Actively Flying a High Quality Free-Fall trajectory in the BOOSTER Sub Orbital Aircraft *

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Throughout the world today, there are a number of different platforms available to conduct microgravity research. There are many flying microgravity platforms that can accommodate extended duration payloads. They all vary in quality, cost, availability, and frequency.

BOOSTER is developing a sub-orbital aircraft with a set of characteristics that could be well suited to flying experiments for microgravity research. The aircraft itself is subjected to a ballistic flight trajectory that approximates free-fall. However atmospheric drag, internal vehicle systems, and orientation manoeuvring can appreciably diminish the quality and length of time during which a microgravity quality trajectory is available.

Also the presence of passengers and pilots affect this quality by setting up low level shocks and vibrations that resonate through the craft and can find their way into an experiment.

This paper references some of the world's main protagonists in order to benchmark quantitatively what is available for the purpose of comparing these alternatives with what could be offered by a sub-orbital aircraft.

Many lessons have been taken from studying how existing platforms provide their microgravity environment and from feedback from researchers who have used these facilities.

A benchmarking of the many different platforms has allowed us to compare and contrast the quality of the service provided and to also gauge their value. It has revealed that most research opportunities and conditions vary greatly. For some platforms, the particular engineering or flight profile operations of the platform itself reduce the quality of the microgravity that can be obtained.

BOOSTER has also found that there is still great room for improvement in microgravity quality and that a more customer orientated flight service is possible. Some of these lessons are already being incorporated in the sub-orbital aircraft design.

Both filtering and damping of the interfaces with the experimental apparatus are possible. And we have found through some of our flight testing work that specific trajectories can be flown by our sub-orbital aircraft with the use of special piloting skills and algorithms to give a microgravity research optimised flight.

This paper presents many of these flight optimisation ideas and discusses some of the active solutions that can greatly improve the environment with a presentation of what trade-offs are possible for the research community to consider.

It is also possible that a sub-orbital flight trajectory could provide a high quality environment in specific areas that would be difficult to replicate using any other currently available platform.

Summary

This paper aims:

1) to chart the free-fall characteristics of a suborbital flight using the BOOSTER sub-orbital aircraft as the reference,
2) to compare it with established microgravity test platforms, and
3) to offer some design and operations improvements that can improve the sub-orbital environment microgravity quality with a qualitative discussion of what can be accommodated.

***** Paper accompanying a presentation made at the Next-gen Sub-orbital Researchers Conference held on the 27-29 Feb. 2012 in Palo Alto, California.

BOOSTER and the BOOSTER SOA

BOOSTER leads a consortium of European and US based aerospace partners that are currently developing a sub-orbital aircraft (SOA) that will be operated by BOOSTER on US soil in a few years' time.

This sub-orbital launch system, as currently designed, can carry up to 8 passengers, 2 pilots, and experimental payloads on a sub-orbital free-fall trajectory to higher than 100 km altitude.

The chosen architecture as well as the size and flight performance of this vehicle lends itself to a number of unique selling points that could be of value to research and experimentation. BOOSTER plans to lead-in a number of customers with an earlier start of payload testing flight operations using nearer term assets.

Figure 1 . BOOSTER Sub-Orbital Launch System

The flight architecture is based on the reuse of commercially available hardware and technologies with the aim of operating within the rules of international air law for all atmospheric flight: i.e. holding a Type Certificate.

A two stage system was therefore chosen where the first stage would be a conventional commercial jet aircraft, similar to an Airbus A300-600, capable of carrying the sub-orbital aircraft to an altitude of approximately 40 thousand feet (12 km) for launch. Its characteristics allow it:

- To operate at a commercial airport, integrate with ground infrastructure and comply with air traffic control procedures and regulations.
- To act as a "recovery and repair" platform for the sub-orbital spacecraft, if unable to launch the same
- To ferry sub-orbital spacecraft for maintenance or publicity, and
- This carrier itself will have some unique external and internal load-carrying capabilities through which additional services can be leveraged.

Figure 2 . The SOA flying alongside its Carrier

The Sub-Orbital Aircraft is a rocket boosted glider with 2 rocket engines fuelled by liquid hydrogen and liquid oxygen. This propulsion choice was performance and environmentally driven. The sub-orbital experience includes the following:

1. Rocket engines kick-on after separation from the carrier aircraft when pull up begins, are operational for just under 2 minutes, and accelerate the craft to 4 times the speed of sound on a vertical ascent up through the atmosphere.
2. The engines shut-down and spacecraft continues coasting upwards into the edge of space.
3. When external drag forces become negligible, the vehicle, its occupants, and its payloads begin "free-falling," at which point these passengers can unbuckle from their seats and float around in a voluminous cabin of more than 3 m (10 feet) in diameter and better than 6m (20 feet) in length.
4. The cabin has large panoramic windows that provide unobstructed views of the Earth's landmasses and cloud structures for almost 1000km in every direction, and the thin blue atmosphere along the distant curved horizon set against the dark background of space.
5. Free-fall (weightlessness/microgravity) lasts between 3 to 5 minutes depending on the maximum altitude reached. Passengers will get a first taste of real space with this

experience. Passengers return to their seats for deceleration and the onset of the g-loads.

6. Spacecraft points nose first towards the Earth with the passengers' seats rotating downwards as deceleration increases.
7. Spacecraft re-enters the atmosphere, slowly pulling up and thus controlling g-loads.
8. Re-entry lasts half as long as the boost upwards, with passengers subjected to decelerations that would peak at 4g [1].
9. The aircraft transitions into a fast horizontal glide in the stratosphere.
10. The gradual gliding descent culminates in a landing at the air/spaceport.

The SOA is designed to meet existing regulations for conventional subsonic commercial (general aviation) aircraft for the carriage of passengers.

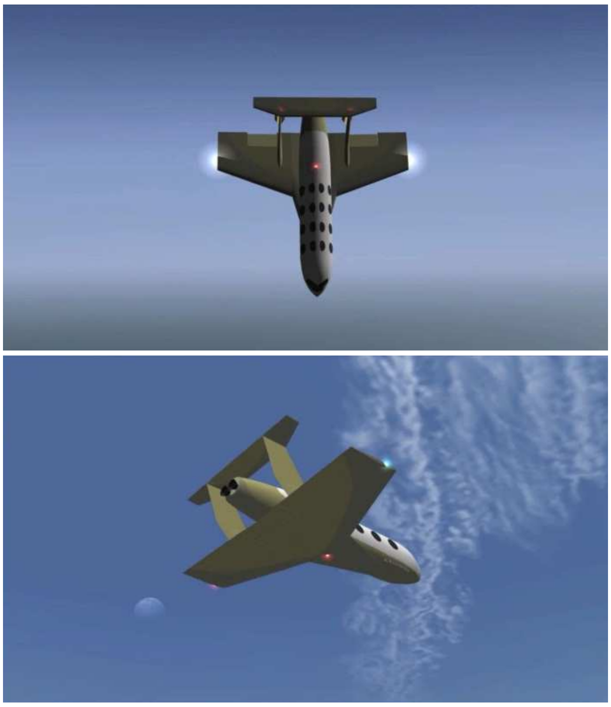

Figure 3 . Photos of the SOA in free flight

Benchmarking Freefall Research Opportunities: Microgravity platforms

There are currently a number of different means of achieving microgravity conditions for conducting experiments. Different platforms have their advantages and disadvantages [see Penleya et al, Thomas et al, and Tsujino]. A number of the more common means are presented in this paper and their conditions are discussed.

They have been separated into 3 main categories. They are:

1. Ground based platforms
2. Orbital(space) based platforms
3. Platforms in between: i.e. Sub-Orbital

Let us look at each set separately.

1. Ground Based

These platforms take the form primarily of a Drop Tower arrangement.

Drop towers have been built of varying heights by different countries and institutions so that reasonably short duration microgravity experiments can be conducted without necessarily having to fly into space. The freefall of an experimental package provides "microgravity" conditions for a duration that depends on the height of the tower. Freefall through the air initially gave microgravity levels of the order of <1000µg. Later designs improved this to <10µg by adopting different techniques to counter some of the perturbing effects experienced by the payload during its acceleration due to gravity. The best method is to evacuate the tube. Another method counters air drag by either isolating the air flow from the experiment or by driving the experiment downwards at an acceleration of 9.8m/s or 1g using a thrusting device.

There are a number of small towers that give 1-2s of freefall. These find themselves frequently in universities. However NASA has an evacuated tube free-fall tower that can provide an experiment with up to 5.2s of 10µg conditions. Japan had a 490m drop facility installed in a decommissioned mine shaft at the Japan Microgravity Center in Kami-Sunagwa, Hokkaido with a 10s free-fall capability. The drop platform was large. (It had a 5 tonne mobile mass) but it

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[1] A multiple of gravity: $g \approx g_0 = 9.8\ m/s^2$. $4g_0$ is the feeling of 4 times your weight on the surface of the Earth.

gave a <10µg microgravity level. It has since been shut down because it was expensive to operate [Tsujino].

A major disadvantage of the drop tower solution is the short duration of the microgravity where the cost of building a tower especially with evacuation facilities is high and the utilization rate can be low due to the recycling of the vacuum between tests and the time required for pre-test and post-test processing.

Germany has at the University of Bremen a 146m drop tower where the shaft can accommodate a 160kg payload on a 400kg platform[2] measuring 700mm in diameter and 950mm in length. Using its unique catapult launch system, this facility also offers microgravity levels of <10µg for 9.3s duration. It can drop up to 3 times per day although typical campaigns achieve an average of 2 drops per day. It is currently the longest duration and best quality drop tower in the world where the free-fall quality across the frequency spectrum achieves a 10µg to 1µg microgravity disturbance level [**Figure 4**]. Nevertheless, payloads are subject to 30g accelerations and 50g decelerations with physical access to the experiment still restricted to up to 2 hours prior and post-test due to the drop operation process.

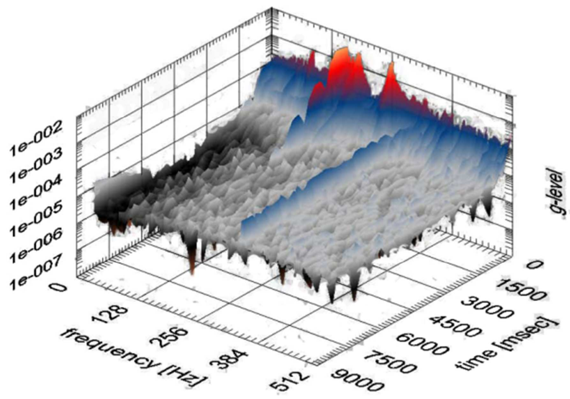

Figure 4 . µg environment in the ZARM tower

2. Orbital Space Based Platforms:

The International Space Station (ISS)

The ISS is currently the world's main reference facility for microgravity research [Penleya et al]. The US, the European countries (ESA), Russia, Canada and Japan all offer dedicated facilities and modules for their microgravity experiments. Japan also offers use of its considerable internal and external facilities under openly available commercial contracts. The ISS orbits at an altitude of a maximum of 400km above the Earth. It provides long periods of microgravity at a level of 10^{-6}g. It is man tended with astronauts capable of running experiments. It is serviced by Russian (Soyuz and Progress), European (ATV), and Japanese (HTV) passenger and cargo ships. In a few years, it will also be serviced by a new generation of US ships (Dragon and Cygnus).

As a large orbital facility, the ISS is subjected to a continuous atmospheric drag deceleration of the order of 1 to 3 x 10^{-7}g. Also depending on the position of the experiment with respect to the flight centre of mass, it can be subjected to a continuous centripetal force.

This continuous atmospheric drag must be corrected for to maintain orbit. And this is done using a rocket re-boost of the Station. From **Figure 5**, it is apparent that these re-boosts occur frequently. And they destroy the microgravity environment when they are underway. Therefore the ISS does not really experience continuous microgravity conditions for more than 2 months on average.

Furthermore, it is clear that the vibration environment can be high at certain frequencies [**Figure 6**] due to the fact that the ISS is a large, complex and manned facility where maintaining the microgravity is but one of its objectives. The US has worked with Canada to develop isolation techniques for controlling perturbations in the microgravity racks. They have achieved successful results, but the mechanisms have proven to be complex.

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[2] ZARM proposes a future enhancement of its catapult system allowing for a heavier capsule of up to 500kg.

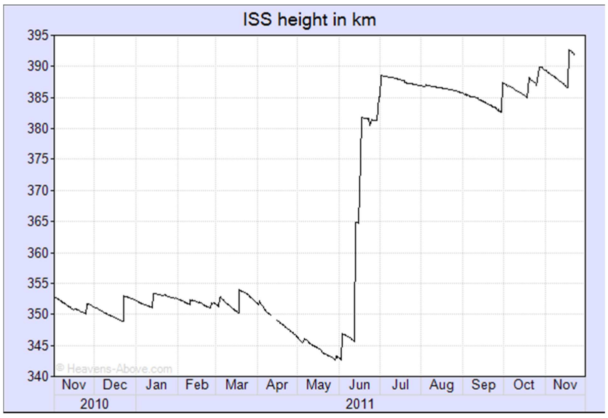

Figure 5 . Most recent ISS orbital apogee sample [3]

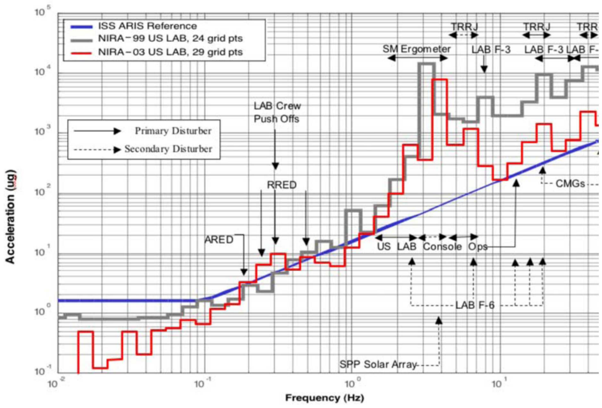

Figure 6 . Unfiltered µg environment in the ISS US Destiny module [Penleya et al].

The ISS is also subject to very extensive safety rules to protect the facility and its occupants. This has been found to be very discouraging to experimental research. Compliance is time consuming and expensive and preparations for approving access to the facility take years.

With the retirement of the Space Shuttle, transportation opportunities to and from the facility are now increasingly restricted, although once an experiment is installed, it can potentially run for many years providing the longest and highest quality man-tended microgravity research opportunity: for the present and for the foreseeable future.

Recoverable Satellites and "Stations"

Manned facilities give experimentation the flexibility needed to handle complexity. Nevertheless, for certain experiments, a higher quality, shorter duration and therefore riskier environment can be tolerated.

Dedicated satellites can provide an on-orbit laboratory for conducting research in microgravity as well as for materials processing and production. The satellite would fly a low Earth orbit of typically 500km in altitude where continuous microgravity levels of better than 10^{-5}g and vacuum levels of 10^{-6}mbar can be obtained for a few months duration.

Some materials processing experiments would require a few hours of operation and can only be conducted in the high vacuum and high quality µg available in space. Some plant biology experiments would require a microgravity environment for 1-2 months. These are served well by the recoverable satellite that can be recovered safely through a de-orbit, re-entry, and recovery manoeuvre.

The recoverable satellite is also an attractive proposition to those countries that do not have access to the ISS. For example, both China and India have developed recoverable satellites. China has its 'FSW' series. India has its 'Microgravity Applications Recoverable Satellite' (MARS).

Prior to the ISS, many countries had their own recoverable satellite. Russia developed FOTON. Germany and Japan flew the 'Express'. The US had developed the 'COMET' and 'RRS' (Reentry Reusable Satellite) exclusively for conducting microgravity experiments. The European countries flew Spacelab and EURECA using the Space Shuttle to transport them. All of these facilities are now defunct except for FOTON which is still available and which has flown a number of times in the past decade.

For certain microgravity research and future processing/manufacturing, the unmanned or man serviced recoverable satellite still remains a promising alternative to the ISS. The Bigelow Aerospace modules are a recent and commercially interesting solution that may soon

[3] http://www.heavens-above.com/IssHeight.aspx (retrieved December 2011).

be of great utility[4]. Bigelow is a very promising development and could be a potential game changer in terms of:

1. The quality and accessibility of the facility: They are a commercial provider that will provide their services on a commercial basis. They already have a number of path finding agreements with countries around the world. Many of these are not traditional spacefaring nations. They will become such through the Bigelow services.
2. The sheer size available for experiments and manufacturing: The launch of an operational Bigelow facility would immediately double the worldwide microgravity real estate overnight.

Nevertheless, access to these “free flying” platforms is still very expensive due to their launch costs and infrequent with similar lead times in preparatory campaigns as those experiments going to the ISS.

However, experiments accessing man-tended orbital facilities can be far more delicate than those flying on robotic platforms as they will be handled within the same tolerance limits used for humans.

3. Platforms in between:

Parabolic flights

Aircraft can offer free-fall conditions for durations of up to 25s by executing a parabolic manoeuvre along the flight path.

The US National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Ecuadorian government, all have converted jet aircraft that have offered microgravity research facilities. A number of tests can be carried out in a single day with up to 30 parabolas of more than 20s duration being made during the 2-3 hour flight giving a total cumulative free-fall of 10 minutes per day.

Previously, NASA had offered the KC-135A aircraft up to 2005, when they began using a McDonnell Douglas DC-9B (C-9) aircraft. ESA had been using a Caravelle aircraft. Today, NASA procures services from the Zero Gravity Corporation that operates a commercial, converted 727 aircraft. ESA also procure services from Novespace who operate a converted A300 that is supported by the French Space Agency (CNES).

Partial Gravity Requirements	Time Requirements (continuous seconds)
0.00 g +/- 0.02 g	10
0.00 g +/- 0.05 g	17
0.10 g +/- 0.05 g	20
0.16 g +/- 0.05 g	20
0.20 g +/- 0.05 g	20
0.30 g +/- 0.05 g	20
0.38 g +/- 0.05 g	20
0.40 g +/- 0.05 g	20
0.50 g +/- 0.05 g	20

Figure 7 . Parabolic Flight Specification [see NASA report: IG-10-015]

Parabolic flights can offer disturbance levels of better than $5x10^{-2}$g for >10s. If the experiment is allowed to free-float, then a 10^{-4}g level is possible, although safety protocols dictate that it can only do so freely for about 5s per parabola.

The external airflow and engine operation also creates a very noisy environment during the parabola. These factors diminish the quality of the environment and their use is best for proving spaceflight experiments and for some of the more macro biological research. The length of the free-fall is also less than 20s at most. However they do offer a very short turn-around time (typically less than 2 minutes). Thus multiple parabolas can be flown on a mission (single flight). Investigators can also directly adjust their experiments whilst on-board or modify them between flights. A typical campaign lasts for a week for multiple flights.

Aircraft are also potentially much more accessible being able to fly out of commercial airports if necessary. Commercial rates for flight hours are also very accessible. The published hourly rate paid by NASA to the Zero Gravity Corporation was approximately $28k per flight hour for a 2 year 70 hour campaign in 2008-2009 [see NASA report: IG-10-015]. Such a cost could be shared between 10-15 experiments and 30-40

[4] www.bigelowaerospace.com/

experimenters. However, this also means that resources also need to be shared and the working environment can be very disturbed unless the flight is dedicated to a single experiment. A trade-off against real costs, useful results, and commercial confidence ensues.

Balloon drops

Balloon missions are used as drop platforms for microgravity research. Modern stratospheric balloons can reach altitudes of over 40km. There are a number of commercial and agency supported companies that use them regularly for a variety of high altitude missions that involve space science.

Germany and Japan have developed such systems. Germany has developed a microgravity test-bed named MIKROBA. It is recovered by a parachute. It offers a disturbance level of 10^{-3}g with a free-fall duration of 55 seconds. Japan has a platform with a payload free-fall drop altitude of 32km that offers a microgravity duration of 20s.

There are also flight campaigns in the US. NASA runs a high altitude balloon program. Additionally a private company called Near Space Corporation is proposing a balloon drop system using a glider aircraft for a landing recovery back at the base of operations that would allow a rapid turn-around of the research payloads. The glider would be dropped from a height of 40km giving similar free-fall performance to that of the German MIKROBA platform.

Balloon-drop tests offer advantages compared to parabolic flights in terms of the achievable free-fall duration and level of microgravity quality attainable, keeping the turn-around time short.

Sub-Orbital: Sounding rockets

A single stage sounding rocket such as the Maxus can carry an 800kg payload to a peak altitude of more than 700km and during its parabolic flight it can attain a free-fall disturbance level of better than 10^{-4}g for a duration of about 730s (>12 minutes). A 4 stage Black Brandt rocket can carry a 100kg payload to over 1500km altitude giving about 18 minutes of free-fall.

Germany, Japan, China, France, India, Poland, Iran, Britain, Australia, Sweden, and the US have used sounding rockets for conducting microgravity experiments. Payloads are subject to high accelerations and decelerations. Frequently, experiment payloads are recovered at distances that extend beyond the peak altitude where high costs can be incurred. And some of the sounding rockets have frequent recovery failures.

Sounding rockets can give access to a very high quality free-fall environment for more than 15 minutes. However, the cost of a launch can be anywhere from $1M to $10M making them still an expensive source of microgravity.

Benchmarking Free-fall Research Opportunities: A Performance Summary

There are a variety of different methods currently available to the investigator for accessing the microgravity environment. Each platform has advantages and disadvantages and depending on the experimental, budgetary, and political requirements: each option can be favoured.

The previous section of this paper served to present most of the currently available or foreseen platforms in order to benchmarking them. Further research also allows for a historical platform based presentation of microgravity flight options [Zhang].

Figure 8 gives a summary of what microgravity platforms can provide, what quality of disturbance is attainable, and for how long. It can be seen that the 3 distinct categories discussed in the previous section also are grouped into three distinct performance domains. An orbital platform provides the longest and best quality, but would be subjected to the longest lead times and costs. A ground-based platform is very accessible and of low cost, but provides the shortest duration. However, even for those short durations, a high quality (space-equivalent) microgravity environment can be obtained that in many ways can sometimes be better than the disturbance prone conditions of the International Space Station over a period of less than 10s. Nevertheless, the International Space Station (or a commercial equivalent such as that proposed by Bigelow) remains the best solution for very long duration man-tended research.

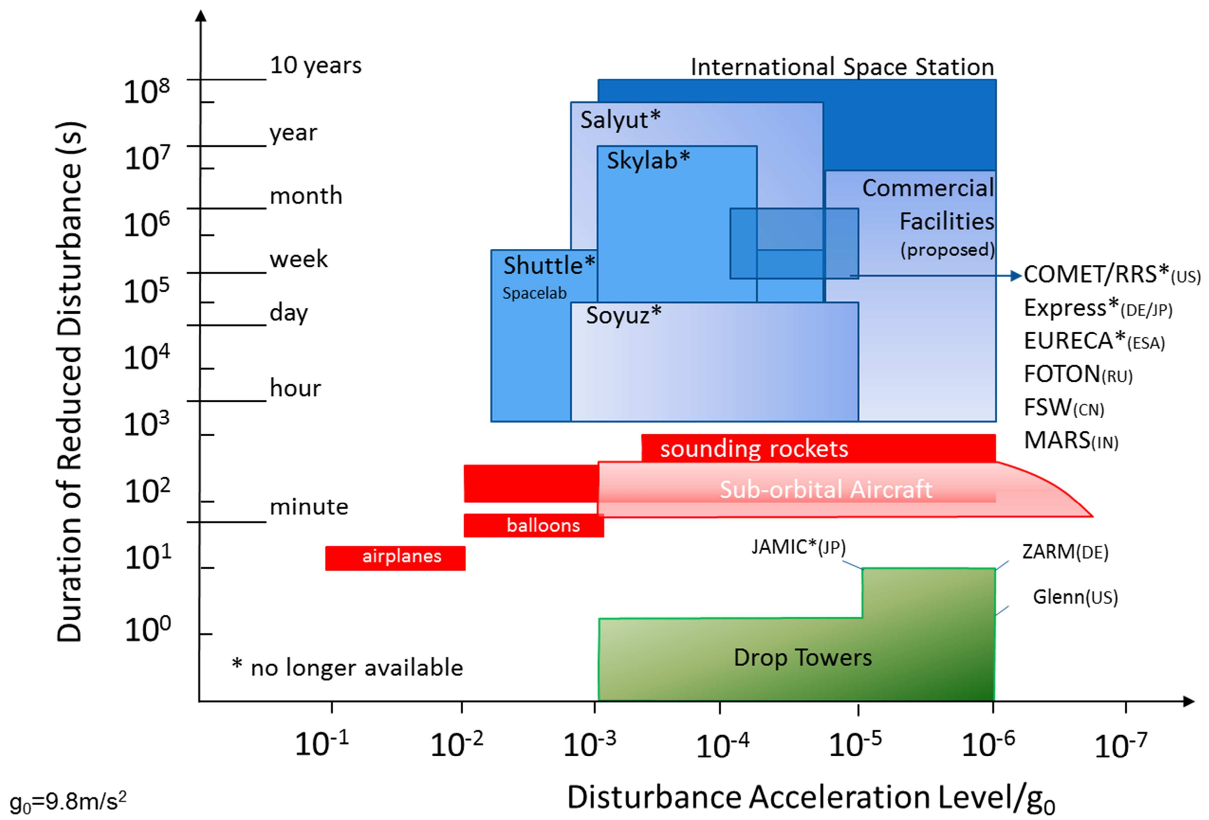

Figure 8 . Free-Fall Platform Performance Survey with Benchmarked Sub Orbital Aircraft performance

Sub-orbital finds itself in between space and ground-based platforms in terms of quality and duration.

The advent of a new class of sub-orbital platforms (including aircraft) has allowed an additional performance benchmark to be made. **Figure 8** shows the superposed duration and quality envelop that should be possible using these aircraft and where they fit into this benchmark diagram.

This benchmarking exercise was done as an ab initio technical survey from which the performance of a sub-orbital aircraft like the one that BOOSTER is developing can be benchmarked. It is important to drive the design from the very beginning from the perspective of the customer which is where current efforts are being applied. Even so, the design process is further engaged to push technical and economic performance as far as possible. This uses the perceived first generation technologies and equipment of the first sub-orbital aircraft in order to see what could be a possible offering.

Sub-orbital Aircraft Flight Performance Elements: Filling a Sub-Orbital Aircraft niche

The near space environment attainable along a sub-orbital trajectory has a free-fall phase where some very low levels of relative acceleration are possible. This microgravity zone lasts longer than that achieved by atmospheric platforms but shorter than that present in orbital platforms (satellites).

Taking the basic trajectory of a sub-orbital aircraft, a general performance map can be made. **Figure 9** shows the flight trajectories for the BOOSTER aircraft for 3 payload masses: the lighter the payload, the higher the peak altitude. And also the longer will be the time below which the atmospheric forces create disturbing accelerations below a specific threshold (here measured in parts of $g_0 = 9.8m/s^2$).

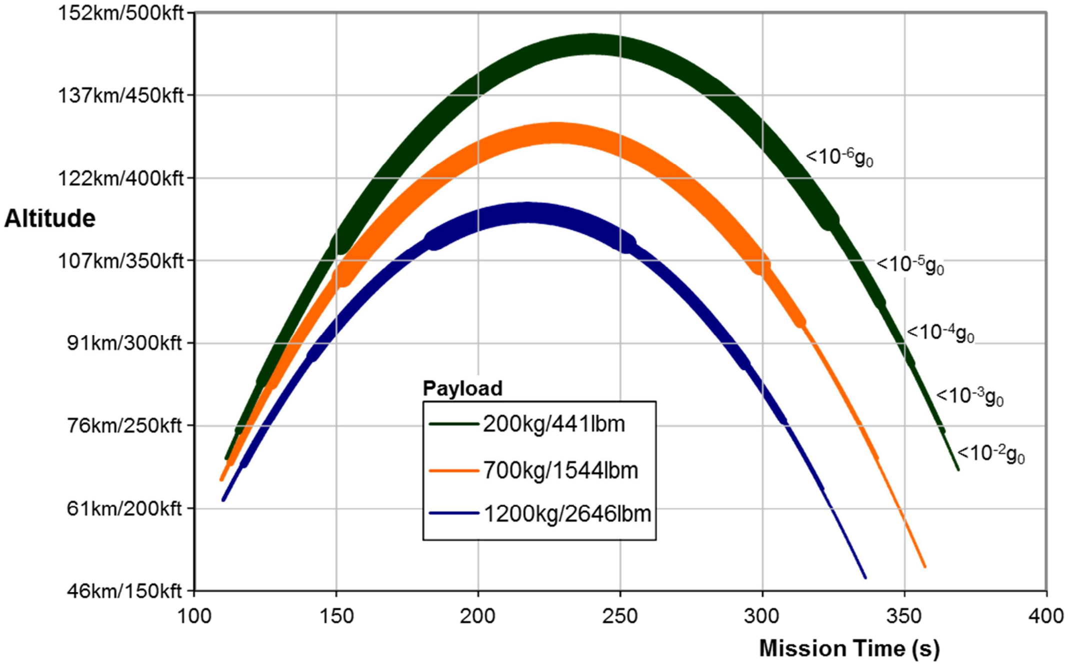

Figure 9 . BOOSTER Suborbital Aircraft Performance Time Trajectory and External Disturbance Levels

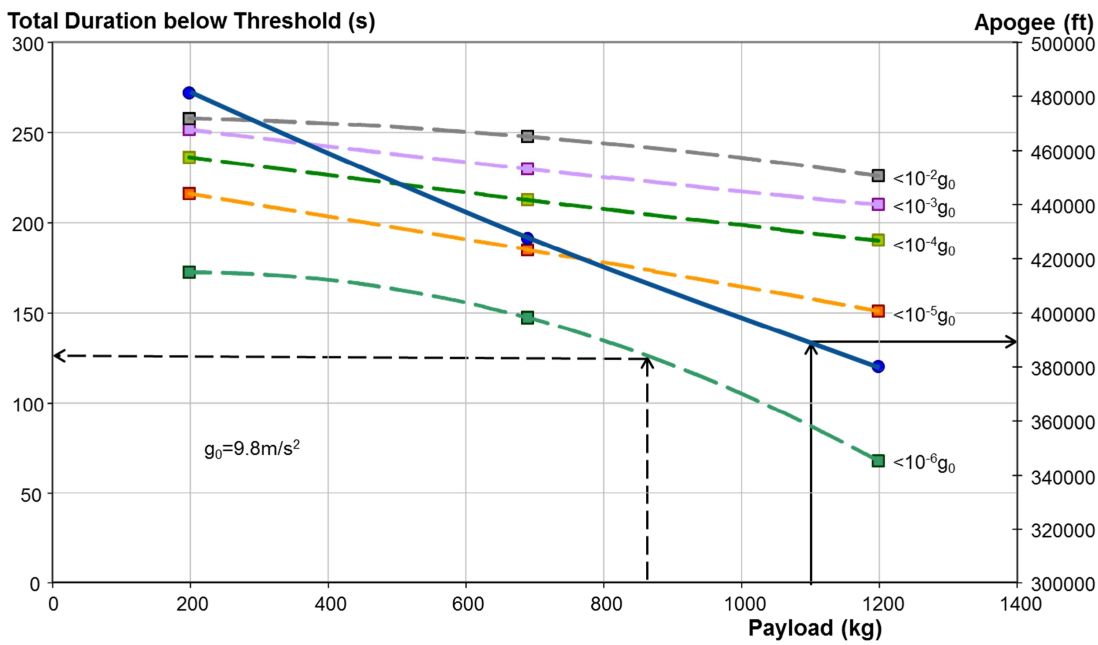

Figure 10 . BOOSTER Suborbital Aircraft Times of Low Disturbing Acceleration

Figure 10 presents a data summary of the times of low atmospheric disturbance that allow the microgravity quality to be determined. A 200kg payload allows a peak altitude (apogee) of 480kft to be reached. The aircraft therefore experiences 170s (<3 minutes) of microgravity (better than 10^{-6}g) and 250s (>4 minutes) of milligravity (better than 10^{-3}g). A heavier payload reaches a lower apogee. In this case carrying 1200kg takes the aircraft to 380kft. Here the time spread of the low accelerating disturbances increases and the higher quality durations are much shorter: microgravity is experienced for a little more than 1 continuous minute, although milligravity or better can still be present for more than 220s (<4 minutes).

Overall quality is higher and the duration longer than for a parabolic atmospheric flight because the trajectory is above most of the atmosphere. However, the real µg environment is degraded due to many other contributing factors. It is useful to classify these sources of disturbance into categories before work to mitigate them can be considered. Here, 2 primary categories can be defined which come from a combination of criteria: the source, and the type of the disturbance.

Category 1: External Quasi-static Disturbances

Any object travelling across the Space-Time fabric is perturbed by gravity. Whereas we could consider such an object to be a point mass, it is not. In its simplest manifestation, an object travels on a gravity curved trajectory determined by its common centre of mass and the centripetal force. Anything separated by a finite distance from the centre of the combined mass will always be pulled towards it: creating a disturbing acceleration on it. Normally these accelerations are miniscule. But they become significant when we talk in terms of microgravity. At suborbital velocities, they have a lower influence and can be neglected.

Likewise, travel through the upper atmosphere must still be considered. The upper atmosphere remains aerodynamically influential on space objects up to about 1000km. At low Earth orbital velocities and altitudes (~400km), they are of the order of $10^{-7}g_0$. And within the 50km to 200km range of a sub-orbital, the aerodynamic forces can be important. For example, at 250kft (76km), they can be of the order of 100N (20lbf) for the sub-orbital velocities experienced. Above 300kft, these forces drop to below approximately 10N (~2lbf). Their effect is not negligible. They are continuous rather than periodic, but the resultant monotonic accelerations generate a movement of the aircraft with respect to a pure free-fall trajectory and this manifests itself as a microgravity disturbance to any experiment that is attached to the aircraft structure.

Category 2: Internal Vibration Disturbances

Vibrations can be periodic or look like shock impulses. They come from the flexure of structures that are non-rigid bodies. They also can come from internal systems having mechanisms such as motors, cranks, and switches or valves that generate movement. Even the circulation of air around an object can generate accelerating movements or vortices that induce vibrations of significance at microgravity levels. And one of the major sources of disturbances is people: be it a pilot, a passenger, or an experimenter.

For example, a fully equipped human astronaut can weigh approximately 100kg. Movement of a head, an arm or a leg at typically used speeds, or the impact of the free-flying whole body against the fuselage wall creates disturbing forces. Experience on the ISS [DeLombard et al] and previously on the Mir Station [Newman et al] have shown that these disturbances can be substantial. For an aircraft, the higher its inertia, the lower the resulting accelerations induced from these movements. But a sub-orbital aircraft such as BOOSTER's can still experience significant accelerations due to these movements. **Figure 11** gives a general idea of their magnitude from different types of movement.

CASE 1: Human Impact Impulse with Cabin Wall

pitch	480 µg
yaw	120 µg

CASE 2: Attached Human Orientation Manoeuvres

waving forearm & hand	6 µg
moving a leg	210 µg
moving head & neck	8 µg
moving body	130 µg

Figure 11 . Example of human movement induced disturbance levels (on the BOOSTER platform)

It can be observed from **Figure 11** that:

1. The presence of a human passenger with uncontrolled movements will degrade the µg quality to not better than $10^{-3}g_0$ at least.
2. Basic head or arm movements used to tend to an experiment would give at best a $10^{-5}g_0$ quality, provided that those movements are carefully executed.

Years of effort have been made to mitigate these disturbances in spacecraft design [eg DeLombard et al]. These normally end in compromises between: engineering limitations, operational requirements, and competing mission objectives.

For a sub-orbital aircraft however, ideally once the boost phase has been completed, the aircraft can be aligned along a low drag trajectory and most of the mechanical systems shut down or held silent during the ballistic coast phase of approximately 5 minutes. This should provide an almost silent and completely undisturbed environment to any payload.

Un-hindering research from an operational perspective

When the ability to repair or replace a resource is limited, then the consequences of damaging that resource are taken very seriously. Or when a platform is shared between many experiments whose opportunity for experimenting may occur only once, an experiment's susceptibility and possible interferences are closely scrutinized. This is the circumstance of unique treasures such as the International Space Station. Here, the security of the station has to take precedence. This is more so when human astronauts share the environment with the experiment. And this imparts many experimental restrictions from the outset: to the point of being draconian for many experiments.

Many operational rules can often be pretty detrimental to productive µg research. Safety matters. But many of today's platforms are prohibitively restrictive for conducting breakthrough or pioneering research where the intention is to push limits of investigation to foster discovery. Clearing such an experiment for flight is much harder than conducting it. So what has happened with space research is similar to how space exploration has been conducted. It is highly scripted and rehearsed and as a result, most of the randomness has been removed from the investigation.

It is not moot that the vast majority of human discovery has been accidental and has come about from un-programmed and unscripted research activities: here the factors of what if, or what would happen if…have had an important role. They were the result of tinkering and first person observations. When you fly infrequently or fly without a tinkering human, experimentation becomes very scripted and programmed: whether it be carried out by a computer or an astronaut.

At BOOSTER, there is a strong belief that the act of enabling new industries and new markets needs to come from the creation of a research favoured environment that gives maximum flexibility and access to the customer. The tinkerer should be brought back. Getting accessibility up and un-scripting some experimentation should be a goal. BOOSTER would hope to foster such an environment by pursuing 4 objectives:

1. Reduce the safety analysis process back to something logical and reasonably attainable by the wider scientific community.
2. Have a flight environment where precision diagnostic equipment originally designed for use on the ground can be attached to a 'homemade' experiment with minimal modifications.
3. Provide an 'uh-oh' or 'accident' tolerant environment.
4. Create a service where the "geniuses" can fly with their contraptions and be encouraged to observe and tinker with and adjust the experiments in operation. Or at least, give them a real time tele-control capability from their mission lab to achieve the same results.

And in addition, the objective should be to create as close to "perfect" a microgravity environment as possible. The opportunity to take real technical advantage of the sub-orbital environment should not be missed during the design process. It is proposed that striving to create an environment of a quality beyond what is currently available on most existing platforms will stimulate new research opportunities and markets. This would take the objective of removing all sources of acceleration disturbances and noises to really take advantage of microgravity.

Mitigating the disturbances:

1. Category 1

For sub-orbital trajectories, the main source of category 1 disturbance comes from atmospheric drag. Drag (disturbing forces) can be minimized by aligning the aircraft along the lowest drag flight path orientation.

The BOOSTER sub orbital aircraft is to be equipped with a cold gas thruster system whose primary aim is to increase manoeuvre control authority in the upper parts of the atmosphere and to allow for attitude control of the aircraft during the ballistic phase of its flight. Is it also possible to use this external reaction control system (RCS) to adjust the free-fall trajectory.

With the appropriate design of a variable proportional RCS, it is possible to compensate the atmospheric effects on the aircraft up to a certain limit.

Figure 12 and **Figure 13** show the results obtained from operating an RCS that would balance any monotonic aerodynamic forces to within a target accuracy of $10^{-6}g_0$. Simulations show that when the disturbance to be balanced out becomes greater than $10^{-3}g_0$, use of the RCS system becomes impracticable. Part of this limitation comes from the sizing of the RCS variable thrust jets: beyond a certain size they become impractical to implement. Fuel consumption plays an equally important role. Beyond a threshold, further compensation uses increasingly higher amounts of fuel for little gain in microgravity duration. Thus the gain in µg time from further RCS operation becomes unjustifiable.

When this compensation process is in operation, it is possible to extend the duration of the experienced µg up to 210s continuous for a 1200kg payload and up to 250s continuous for a 200kg payload.

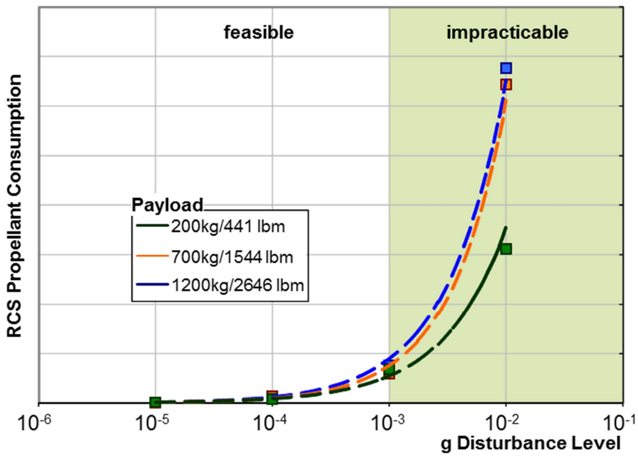

Figure 12 . Compensating External Forces

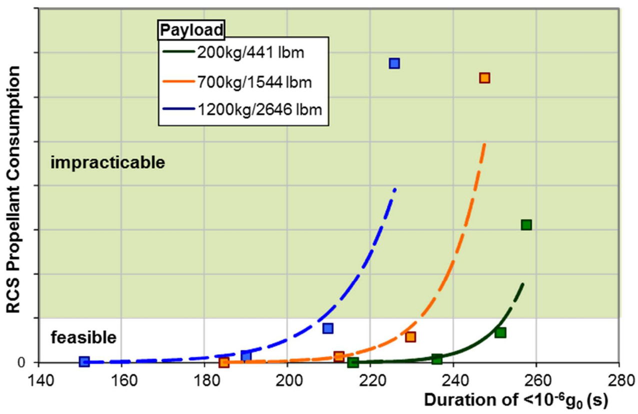

Figure 13 . Extending duration of experienced µg

2. Category 2
How can mg vibrations be reduced to µg?

A sub-orbital aircraft equipped with systems and people and apparatus can produce sources of vibrations and shocks that would degrade the quality of microgravity experienced by an experiment.

A sub-orbital aircraft has the unique characteristic of being a temporary spacecraft. The upper atmospheric trajectory is “airless” and therefore noiseless. And once the boost phase has ended with the shut-down of the rocket engines and a safeing of the propulsion system (purging or venting can be delayed), the craft can be placed into a stasis for the duration of the microgravity (space) part of the trajectory. This is possible because this lasts for only 5 minutes over which a pause of some systems such as air conditioning is tolerable. This can create a very quiet and vibration-less environment.

Another technique that can be borrowed from both drop towers and aircraft parabolic flights is the free-flyer. A payload assembly can freely fly within the cabin. The air gap between the cabin wall and the experimental apparatus acts as a disturbance filter. In this way, an external disturbances or impulsive trajectory corrections are not transmitted directly to the experiment.

Taking guidance from both [Zhang] and first principles, an idea of the effectiveness of this air-gap-filter for a very large payload module (**Figure 14**) can be made. It was found that for a cabin pressure altitude of 8000ft, the static air effects on the payload would induce residual accelerations of lower than $10^{-7}g_0$: over a continuous period of at least 60s. The sub-orbital aircraft would be flown about this free-falling payload module giving it as close to a pure gravity affected free-fall as possible.

Also, disturbances are not just mechanical in nature. They can also be electromagnetic. Having an electrically separate payload module also aids to minimise potential electromagnetic interferences.

Mitigating Safety Derived Limitations

The free flying payload module has another benefit. An experiment flying within a manned aircraft still has to pass a safety review. And from an airworthiness viewpoint, the "safe continuation of flight and landing" must be confirmed in the event of a mishap. Parabolic aircraft such as the Novespace A300-600 provide facilities for venting dangerous gases overboard. But safety reviews are still important for an Airbus that can have up to 40 researchers. For example, the carriage of multiple experiments and different types and forms of apparatus has an effect on the crash worthiness of the aircraft. They will also be important for a sub-orbital aircraft.

What is proposed for the BOOSTER sub-orbital aircraft is to use the payload module as not only a vibration isolation box as described in the previous paragraphs, but also as a containment shield that would protect the cabin, the pilots, and the aircraft from the consequences of any undesired accidents or those "uh-oh's".

Taking a cue from the formula of the European Spacelab that flew many times on the US Space Shuttle, BOOSTER proposes to create a "Lab" that would:

1. Provide the necessary physical <u>isolation</u> from the aircraft of all the experimental apparatus. It could also contain a free-floating but tethered shell within that would act as the mechanical disturbance filter.
2. Provide physical and electromagnetic <u>insulation</u> of the experiment. This would be a Firewall from the aircraft and its systems.
3. Be entirely under the control of the customer.

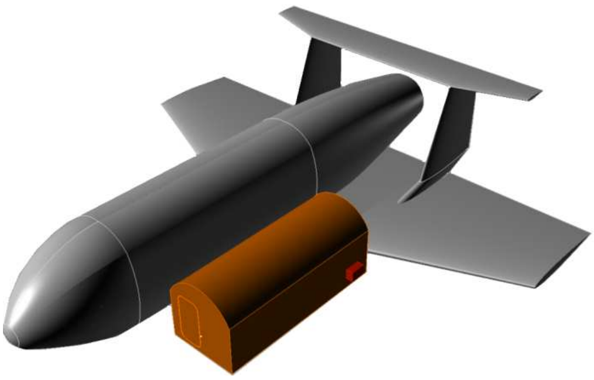

Figure 14 . BOOSTER Sub orbital aircraft "Lab": An Independent Scientific Payload Capsule

The Lab would measure:

Length	4.5m	15ft
Width	1.8m	6ft
Height	1.8m	6ft
Volume	$14m^3$	$1400ft^3$

The Lab would be large enough to walk upright inside. It would also have a hermetic internal space where a high class cleanliness level could be maintained for special types of experiments. And an important feature would be that it is a self-contained unit that could be worked on independently of flight operations either at a customer's own facility or a suitable integration centre. The full assembly could therefore be operationally checked and tested before installation into the sub orbital aircraft.

One of the frequent lessons learnt from previous microgravity campaigns has been the commercial and legal danger of operating more than one payload from more than one customer on the same flight. Payloads can interfere with each other. And it can be hard to determine in advance what the potential sources of interference can be if each payload is confidential. In these circumstances, running a pre-flight susceptibility and interference ground test campaign on the fully assembled and independent module can remove many of these risks and unknowns.

A customer could also have multiple Labs that are prepared in series for a continuous flight research or production campaign. They would have their own power, dedicated safety systems, and different internal configurations depending on the payload(s) or experiment type(s).

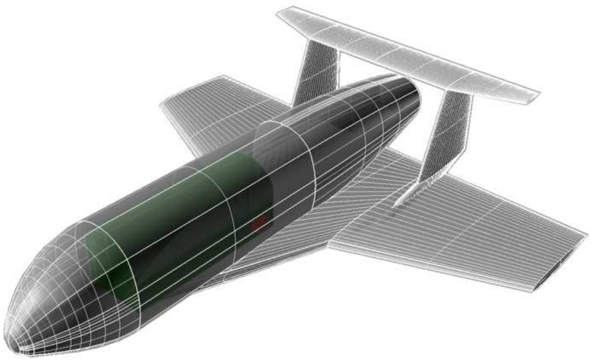

Figure 15 . "Lab" installed in the Sub orbital Aircraft

The Defining and the Marketing Differentiators

The fundamental marketing niche for BOOSTER is the basis of operating within an international and legally certified system. The aim is to operate like any aircraft flight that can therefore fly anyone.

Key elements of the offering include the following:

1. An experience that leverages the launch location as a pole of competence.
2. Multiple launch locations with the potential to provide a doorstep service to customers. The aircraft would be capable of going to the domicile of the experimenter to pick up the payload. When running an experiment, one commonly has to move house to bring everything one needs and everything one thinks one might need for contingencies. There is a difference between travelling across the country or the planet and just a few 'miles' down the road.

For BOOSTER, primary operations will be in the United States. Operations outside the US would expect to be hosted initially within the European arena following an agreement between the US government and the host European country.

For payload customers, BOOSTER would be the "development partner" who works with the customer through all stages of their experimental design and development. The customer relationship would begin early, through interactions during experimental development and trials aboard "BOOSTER" parabolic flights. BOOSTER positions itself as a "hands-on" partner that delivers on-demand parabolic flights, assists in streamlining viable experiments, and eventually places the mature experiments aboard a sub-orbital flight.

Summary and Conclusions

A high quality µg environment platform is being developed that will be capable of carrying a potential experimental payload of a mass of 1200kg and a volume of between $14m^3$ for a dedicated "Lab" to over $40m^3$ for the available cabin space The flight trajectory can be flown to provide >4 minutes of continuously low disturbances below $<10^{-5}g_0$. This platform will start flying from the end of 2016 onwards.

BOOSTER also plans to assist in developing the market by using preparatory campaigns with parabolic aircraft flights from 2014 onwards.

BOOSTER is focussed on implementing both a design and an operations scenario to which realistic and achievable safety criteria can be applied. These would favour experimentation and tolerate discoveries. And BOOSTER expects this offering to be competitively priced to bring access to within the means of the tinkerers.

BOOSTER has been in dialogue with experts in the field of space research for some time. However, it is necessary to further open this dialogue into the wider commercial world for BOOSTER believes that it is on the onus of the providers to help enable the many markets identified for space research and in particular the forthcoming sub-orbital flights.

This paper forms part of that dialogue with a continuing objective to present a customer driven technical and operations' solution.

Bibliography and Further Reading

Newman, Amir, and Beck, Astronaut-Induced Disturbances to the Microgravity Environment of the Mir Space Station, Journal of Spacecraft and Rockets, Vol. 38, No. 4, July–August 2001.

DeLombard, Hrovat, Kelly, and McPherson, Microgravity Environment on the International Space Station, NASA/TM—2004-213039, AIAA–2004–0125, April 2004.

Haruhiko Ohta, Review of Reduced Gravity Boiling Heat Transfer: Japanese Research, J. Jpn. Soc. Microgravity Appl. Vol. 20 No. 4 2003, pgs. 272–285.

International Space Station User's Guide, http://www.scribd.com/doc/47571535/International-Space-Station-User-s-Guide, retrieved December 2011.

IG-10-015, Review of Nasa's Microgravity Flight Services, Audit report, 18 June 2010.

Montenbruck and Markgraf, Maxus-4 Orion GPS Tracking System Flight Report, DLR report MAX4-DLR-RP-0001, ver. 1.1, 5 July 2001.

Parabolic Flight Campaign with A300 ZERO-G User's Manual, Edition 5, July 1999, Novespace, 15 rue des Halles, 75001 Paris, France.

Penleya, Schaferb, and Bartoec, "The International Space Station as a microgravity research platform", IAF-97-T.5.01, 48th International Astronautical Congress, Oct. 6–10, 1997, Turin, Italy.

Teruhisa Tsujino, Trends in Research on the Utilization of Microgravity-Competition and Collaboration between Research in Space and Research on the Ground, Science and Technology Trends Quart. Review No; 21, October 2006.

Thomas, Prasad, and Reddy, Microgravity research platforms – A study, Current Science, Vol. 79, No. 3, 10 August 2000, pgs. 336-340.

UIC-ESA-UM-0001, European Users Guide to Low Gravity Platforms, Issue 2 Revision 0.

Xiaoqian Zhang et al, Some key technics of drop tower experiment device of National Microgravity Laboratory (China) (NMLC), Science in China Ser. E Engineering & Materials Science 2005 Vol.48 No.3 pgs. 305-316.

ZARM Drop Tower Bremen User Manual, ver. 20 June 2011, Drop Tower Operation and Service Company, ZARM FABmbH, Am Fallturm, D-28359 Bremen, Germany.