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Sébastien Rouquette

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Guest editors: Olga Budenkova (CNRS, Université Grenoble Alpes,Grenoble INP, SIMaP, 38000 Grenoble, France), Catherine Colin (IMFT, Université de Toulouse, CNRS, INPT, UPS et GDR 2799 Micropesanteur Fondamentale et Appliquée) and Guillaume Legros (ICARE, CNRS UPR 3021, Univ. Orléans et GDR 2799 Micropesanteur Fondamentale et Appliquée)

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Physical Science in Microgravity within the Thematic Group Fundamental and Applied Microgravity / *Sciences physiques en microgravité au sein du GDR Micropesanteur Fondamentale et Appliquée*

30 years of CNES parabolic flights for the benefit of the scientific community

Sébastien Rouquette[a]

[a] Human spaceflight experiment development department, CNES, 18 avenue Edouard Belin, F-31401 Toulouse Cedex 9, France
E-mail: Sebastien.Rouquette@cnes.fr

Abstract. Parabolic flights allow short microgravity investigations in Physical and Life Sciences, technology and instrumentation tests. The use of parabolic flights is complementary to other microgravity carriers, and preparatory to manned space missions onboard the International Space Station and other manned spacecraft, around the Earth or beyond, to the Moon for example.

The main advantages of parabolic flights for microgravity investigations are the short turn-around time, the relatively low cost, the flexibility of experimental approach, the possibility of direct intervention by investigators on board the aircraft during and between parabolas, and the possibility of modifying the experiment set-up between flights.

Keywords. Parabolic flights, CNES, Novespace, Microgravity, Weightlessness.
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1. Introduction

1.1. *Sciences in weightlessness*

The aim of research in microgravity is to study phenomena that are usually hidden by Earth's gravity. Researchers therefore try to obtain data under microgravity conditions that are impossible to reproduce on Earth.

The experiments cover a wide range of topics: fundamental physics, physical sciences, life sciences, material sciences, sciences of the universe, technological experiments, tests of space devices and preparation for manned space missions.

There are several types of access to microgravity. From drop towers, sounding rockets and automated capsules to the International Space Station, these devices offer a wide variety of facilities to carry out science experiments (see Table 1). Of the five means of accessing weightlessness, only parabolic flights allow scientists to operate their own experiments (laboratory type instrumentation is most commonly used), without the need to automate, miniaturise or entrust them to operators such as astronauts, in a short time frame (typically about one year between the experiment proposal and its performance). In addition, during a parabolic flight, researchers can repeat their experiments many times and modify their parameters. Aircraft parabolic flights

Table 1. Comparison between microgravity platforms.

Mean	Duration of microgravity	Level of residual gravity	Payload capacity	Development duration and accessibility
Drop towers	4–9 s	10^{-5} g	165–225 kg dimension lower than 1.7 × 0.6 × 0.6 m^3 automated	>6 months depending on complexity several campaigns a year
Parabolic flights	20–24 s	$\pm 10^{-2}$ g accuracy around the selected level between 0 g and 1 g for reduced gravity level	Several tons separated in racks laboratory hardware	Typically 6–12 months 5 campaigns a year (×10 experiments)
Sounding rockets	3–15 min	10^{-4} g	100 kg, diameter lower than 60 cm automated	>18 months variable availability
Capsules	15 days	10^{-5} g	Lower than 600 kg, dimension lower than 1.7 × 1.7 × 1.0 m^3 automated space developed hardware	>18 months availability depending on current capsule development and availability (USA)
ISS	Up to year	10^{-5} g	Few kg automated space developed hardware	>18 months typically one call for experiments a year in France

repetitively provide 22 s of zero gravity and up to 35 s of reduced gravity (Martian or lunar gravity) during ballistic flight manoeuvres.

In this context, the parabolic flight offers great flexibility in the implementation of experiments at a low cost and with a large boarding capacity.

1.2. *History of the program*

The parabolic flight program in Europe was initiated by CNES astronauts Jean-François Clervoy and Jean-Pierre Haigneré, following the thesis presented by Jean-François Clervoy as part of his training as a test flight engineer, in 1984. The chosen aircraft was Caravelle serial number 234 belonging to the Flight Test Centre (CEV) of French general delegation of armament (DGA).

Shortly after the first scientific campaigns organised by CNES and CEV, CNES decided to entrust the management of the program to Novespace, a new private company subsidiary of Cnes, which has since retained responsibility for the program with the success that we know, on board 5 successive aircraft.

For these purposes, CNES, DLR (the German space agency) and ESA (the European space agency) have organised 170 campaigns since 1984, with several airplanes: CNES' Caravelle, NASA's KC-135, the Russian CTC Ilyushin IL-76-MDK, the Airbus A300 Zero-G and the A310. In addition, two Joint European Partial-g Parabolic Flight Campaigns were organised by ESA, CNES and DLR using the Airbus A300 Zero-G for experiments at reduced gravity levels, typically at Moon and Mars g levels [1, 2].

In 2014, CNES, DLR and ESA supported Novespace in the acquisition of the A310 "Konrad Adenauer", which was used to transport the German Chancellor and her government.

The excellent cooperation between the three agencies has ensured the success of the program to date.

Parabolic flights are therefore a superb example of European cooperation. They have become the world's leading reference in this activity, in the aircraft offering the largest volume in parabolic flight. They represent 30 years of continuous success.

For 30 years, the Zero-G aircraft, as they have been called since their inception, have been used to carry out research work in zero gravity. CNES, for its part, has carried out 65 parabolic flight campaigns, i.e. a total of around 200 flights, more than 200 different scientific experiments, resulting in thousands of high-level publications in all research disciplines and a large number of student researchers have obtaining their doctorate degree.

2. Gravity, weightlessness, microgravity… Let's clarify the concepts

Gravity is one of the fundamental interactions that govern our universe. It is in fact the attraction of bodies to each other due to their mass. This law applies to our Earth as well as to any other star.

Gravity is the feeling of this attraction on the surface of a planet. It is, for example, the force of gravity that acts on a human being when he or she touches the ground. Gravity is directed towards the centre of the Earth.

Weightlessness is the absence of feeling this force. It is therefore not at all the absence of attraction. It is a state reached by a body when the force of gravity has no obstacle to its action. Note that weightlessness is not the absence of gravity, but the absence of other forces that would oppose it. Indeed, a planet exerts its attraction over astronomical distances, which is why the Moon revolves around the Earth. It is captive in its field of attraction. The Sun holds the objects of the solar system under its influence billions of kilometres away.

On Earth, the effects of gravity are defined by weight. The effects of weight are felt due to the reaction of the Earth's ground and friction when falling (e.g. air or water friction). Weightlessness is therefore the state in which neither the reaction of a support nor friction is felt. It is therefore a state of free fall!

In the Zero-G aircraft, the particularity of parabolic flight makes it possible to create a situation of free fall lasting a few seconds. The absence of air friction inside the cabin creates a situation where we are freed from the sensation of weight. The aircraft and its occupants all fall along the same trajectory.

Nevertheless, perfect weightlessness situation does not really exist. In a parabolic flight, the fall is partly slowed by the air in the atmosphere. In space, on board space stations and spacecraft (in permanent free fall), weightlessness is also affected by factors such as radiation from the Sun, the pull of the Moon and even the shape of the Earth. Astronauts or scientists working on board Zero-G aircraft do not perceive these disturbances, but to take account of these factors, we generally speak of "microgravity", which translates in French to "micropesanteur".

3. Why do research in microgravity?

Research in microgravity tends to better understand structure and behaviour of matter and to prepare the medicine and technology of tomorrow.

To understand a phenomenon (chemical, physical, biological, physiological, etc.), we must try to decipher the mechanisms by which it functions under various conditions. Scientific studies carried out on Earth do not allow to highlight all the characteristics of a phenomenon, because gravity disturbs or masks certain aspects of it. Carrying out the same experiment in weightless conditions can give very different results. It is difficult to give a complete and wide view of the experiments that have been performed in parabolic flights. Bibliography tries to give a short sample of the latest studies.

Here are some examples of the objectives:

Physics of matter: Research on board parabolic flights tries to investigate the structure of matter and its modification at macroscopic or microscopic scales. Physics of fluid [3–6], physics of granular media [7], test of principle of equivalence and atomic clocks [8], combustion [9,10].... At the same time, analyses of fluid mechanics or plasma behaviour are used to find improvements in industry.

Medical research: Medical research in zero gravity is not only a field of study for the preparation of astronauts. Above all, it continues to shed light on the mechanisms of human physiology, even during short duration microgravity conditions. Parabolic flights offer a test platform to specifically study physiology or neurology, as cardiovascular adaptation, motor adaptation or environment perception perturbation [11–19]. Longer stays in a microgravity environment have effects on the human body that are very similar to those of ageing (loss of bone and muscle mass, degradation of arteries, etc.). The experiments carried out in this particular environment therefore frequently find applications in medicine on Earth in order to prevent and treat certain very terrestrial pathologies (osteoporosis, balance disorders, etc.).

Space technologies: The Zero-G aircraft also makes it possible to test the space technologies of the future. Indeed, the duration of microgravity makes it possible to deploy antennas or observe the behaviour of tanks such as those used on launchers or satellites as if they were in space [20]. It is also a training ground for European astronauts who are preparing to navigate, work and manipulate objects while floating. Similarly, some of the experiments that are carried out on the International Space Station are tested beforehand during parabolic flights.

Preparing for exploration: of course, research in microgravity also makes it possible to prepare for the great space journeys that human beings have dreamed of since time immemorial. Deciphering the mysteries of microgravity already makes it possible to design and prepare the long-term manned flights planned for the Moon and Mars in the coming decades.

4. The Zero-G aircraft, a unique laboratory

Studying certain phenomena can be complicated in conventional laboratories on the ground. To avoid some of the parasitic effects of gravity, many researchers use parabolic flights. Few means exist for conducting research in microgravity. The Zero G aircraft is the ideal laboratory. It is effectively the only manned access to microgravity on Earth (as opposed to capsules, towers or sounding rockets).

The scientific teams can interact directly with their equipment. This is a big difference from other means of accessing microgravity, where the experimental devices must be fully automated.

From an organisational point of view, the preparation time for an experiment is relatively short compared to other microgravity platforms, particularly the International Space Station (ISS). An experiment can be on board a parabolic flight in about 12 months, while the average time to reach the Space Station can be up to 5 years. With the Zero G, scientists benefit from a flexible and fast access tool to conduct cutting-edge research, without waiting years for results.

In addition, parabolic flight campaigns are less expensive than access to the ISS, with its imperatives in terms of safety, space requirements, availability of the astronaut, etc., is much more expensive (and restrictive) for scientists. In comparison, the Zero-G aircraft also offers the possibility of carrying larger experiments that are very difficult to send into orbit. Its experimental area, which is rather open, free of cables and other sensitive equipment, is over 200 m^3.

The overall microgravity time is also significant on a parabolic flight campaign (90 parabolas of 22 s).

The Zero-G aircraft (see Image 1) is a tool that offers many advantages for researchers thanks to its technical characteristics, its accessibility and its organisational aspects. A real avant-garde aerial space laboratory!

Image 1. Airbus Zero-g beginning microgravity phase. Picture taken by Alex Magnan during a demo flight. © Novespace.

United States, Russia and Ecuador have similar aircraft to the European Zero-G aircraft, in terms of cabin volume available for science experiments. The A310's activity is nevertheless much more intense than that of its peers and offers at least five campaigns slots a year provided by CNES, DLR and ESA.

Aircraft parabolic flights are a useful tool for performing short duration scientific and technological experiments in reduced gravity. Together with drop towers, sounding rockets, the International Space Station (ISS) and other manned and unmanned spacecraft, aircraft parabolic flights with the Airbus A310 Zero-G completes the set of flight research opportunities for European scientists.

The principal value of parabolic flights is to provide a flying laboratory in which the gravity level can be modified, producing, at a relatively low cost, scientific results for experiments operated by the scientists themselves and for which the microgravity duration and levels are adequate. Aircraft parabolic flights are the only flight opportunity beside ISS and Chinese spacecraft where medical research on human test subjects can be performed in weightlessness.

To summarize, the main advantages of parabolic flights for microgravity investigations are: the short turn-around time (typically about one year between the experiment proposal and its performance), the reliability of the campaign dates, the relatively low cost involved for ESA, CNES and DLR sponsored investigators, the flexibility of experimental approach (laboratory type instrumentation is most commonly used), the possibility of direct intervention by investigators on board the aircraft during and between parabolas, and the possibility of modifying the experiment set-up between flights. Other more detailed objectives are presented in [2].

5. CNES, specialist to support research

CADMOS (*Centre d'Aide au Développement des Activités en Micropesanteur et des Opérations Spatiales*), prepares and organises CNES parabolic flight campaigns.

This operational structure, based in Toulouse as part of CNES, helps scientists to prepare and conduct their experiments.

Its experts participate in the selection of experiments by giving an opinion on their technical feasibility. They design and develop complementary equipment if necessary. Its teams also manage the planning, safety aspects and procedures to be followed in flight to get the most out of the experiment. They accompany Novespace in the loading of the equipment and the conduct of the experiments on flight days.

Since the beginning of the CNES parabolic flight activity in 1989, CADMOS has hosted more than 200 different experimental studies, representing 1000 people involved and thousands of top scientific publications.

Over the last 12 years, CNES organized 24 campaigns and participated in four joint campaigns, with DLR and ESA. The total number of experiments tested in flight is 261, with a major contribution of Life sciences and Matter sciences. The average number of experiments onboard for a flight campaign is 10. Some research need a large amount of data, requiring several campaigns.

Most experiments conducted on microgravity research campaigns are proposed to an International Announcement of Opportunities and selected after a peer review. Proposals for microgravity experiments to be conducted during parabolic flights can be submitted at any time to ESA's Announcement of Opportunity and DLR proposals are peer reviewed on an annual basis.

On CNES side, flight campaigns enable the scientific programs of more than forty laboratories in France (Inserm, CNRS, universities, etc.) to be conducted. A call for experiment is announced on CNES Website. Experiments are selected by working groups including experts from outside CNES, who examine the scientific or technology merit of each one. This committee meets several times a year to study the numerous applications submitted in response to the annual calls launched by CNES.

After peer recommendation, the technical feasibility of the proposal is assessed and, upon positive assessment an experiment proposal is manifested for a specific campaign. ESA, CNES and DLR offer the opportunity of participating in the parabolic flights to selected investigators free of charge.

With these campaigns, France and Europe are at the forefront of scientific research in microgravity at international level.

6. Parabolic flight science campaigns

Each year, Novespace organises 5 to 6 flight campaigns on behalf of CNES, DLR and ESA. These campaigns take usually place from Bordeaux-Mérignac airport and involve between 10 and 15 experiments.

During each campaign, scientific and technology experiments prepared by research laboratories are flown on board the Airbus Zero-G.

6.1. *The course of the campaigns*

The experiments are selected, designed and tested at least 6 months in advance by the CNES thematic groups (see Figure 1 to have the repartition of thematics in CNES parabolic flights since 2009). Thus, fundamental or applied research projects, physiology/neurology, biology, fluid physics, astrophysics as well as technology experiments are flown. Some researchers fly regularly when their research projects require it.

As aircraft parabolic flights are considered to be test flights, particular precautions are taken to ensure that all operations during flights are conducted safely and that flying participants are adequately prepared for the repetitive high and low gravity environments. Prior to a campaign, Novespace provides support in the experiment equipment design and in all related safety aspects. All experiments to be performed and all equipment to be installed onboard the aircraft are reviewed from a structural, mechanical, electrical, safety and operational points of view by experts several months before a campaign. Technical visits are made to the experimenters' institutions to review equipment. A safety review is held one month before the campaign. During this review, the integration of all equipment is discussed, and the overall safety aspect of the campaign is assessed.

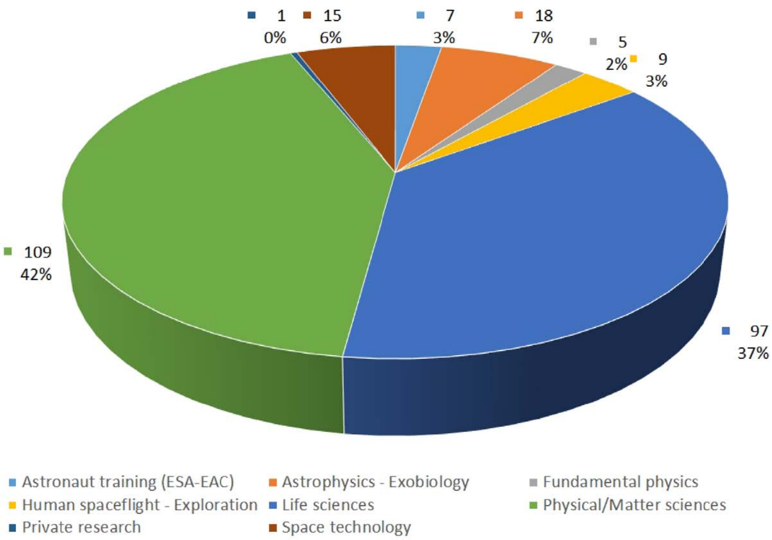

Figure 1. Overall repartition of thematics in CNES parabolic flights since 2009.

Image 2. Early morning flight preparation at Novespace. © S. Rouquette/CNES.

The campaign itself takes place over two weeks. The first week is devoted to the experiment preparation and loading into the aircraft. A final safety review visit is conducted on board the aircraft to verify that the experiments are ready for flight and that all safety requirements have been fulfilled.

Before the flights, a detailed briefing is given on the procedures to be followed during the flight and the safety standards to be respected. Everyone takes part: scientists, subjects, pilots, doctors, technicians, safety personnel and CNES managers.

Take-offs and landings are usually made at the Bordeaux airport, although other airports have been used in the past in Köln, Brussels, Paderborn, Dübendorf and Berlin. Parabolas are flown in dedicated air zones over the Gulf of Biscaye, the Mediterranean Sea, or Germany respectively.

Typically, three flights of 30 parabolas take place each morning on the Tuesday, Wednesday and Thursday, followed each time by a debriefing during which the needs and requests of investigators are reviewed and discussed (Image 2 shows the aircraft just before departure during a campaign).

All experimenters invited to participate in parabolic flights must pass a medical examination. During the flights, specialised personnel supervise and support the in-flight experiment operations. In addition, a Flight Surgeon participates in all flights to supervise the medical aspect of in-flight operations. Due to the alternation of flight phases of low and high gravity, parabolic flight participants might suffer from motion sickness. Therefore, prior to the flights, anti-motion sickness medication is made available upon request to flying participants.

After the campaign, parabolic flight investigators are requested to send a report with results of their experiments to the agencies.

7. The Airbus A310 Zero-G

7.1. *History*

Microgravity flights have been tested in France since 1946. It was the "*Direction Générale de l'Armement - Essais en vol*" that first tested aeronautical equipment in parabolic flight. It was onboard a Martinet NC-702, a twin-engine propeller plane. Its successor was the Caravelle F-ZACQ, which was in service from 1957 to June 1995. Its nickname was Caravelle Zero-G.

In 1989, CNES carried out a first campaign for space technology and scientific research onboard the Caravelle. The Caravelle carried out a total of 38 campaigns, i.e. 3770 parabolas or 24 hours of microgravity. One third of these campaigns were conducted by CNES.

In 1997, after three campaigns with the NASA KC-135 aircraft, Novespace acquired a new aircraft. It was an A300 registered F-BUAD, the third Airbus built by the manufacturer (in 1973) and only made test flights. It served for 18 years until 2014, when it reached its age limit. At the end of its service in 2014, it had flown more than 13,000 parabolas in 110 campaigns, including more than 30 campaigns for CNES.

In 2015, Novespace commissioned the Airbus A310 Zero-G to maintain a rhythm of 5 or 6 campaigns per year. It offers the same flight characteristics as the A300. The format of the standard flight campaigns is therefore based on the same model (3 flights of 30 parabolas).

For a complete overview of parabolic flights history in the word, refer to [21].

7.2. *An aircraft like no other*

The former "Chancellor Airbus" A310-304 (registered as "10 + 21") was delivered from aircraft manufacturer Airbus to East German airline Interflug on 24 June 1989 and was used by Interflug for East German government leaders and normal flight business until 1991. On 27 August 1991, the aircraft became the property of the German Air Force and was named "Konrad-Adenauer", after one of the Fathers of Europe and co-author of the Franco-German reconciliation.

Configured as a "VIP" aircraft; it was used for journeys and state visits by German Federal Chancellors and government ministers between 1993 and 2014. The A310 was stationed at the Cologne Bonn airport during its mission for the German Federal Ministry of Defence. Exactly 25 years after the initial handover, the "Konrad Adenauer" was handed over to its new owner, Novespace, on 24 of June 2014.

Converting the aircraft to a flying laboratory for weightless research is a symbol of Franco-German and European cooperation.

After a series of qualification flights in the summer of 2014 from the airport of Bordeaux-Mérignac, Lufthansa Technik in Hamburg overhauled the aircraft and converted it for use in parabolic flights. The certification process took place from July 2014 until Spring 2015 in agreement with the regulations of the European Aviation Safety Agency (EASA) and the French *Direction Générale de l'Aviation Civile* (DGAC).

Image 3. Crowded experimental zone during parabola. © S. Rouquette/CNES.

In excellent condition, perfectly maintained and with few flights to its credit, the aircraft, now registered as F-WNOV, passed from the status of a military aircraft yesterday to that of a laboratory aircraft today.

The aircraft was not modified in terms of airframe structural basis, wings, engine, hydraulic circuit, etc. It entirely remains in its basic configuration as parabolic flights are within the flight envelope of the aircraft. The Airbus A310 has approximately the same dimensions as the Airbus A300, except that it is shorter in length by about 5 m. However, as the seating accommodation in the Airbus A310 is slightly different from that of the Airbus A300 after modifications for parabolic flights, the cabin area and the interfaces for experiments are similar: approximately 20 m long by 5 m wide and 2.1 m high. This space is fully padded, equipped with handrails, vertical straps, seat racks, power units and light panels, allowing safe movement and scientific experiment interfaces (see Image 3 for an example of accommodation).

The Airbus A310 Zero-G has largest volume for parabolic flights in the world, in terms of passenger and experimental capacity Table 2 shows some technical characteristics of the A310 Zero-G aircraft.

The first scientific campaign took place in the April–May 2015 timeframe. The three main European space agencies CNES, ESA and DLR, which are the regular users of parabolic flights, decided to organise jointly a cooperative microgravity parabolic flight campaign to mark this beginning of a new era in microgravity and reduced gravity research. Twelve experiments, representing a mixed payload of physical and life sciences, have been conducted by investigators invited by the three agencies [2].

From May to November 2015, five more microgravity research campaigns were performed with the new Airbus A310 Zero-G: two campaigns each for ESA and CNES, and one for DLR. Research campaigns will continue at a rate of two campaigns for each of ESA and CNES per year, and one or two campaigns for DLR per year.

8. A synchronized piloting dance

Parabolic flights are performed in an aircraft that follows a flight profile alternating ascending and descending manoeuvres with intervening periods of level flight. It places the aircraft in unusual flight attitude with the pitch angle varying from 45° (nose up) to −45° (nose down), whereas for a conventional take-off it is lower than 20°. Each manoeuvre, called a parabola, put the aircraft and its occupants in free fall, giving up to 22 s of microgravity. A flight consists of a series of 30 parabolas, which represents about 10 minutes of cumulated microgravity.

Table 2. Characteristics of the Airbus A310 Zero-G.

Aircraft	Manufacturer serial number	498
	Two-engine	General Electric CF6-80
	Overall length	46.4 m
	Wingspan	43.9 m
	Fuselage diameter	5.64 m
	Total cabin volume	300 m^3
	Passenger doors	4
	Dimensions of front doors	1.80 × 1.06 m (H × W)
	Maximum mass	157 tons
	Based at	Bordeaux–Mérignac Internat. Airport, France
Experiment area	Dimensions	20 × 5 × 2.25 m (L × W × H)
	Volume	210 m^3
	Illumination	LEDs, continuous
	Accommodation	White padding on walls, floor and ceiling Nets at front and back
	Handrails	Rigid on sides, flexible on ceiling
Electrical	10 electrical panels	220 VAC, 50 Hz, (2 kVA + 3.5 kVA)
	Ground Fault Interrupt	Integrated in electrical panels
	Electrical power box	Integrated with plugs, fuse and emergency switch-off button, provided to experimenters
Mechanical	Experiment fixation	On rail tracks 503mm apart (identical to A300)
	Structural requirements	9 g/1.5 g (for/aft), 3 g (lateral), 4.2 g/7.3 g (up/down)
	Vent-line	4 ports, direct evacuation through fuselage skin
Data	Live data	3D acceleration, time reference, parabola n°, 3D position (GPS position)
	Distribution	On file post-flight

8.1. *Flight mechanics details*

An aircraft is flying considering four forces applied to its body and wings. Weight is driven by Earth gravity. Thrust is given by engines power. Drag is in the opposite direction of thrust because of the atmosphere resistance to the motion. Lift is also a consequence of air displacement around the wings that allows the aircraft to fly. Lift is oriented upward. During a stationary flight, forces equalise resulting in a straight uniform flight path.

To be in free fall, the forces must be cancelled out, except for the weight which cannot be changed.

Drag and thrust must be balanced so that their sum is zero.

The incidence will be reduced to zero by a steering action during the parabola to reduce incidence. Practically, pilot lowers the airflow incidence angle down to −3° relative to the wing profile (i.e. the air stream then comes from the upper face of the wing), where the lift force reduces to zero. The only remaining force is weight, which is the exact condition to create microgravity.

The microgravity environment is created in the Airbus A310 Zero-G flying the following manoeuvres:

- from steady horizontal flight, the aircraft climbs at 45° (pull-up) for about 20 s with accelerations between 1.8 and 2 g;
- the aircraft engine thrust is then significantly reduced for about 20 to 25 s to the point where it is only compensating for air drag (parabolic free fall);

Image 4. During the parabola. Pilots at the pitch axis (right), Roll axis (left), thrust (centre). © S. Rouquette/CNES.

Table 3. Main characteristics of a typical Zero-G parabola.

Altitude prior to the dish entry resource	6000 m
Speed prior to entering parabola resource	640 km/h (340 kt IAS)
Nose up angle at injection	45°
Parabolic injection altitude	7600 m
Parabolic injection point speed	460 km/h (250 kt IAS)
Parabola top altitude	8000 m
Parabola top speed	240 km/h (130 kt IAS)
Angle to dive at exit resource	45°
Weightlessness duration (0 g)	22 s ± 2 s
Weightlessness accuracy	±0.03 g
Weightlessness (heaviness at parabola entry/exit)	1.8 g
Total duration of parabolic manoeuvre (0 g)	74 s

- during the free fall phase, pitch angle varies from 45° nose up to 45° nose down;
- towards the end of the parabola, the aircraft is oriented in 45° nose-down attitude. It is pulled out of the trajectory and is accelerating at about 1.8 to 2 g for approximately 20 s, to come back to a steady level flight.

General flight parameters are given in Table 3.

8.2. *Three pilots in a row*

A high degree of piloting precision is required to operate a Zero G aircraft. Novespace currently has only seven highly qualified pilots who are experienced in this type of flight.

The Zero G aircraft is flown simultaneously by three pilots (Image 4). One pilot only handles the pitch (the nose-up or nose-down angle) to accurately follow the trajectory. Next to him, a second pilot handles the roll (keeping the wings horizontal) to prevent the aircraft from turning. A third pilot, seated behind them, manipulates the throttles to manage the engine power. He also monitors the flight parameters (alarms, temperatures, pressure, etc.).

To prevent the sun from bleaching out the instruments and to increase pilot concentration, the side windows of the cockpit are covered so that the pilots' view is concentrated on the central instrument panel.

In the pitch position, an additional control stick is attached to the control column for the parabolas (visible at the right of Image 4). It allows to act on the pitch axis without intervening in the roll axis. The pilot in charge of the roll has two small strings attached to the standard control column. It allows him to manage the roll without interfering with the action performed by the other pilot (the control columns of an aircraft are doubled, visible at the left of Image 4).

Accelerometers give each pilot a precise indication of the residual force along the corresponding flying axis. The main indicator is a vertical accelerometer that helps in controlling the pitch angle to maintain zero-g value.

Manoeuvres are separated by intervals of several minutes. Duration of these intervals between parabolas can be arranged prior to the flight such as to give enough time to investigators to change an experimental set-up. A typical flight lasts between two and half and three hours and includes 30 parabolas, in sets of five, with approximately two minutes intervals between parabolas and with four to six minutes between sets of parabolas. A parabalola typical profile is given in Figure 3. During the reduced gravity period, after a transitory phase of a few seconds, the residual accelerations sensed by experimental set-ups attached to the aircraft floor structure are typically in the order of 10^{-2} g, while for an experiment that is free-floated in the cabin, the levels can be improved to typically 10^{-3} g.

8.2.1. *"Pull up!"*

During the first phase, the aircraft is flying horizontally. The pilot prepares for the parabola by gradually increasing his speed to about 800 km/h, which is 640 km/h Indicated Air Speed (IAS), the maximum speed allowed for this type of aircraft.

Then, he gradually pitches the aircraft up to an angle of 45°. During this manoeuvre, known as the "pull up", gravity increases to 1.8 times the Earth's gravity level. The feeling of weight is greater. This is called hypergravity. This phase of flight lasts about 20 s.

8.2.2. *"Injection!"*

As the aircraft progressively climbs up to 45° nose up, the pilots will act together on their respective controls to place the aircraft on its ballistic trajectory. This moment is called the "injection". Practically, the pilot on the pitch axis lowers the airflow incidence down to −3° relative to the wing profile, and the pilot on the thrust axis adjust the engine power to equilibrate drag. The aircraft then follows a parabola. It is in a free fall conditions. The same applies to the passengers and instruments onboard.

While the aircraft is in full ascent, 3 pilots will act in concert on their respective controls (the stick for pitch and tilt of the wings, and the engine power control) in order to keep the aircraft on its ballistic trajectory.

An example of accelerometer data during a parabola is given in Figure 2: Example of a zero-g parabola. Horizontal axis shows duration since "injection". Parabola duration is 21.4 s. vertical axis gives remaining gravity level. Blue line indicates vertical acceleration (z axis, positive downward), green line stands for longitudinal acceleration (x axis, positive forward), red line is for roll axis (y axis, positive to the left).

8.2.3. *"Pull out!"*

About 22 s later, the aircraft is in a dive at 45° nose-down attitude. The pilot gradually straightens the aircraft. This is the end of the parabola. It is the "pull out resource". The passengers weigh 1.8 times their own weight again.

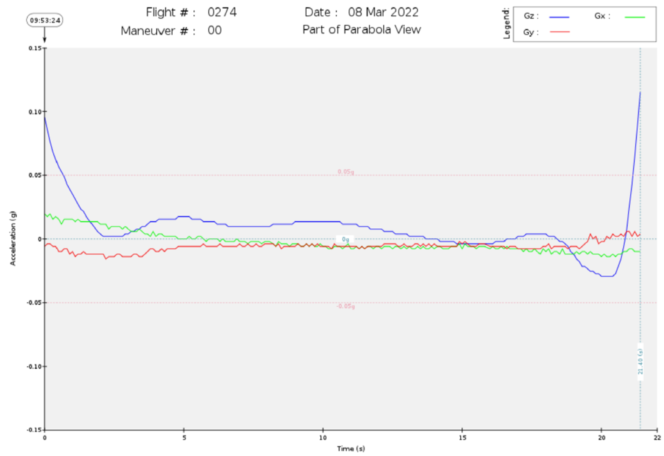

Figure 2. Example of a zero-g parabola. Horizontal axis shows duration since "injection". Parabola duration is 21.4 s. vertical axis gives remaining gravity level. Blue line indicates vertical acceleration (z axis, positive downward), green line stands for longitudinal acceleration (x axis, positive forward), red line is for roll axis (y axis, positive to the left).

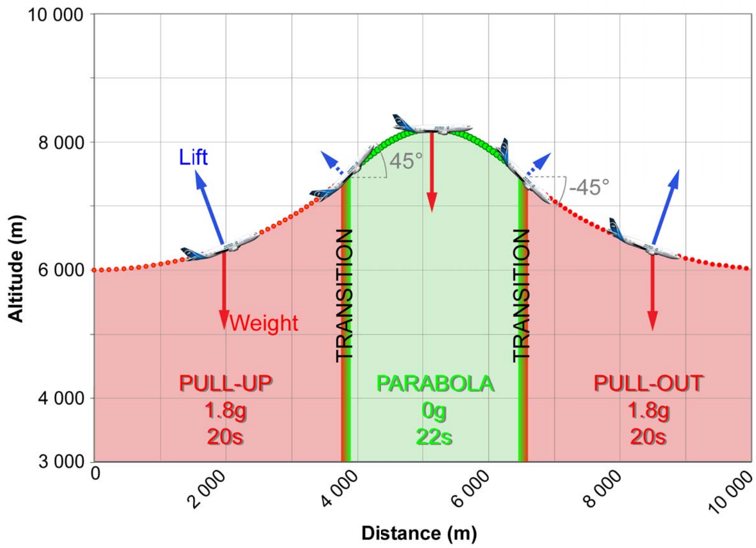

Figure 3. Parabola sequence in a distance/altitude view. Transition phases last for around 3 s. Angles depict the trajectory path relative to horizon. Actual angles of attack of the plane at injection point and pull-out are different due to wing setting angle.

8.2.4. *"Steady flight!"*

After 20 s, the aircraft returns to level flight. This is the "steady flight" phase. A two-minute delay is set between two parabolas, allowing the experimenters to prepare their experiments for the next parabola. The pilots repeat this flight sequence 30 times during the flight.

During the breaks between series, when the aircraft returns to a level flight, the pilots will execute turns, as well as for some of the experimental subjects. The researchers can take advantage of this stable flight phase to make adjustments to the experiments.

8.2.5. *After landing*

Back on the ground, researchers must record the data acquired and analyse their flight procedures. A debriefing takes place on the ground at the end of each flight. The aim is to make a collective assessment of the organisation and progress of the operations. . . .

The free fall duration is directly related to the velocity and the pitch angle at the injection. It is given by: $2 * V_i * \sin(A_i)/g$, where V_i is the velocity at injection point, A_i is the angle of trajectory relative to horizon at injection point, and g is the gravity acceleration.

The free fall duration can be improved by increasing one of these parameters. In fact, with the current aircraft (within its commercial aircraft family), the duration is already maximized with respect to the aircraft flight envelope. This aircraft will be used until at least 2030. In the future, another type of aircraft might be selected and certified. Based on its characteristics and performances, but also depending on the scientific need, parabolic flight program could evolve towards airborne means that we have to imagine tomorrow.

9. Conclusions

Since April 2015, the Airbus A310 Zero-G, the world largest airplane for reduced gravity research, is used in Europe for short duration microgravity investigations mainly by ESA, the French space agency CNES and the German Space Agency DLR. Parabolic flight campaigns are foreseen to continue at a rate of two campaigns per year for CNES and ESA and one up to two campaigns per year for DLR.

With this unique program, developed within an excellent cooperation between space agencies and Novespace, parabolic flights will continue to provide scientific and technical knowledge in the various scientific disciplines and technology fields that take advantage of the microgravity or reduced gravity. Together with drop towers, sounding rockets, the ISS and other manned and unmanned spacecraft, parabolic flights with the Airbus A310 Zero-G complete the set of flight research opportunities in reduced gravity for European scientists and researchers of other countries.

ESA website http://www.esa.int
CNES website http://www.cnes.fr
DLR website http://www.dlr.de
Novespace website http://www.novespace.fr.

Conflicts of interest

The author has no conflict of interest to declare.

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