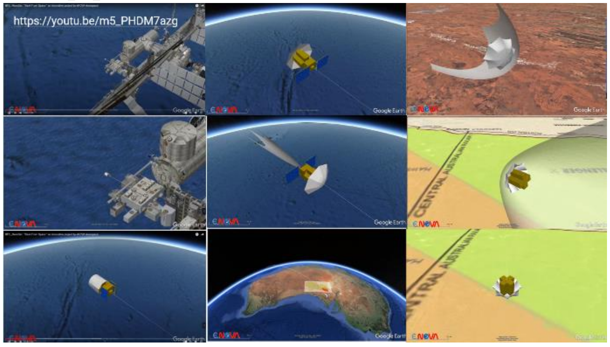


Figure 4: BFS Mission Trajectory

The main BFS spacecraft is planned to weigh 50kg, but other alternatives are considered: 25kg, and 100kg. Several parameters are fundamental to the landing accuracy budget. Namely, the ballistic coefficient of the BFS, the heating rate, and the initial velocity are some of the most important ones. A trade-off was made between a steep re-entry that provides an accurate landing but generates an unmanageable heat flux for our low-cost flexible thermal protection, and a much softer re-entry that is less intense for the thermal protection but can be much harder to predict re-entry length due to atmospheric uncertainties. As of today, we are aiming for a 75km perigee which guarantees a direct re-entry with a reasonable margin of error on a 100 square km landing zone. This landing zone will be shortened by our controllable parachute.

We face another challenge, the burn must be done in a reasonable time as orbits below 200km are very unstable, we must be able to deorbit in one orbit as soon as we go beneath that limit. Doubling the force of propulsion divides the duration of the burn needed. Also, electric propulsion is not recommended for re-entry boosts because of their low force, research is being funded to explore this possibility. Currently, we have had an RFI/RFQ with space propulsion provider Dawn Aerospace. Their 4U CubeDrive module [5] could fit our needs in terms of thrust and fuel capacity while staying within our volume and mass ratio. Unfortunately, because of their burn time, this solution is only viable for our small design, the 25kg CubeSat.

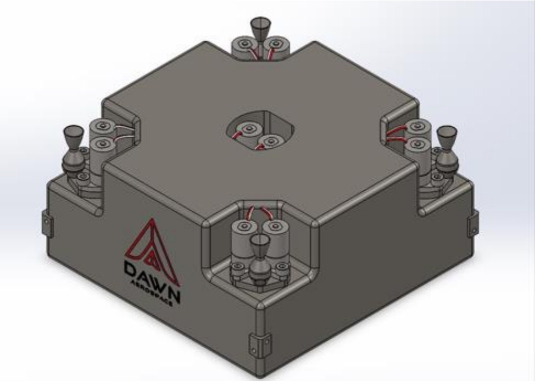


Figure 5: DAWN CubeDrive Propulsion Module

We are, thus, exploring the possibilities offered by OTVs and launchers with their LMD (Last Mile Delivery). The idea is to stay onboard their spacecraft and have them take care of our deorbiting boost. LMD launchers would then consume themselves in the atmosphere as the law forces them to. The OTVs, on the other hand, would propel us toward Earth before reigniting their motors and staying in orbit.

With few calculations, it's possible to determine where the last burn should occur for an ideal reentry and match the phasing burn at the same orbital point. That way, the phasing orbit is "halfway" through the re-entry orbit. Both the phasing and re-entry burn are made at the same position and in the same direction and we don't have to waste any delta-V for this maneuver.

If the landing area's latitude is below the orbit's inclination, there is no inclination change necessary, and reentry can be made on an ascending or descending orbit. If the re-entry corridor can't match with the trajectory, or if the landing site's latitude is outside the orbit's range, a first maneuver is necessary to adjust inclination, which can be done with very few Delta-V.

The last phase of the re-entry is determined by simulations using software like Debrisk, Astos, or Dram. The first position of our simulation corresponds to the last thrust impulse, at the apoapsis. By using reentry time, downrange, and knowing the re-entry orbital period, we can simulate the keplerian parameters of this last orbit. We are then able to our target.

6. BFS CONCEPT & FAMILLY

BFS is the name we use for multiple concepts and products, all of which have the same objective: to bring payload "Back From Space". The first milestone we reached was the validation of our flexible thermal protection system. We are now developing our second technological milestone: the landing capabilities.

The BFS family [6] is currently composed of two designs: The 50kg, 24U, and the 25kg, 12U.

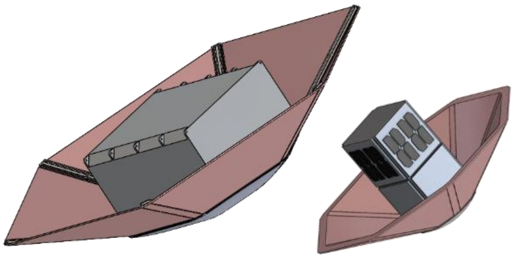


Figure 6: BFS family

7. BFS F-TPS and AEROTHERMODYNAMICS

The Flexible Thermal Protection System (F-TPS) is a core element implemented on deployable projects previously presented. Defining, selecting, and dimensioning this element is a key technological block for any project.
The first step in such a study is to assess the aero thermodynamical effect of the re-entry trajectory on the thermal protection of the vehicle. This was imitated by e.NOVA through a bibliographic review on state of the art and its experience in re-entry calculation software. Consequently, a max flux specification of 400kW/m² is aimed to be compatible with most oxide ceramics F-TPS. This led to consider a low ballistic coefficient of 25 kg/m² and a drag coefficient of around 1.3 for a conical shape of 60°.

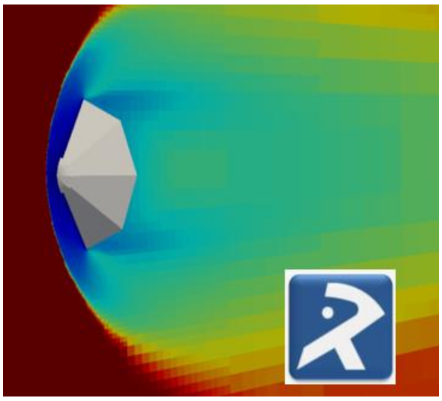


Figure 7: RTech's CFD Graph of the BFS

Those assumptions were confirmed by our partner RTech CFD in the first runs of activity. They used their own development software PAMPERO, MISTRAL, and BLIZZARD to produce the graph [7]. Those flux and temperature profiles were injected in a 1D thermal calculation to assess the performance of the F-TPS with different configurations. First, we tried isolating the F-TPS. Then, we tried isolating the payload before isolating both of those components.

The next step of the project is to procure the materials for our thermal protection system. Contrary to insulating material, aerothermal textiles are much harder to obtain. They are not accessible for industrial and low-cost approaches as required by the NewSpace applications. Therefore, e.NOVA raised an overview of the F-TPS references available on the market around the world. This listing was raised on both external aerothermal textile materials (1rst layer of the BFS) and internal insulating felt materials (2nd layer of the BFS).

The performance of the materials in temperature can be summarized as below:
Oxide Ceramics

- Silica Glass < 1000°
- Silica Oxide (St Gobain Quartzel) < 1200°C
- Alumina Oxide (3M NEXTEL) < 1400°C
- Mix of Silica / Alumina oxide (3M NEXTEL)
- Zircon, Cerium, Yttrium oxide (rare metals)

Composite Ceramics

- Silicon Carbide
- C/C (Carbon/.Carbon)

The outcomes of this market survey demonstrated the few cooperation of US providers. Unfortunately, they remain out of reach for non-US start-up companies as e.NOVA. By chance, European providers are more customer-oriented and could access most of the US References. The cost aspect is their downside (>1000€/m²). The cost objectives required by NewSpace applications is below 250€/m².
After deep investigation, the most promising sources is based in DITF research, a German research laboratory having forwarded its technology to St Gobain France for later production of oxide ceramics with a production objective of a few years. St Gobain is currently addressing the production of Quartzel (silica oxide) as the main material for RF transparency for aircraft radar nose cones or electromagnetic-guided missiles. We could use this same material for our aerothermal shield.

Figure 8: CNRS-ICARE Plasma wind tunnel test

Further characterization sequences were planned for mechanical testing in temperature and for process assembly (weaving, sewing) at the IFTH laboratory and in the CNRS-ICARE aerothermal plasma wind tunnel facility [8]. Mechanical tests were a success for both NEXTEL and NEXTEL-Alternative materials in temperatures up to 1400°C. Quartzel demonstrated an outstanding resistance to these temperatures. On the other hand, zyrcon and pyrogel materials were discarded from the selection due to quick ablation during manipulation, creating an unacceptable particle contamination for space applications.

Once the F-TPS was in our possession, we developed our internal capacity to sew, fold, and attach it to the rest of our structure. In that sense, we bought a professional sewing machine able to manipulate the F-TPS with agility. E.NOVA also developed different ways of folding our shield depending on our specific needs (under the dome, around the payload, etc…).

8. BFS MECHANICAL PARTS & DEPLOYABLE SYSTEM

The system is composed of a front dome and trenched canvas to complete the deceleration cone. Eight ribs are articulated from the cone base to form an extended cone, or more exactly an octagonal pyramid. The structure is completed with struts that unfolds and holds the bottom of the ribs, forming a general shape of a 120° blunted cone.

The objective is to obtain this shape once the shield is deployed. A trade-off of multiple designs is ongoing.

The first of which [9] is the simple mechanical opening of the shield. The F-TPS is folded around the payload making the deployment without risk. The advantages of such a design are the simplicity of fabrication, the slow deployment, and the mechanical resistance of the ribs. This design is not perfect for it has multiple flaws. First, having the F-TPS around the payloads makes it impossible to fit inside a deployer without adapting either the payload or the deployer. Furthermore, the struts have a length superior to the payload's making it complicated to attach to a separator ring. Finally, the F-TPS is surrounding the payload and therefore blocking all transmissions from or to it forcing us to deploy the shield as soon as possible.

Secondly, e.NOVA is looking into inflatable mechanisms for the deployment of their shield. Although this technology has some clear flaws such as the added weight or complications due to cold gazes, it can be a reliable and adaptable deployment system. It would allow e.NOVA to think bigger and one day propose a BFS kit for payloads from 100kg to 1T.

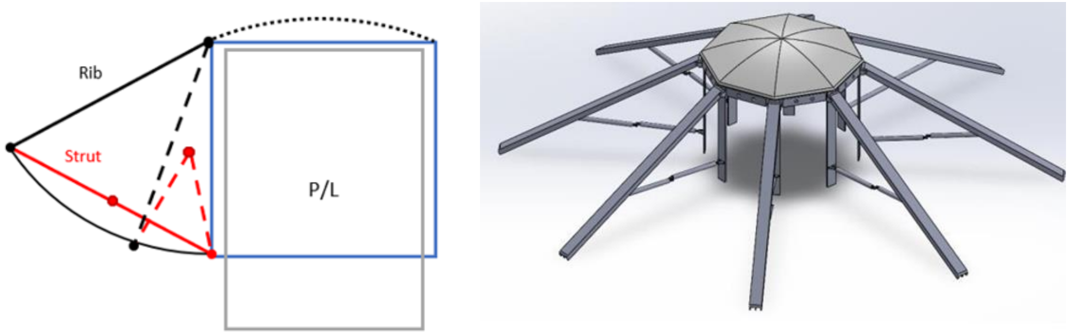


Figure 9: Sketch and 3D design of e.NOVA's first mechanical deployment system

More recently, and with the help of Space Composite Structures, e.NOVA started to study an alternative way of deploying mechanically the shield. Our new design [10] has the advantage of being simple, resistant, and unreversible. It is also extremely lightweight and economical. It allows us to hide the F-TPS under the dome during launch. The main advantages of having the F-TPS under the dome are:

- Allowing the BFS to fit inside a low-cost deployer for RideShare launches.
- It will not block transmission allowing us to deploy the shield when needed.
- The ribs, the struts, and the F-TPS can be as big as needed allowing design changes.
- The mechanism is stable while open therefore, once released, we are certain it will take the shape desired.

The main flaws of the system are:

- Having the dome further from the center of gravity changes the ballistic coefficient. Fortunately, by smartly folding the F-TPS, we can bring the dome closer during the deployment.
- The deployment will create friction on the F-TPS. Studies must be done to ensure the safety of the shield.
- This design will deploy the shield rapidly. To limit the resultant spin of the vehicle, two options are proposed: We can add a mechanism that will slow the deployment, or we can ensure that all sides of the vehicle will deploy simultaneously.

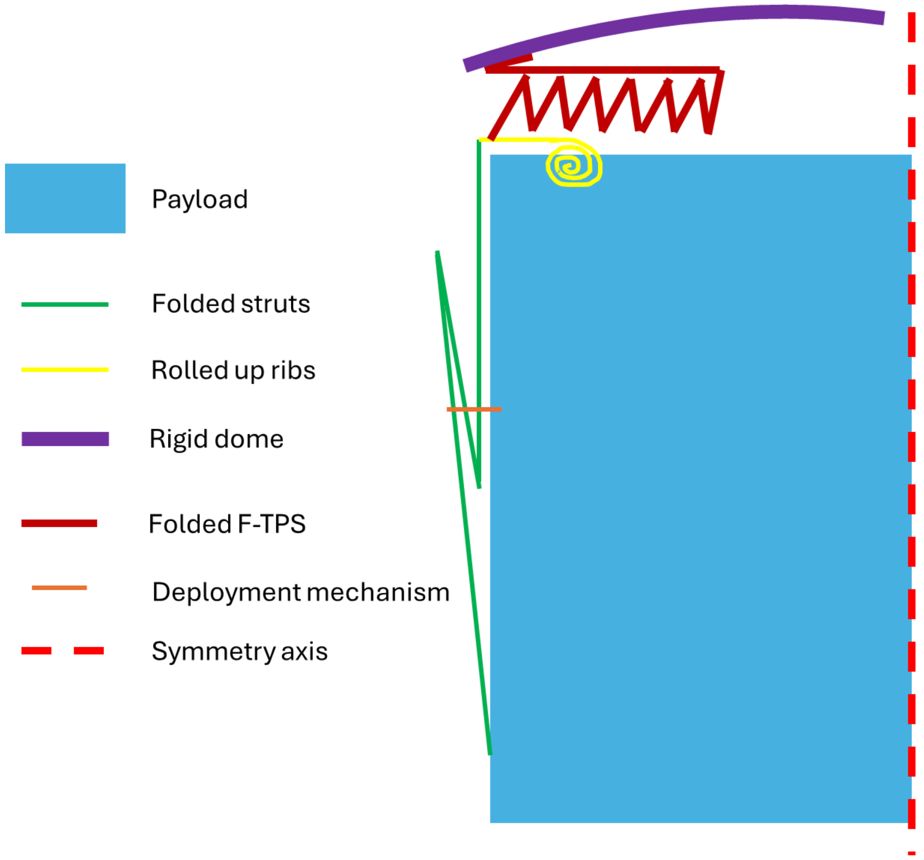


Figure 10: BFS deployment technology

In any case, the struts must resist the re-entry forces. The F-TPS needs to be as tight as possible to avoid heat concentration as much as possible. With the FEM Analysis [11] we were able to determine how tight the F-TPS needs to be and what our margin for error is.

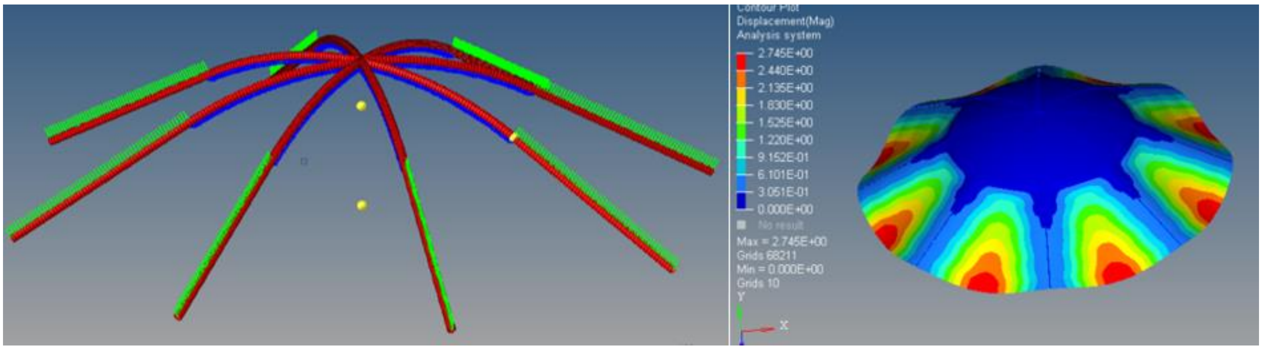


Figure 11: FEM Analysis on Ribs & F-TPS under Max dynamic pressure

9. BFS LANDING CAPABILITIES

The main goal of the BFS is to land the payload safely on Earth with a low-impact force. As of today, the BFS will land on the ground thanks to a parachute. We have recently received funding from our region (PIA4) allowing us to develop this last technological brick.

We are working with Opale Paramodels, a partner with experience in developing parachutes related to space applications [12].

The BFS aims to be as low-cost as possible. Therefore, we chose to have as little propulsion as possible. Without it, and in a ballistic re-entry, our landing accuracy budget has a radius of 50km. Our objective is to lower this budget as much as possible. We intend to do so by making this parachute controllable and autonomous.

According to our latest studies, the BFS would reach subsonic speeds around 35km of altitude. This should be sufficient for the parachute to open and glide towards the target point with small, lightweight, and electrically low-consumption motors. Opale has already made such a controllable parachute and is a great help in our studies.

Figure 12: Opale Paramodels Experience

Once the BFS has landed with a maximum speed of 5m/s, it will roll on its dome minimizing once more the impact received by the payload. A GPS beacon will then allow us to retrieve the payload. E.NOVA’s objective is to retrieve and ship the payload back to the customer within 24 hours.

10. BFS ELECTRONIC UNIT

The unit aims to provide the following tasks:

- Environment Recordings (Pressure, temperature, and microgravity)
- Dynamic Recordings (Accelerations and rates)
- Data Storage
- Data Transmission (RF SATCOM)
- Radio RF beacon (Recovery purposes)
- On-Board Computer
- Battery Pack (28W/h – 6 to 12h autonomy after landing)
- Power Management
- Deployment (F-TPS and parachute)
- Motor activation (Controllable parachute)

During our demonstrator flight, the objective is this module will also collect lots of data of our re-entry. These data will hopefully allow us to validate the concept and to improve further design iterations. Our maiden flight will take place end of 2025. We are currently looking into multiple micro launchers in Europe.

During our commercial flights, all the data is to be sent to the ground via the IRIDIUM link. These requirements are divided into mission requirements (MR), physical requirements (PR), and auxiliary requirements (AR). The BFS avionic schematic [13] represents how some core elements of this unit will interact with each other.

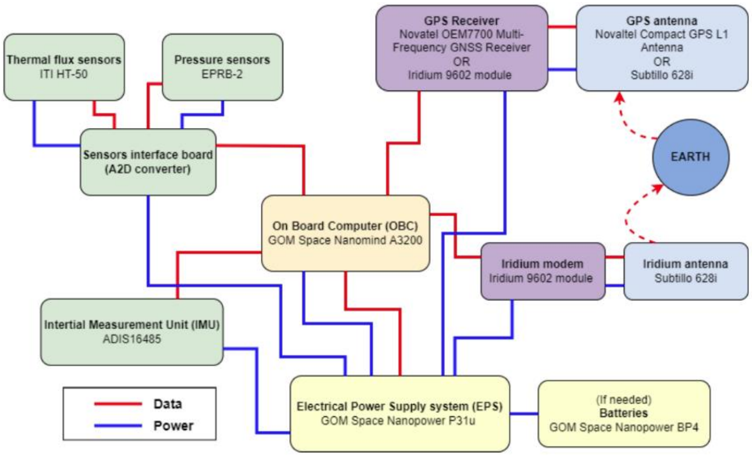
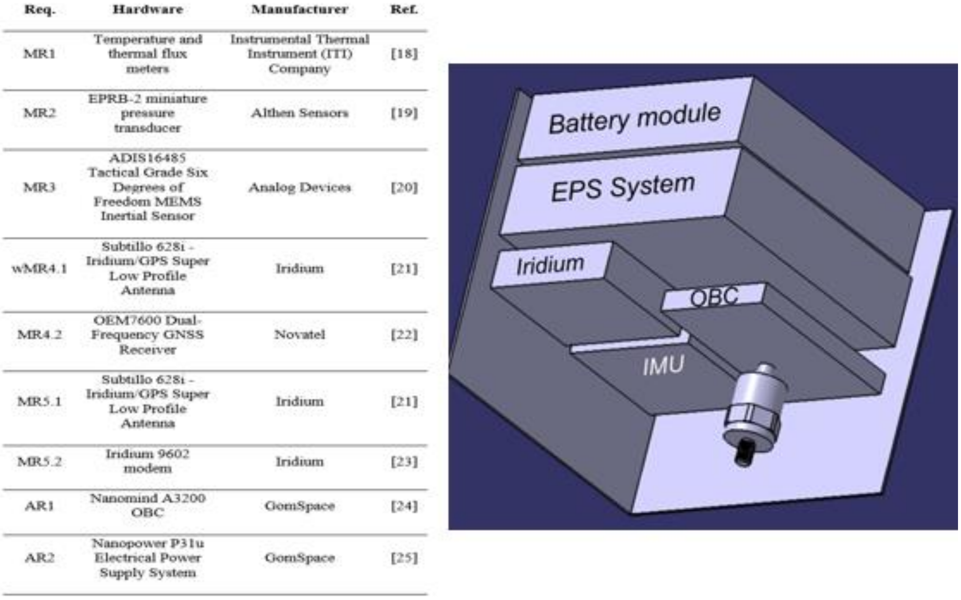


Figure 13: BFS avionic schematic

Hardware choices were made to address the preliminary set of requirements for the payload. The choices presented. Finally, a draft of the CAD model [14] was developed to verify that all these components would fit in the 1U module that is allocated for them. We can easily observe that all the components fit in the 1U module. However, other points would need to be considered. For instance, the harness with all the cables needs to be integrated into the design.



Req.	Hardware	Manufacturer	Ref.
MR1	Temperature and thermal flux meters	Instrumental Thermal Instrument (ITI) Company	[18]
MR2	EPRB-2 miniature pressure transducer	Althen Sensors	[19]
MR3	ADIS16485 Tactical Grade Six Degrees of Freedom MEMS Inertial Sensor	Analog Devices	[20]
wMR4.1	Subtillo 628i - Iridium/GPS Super Low Profile Antenna	Iridium	[21]
MR4.2	OEM7600 Dual-Frequency GNSS Receiver	Novatel	[22]
MR5.1	Subtillo 628i - Iridium/GPS Super Low Profile Antenna	Iridium	[21]
MR5.2	Iridium 9602 modem	Iridium	[23]
AR1	Nanomind A3200 OBC	GomSpace	[24]
AR2	Nanopower P31u Electrical Power Supply System	GomSpace	[25]

Figure 14: BFS hardware choices & CAO model of the EU

11. ROADMAP

Thanks to the "Plan de Relance" funding back in 2022, we were able to develop our first core element, the F-TPS shield. We have gained the knowledge and the capacity of sewing and folding the F-TPS allowing us to adapt it according to our needs. In 2024, we received the funding "PIA4" of our region that should allow us to finish the development of all other core elements. Within the next four to six months, our parachute and landing capabilities should be operational and we are planning to test them with our partner, Opale Paramodels. The development of the electrical unit will occur in parallel. We hope to demonstrate all the technological bricks working together with our demo flight in late 2025. We are currently negotiating with different European micro launchers to join them on their maiden flights.

The goal of the BFS is to propose a low-cost, adaptable, and easy means of transportation from orbit to Earth. We will propose a 50L, 24U laboratory box where the client will be able to add his

production or experiments and not worry about the rest. Although we are not planning on proposing pressurized zones in the box for now, it will probably be a possibility in the future.
The BFS will allow NewSpace actors to launch their products in space every month if not more frequently. It will stay in orbit for as long (or as short a time) as necessary depending on the client’s need.

Different contacts have been established with different companies such as EXOLAUNCH for separation rings and deployers, Dawn Aerospace for propulsion modules, Space Composite Structures for deployable mechanisms, and Opale Paramodels for the parachute and landing capabilities. RFI’s have been sent to potential clients, launchers, and OTVs. E.NOVA is starting its research for investors. Although our product is not yet operational, we believe investing companies are interested in our project and might want to fund us.

Finally, e.NOVA has realized that their F-TPS technology could be extremely useful for micro launchers aiming at reusability. The F-TPS can wrap itself around the parts of the launcher most exposed to the re-entry heat flux and thus protect it and allow the company to reuse it. Requests for Information were sent to the concerned parties.

12. ACKNOWLEDGEMENT

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We are grateful to our sponsors and our country for all their financial support. Thank you for selecting us and granting us the “Plan de Relance” [15] and the “PIA4” [16]. Thank you to ESA for nominating us as part of the BIC family.
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Finally, the author would like to give a big shout-out to all of e.NOVA’s partners for their participation in this beautiful project. Thank you to the CNES, to IFTH, RTech, Nimesis, Opale Paramodels, Dawn Aerospace, Space Composite Structures, Hemeria, Aldoria, and especially to Paul KAMOUN with Space Pharma.

Figure 15: Sponsors for the “Plan de Relance”

Figure 16: Sponsors for the "PIA4"

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