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Aircraft Parabolic Flights: A Gateway to Orbital Microgravity and Extra-Terrestrial Planetary Gravities

Vladimir Pletser

Abstract

Aircraft parabolic flights provide repetitively periods of reduced gravity whose duration depends on the target reduced gravity level and on the type of aircraft used. Typical durations for a large aircraft vary between approximately 20 s for a 0 g environment and 32 s for a Martian g level environment. Parabolic flights are used to perform short duration scientific investigations in weightlessness or at partial-g levels, to train astronauts, and to allow the general public to experience what astronauts' encounters in space during discovery flights. This chapter introduces the aircraft parabolic flights and presents their objectives, the parabolic flight manoeuvre and accelerations, the type of flights organised and a summary of the aircraft used throughout the world.

Keywords: aircraft parabolic flights, weightlessness, microgravity research, moon gravity, Mars gravity

"Pull-up... ". The plane pitches up and the horizon tilts through the windows.

"Twenty... ". I can't miss it; I'm getting heavier and heavier.

"Thirty... ". Around me, most of the researchers are lying down. I have trouble raising my arms. I'm getting heavier and heavier, almost double my normal weight.

"Injection!" And suddenly it's the long-awaited and much-repeated miracle. I'm floating freely and flying. I grab one of the straps on the ceiling and with one impulse, I throw myself parallelly to the ceiling to cross the entire cabin of the plane in its length. Below me, the 40 scientists and engineers invited by the European Space Agency to take part in this campaign of microgravity research in parabolic flights are busy. Some are running their instruments and observing the reactions on their computer screens, others do strange things to their subjects who willingly lend themselves to life science experiments.

But already, the pilot announces the aircraft's nose-down angles at the end of his parabola.

"Twenty". It's time to think about finding a place to land on my feet.

"Thirty". I'm landing between two scientific experiments: one studying manual grip at different gravity levels and the other investigating problems of convection and capillarity in liquids.

"Pull-out". It's about time. After landing gracefully on my feet, I look around. Twenty seconds is finally short but at the same time very long, long enough to conduct research in the absence of gravity. The twelve teams that have been working for several months to prepare their experiments are concentrated and are already preparing for the next parabola that the pilot announces, "One minute". And so, the cycle starts again.

1. Introduction

Aircraft parabolic flights are used in many countries [1], firstly by space agencies to conduct research and to prepare for space flight missions, and secondly by private operators to provide the general public with the opportunity to experience reduced gravity¹ conditions.

Aircraft parabolic flights are a useful tool for performing short duration scientific and technological experiments in reduced gravity, to train astronauts in this new environment and in associated procedures and protocols, and to test experiments and instrumentation prior to future space missions. The principal value of parabolic flights is in the verification tests that can be conducted prior to space experiments in order to improve their quality and success rate, and after a space mission to confirm or invalidate (sometimes conflicting) results obtained from space experiments.

The main advantages of parabolic flights for reduced gravity investigations are:

- the short turn-around time (typically of a few months between the experiment proposal and its performance);
- the low cost involved (space agencies provide the flight opportunity free of charge to selected 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.

Furthermore, aircraft parabolic flights are the only suborbital carrier to provide the opportunity to carry out medical and physiological experiments on human subjects under conditions of microgravity or reduced gravity such as that found on other planetary bodies (Martian 0.38 g, Lunar 0.16 g), to prepare for extra-terrestrial planetary exploration.

This chapter presents first the experimental objectives of parabolic flights with the capability of conducting investigations at Moon and Mars gravity levels in addition to microgravity; second, the parabolic flight manoeuvres, the accelerations and the technical capabilities of a parabolic flight aircraft; third, the type of flights organised, including the safety and medical aspects; and fourth, a summary of the aircraft used throughout the world.

2. Objectives of parabolic flights

An aircraft in parabolic flight provides investigators with a laboratory for scientific experimentation where the gravity levels are changed repetitively, giving

¹ The term 'gravity' usually designates the force associated to the phenomenon of gravitation. One should therefore in all correctness use here the term 'weight', which is the force associated to the phenomenon of weightiness, and the resulting force of gravity and inertia forces existing in the reference frame in which the measure of the weight is done. However, the common (although incorrect) usage of the term 'gravity' and its derivatives (microgravity, hypergravity, ...) instead of 'weight' and its derivatives will prevail throughout this chapter.

successive periods of either 0.38 g (Mars gravity) for up to 32 s, or 0.16 g (Moon gravity) for up to 25 s or 0 g for 20 s, preceded and followed by periods of 20 s at approximately 1.8 g (**Figure 1**), where g is the acceleration created by gravity at Earth's surface, on average 9.81 m/s^2 .

Parabolic flight objectives pursued by investigators vary. From a scientific point of view, the following objectives can be attained:

- the performance of short experiments for which the reduced gravity is low enough for: qualitative experiments of the 'look and see' type, using laboratory type equipment to observe and record phenomena; and quantitative experiments to measure phenomena in reduced gravity, yielding direct quantitative exploitable results;
- the ability for experimenters to perform their own experiments in reduced gravity with the possibility of direct interventions on the experiment in progress during the low g periods and direct interaction by changing experiment parameters between the reduced gravity periods (**Figure 2**);



Figure 1.
NASA's KC-135 during the pull-up phase (Credit: NASA).



Figure 2.
Experiment on vibrational phenomena during an ESA campaign (Credit: ESA).

- the study of transient phenomena occurring during the transition between high to low and low to high g phases.

Furthermore, for scientific experiments to be performed during space missions, the following goals can be pursued during parabolic flights:

- assessment of preliminary results for newly proposed experiments, which can improve the final design of the experiment hardware;
- test of experiment critical phases on which the experiment success depends;
- for human physiology experiments foreseen to be conducted on astronauts in space, to obtain prior to, or after a space mission, a broader microgravity data baseline by conducting parts of the space experiments on a group of subjects other than astronauts;
- to repeat shortly after a space mission parts of experiments that were not fully satisfactory in space or that yielded conflicting results, giving indications on possible interpretations of experiment results.

Results of all experiments conducted during parabolic flights can be found in ESA's Erasmus Experiment Archive database [2]. Some experiment results of European parabolic flight campaigns are presented in [3–7].

From a technical point of view, in preparing experiment hardware for manned spaceflight or robotic missions, the following objectives can also be achieved:

- test of equipment hardware in reduced gravity;
- assessment of the safety aspects of instrument operation in reduced gravity;
- training of astronauts on experimental procedures and instrument operation (**Figures 3 and 4**).



Figure 3.
ESA Astronaut Alexander Gerst training on a treadmill on board the ESA/CNES/DLR Airbus A310 during an ESA campaign before his ISS mission (Credit: ESA).



Figure 4.
 Astronaut training for an EVA exit out of a mock-up airlock on board the NASA KC-135 aircraft (Credit: NASA).



Figure 5.
 NASA Astronauts Alan Shepard and Edgar Mitchell training on the KC-135 before their Apollo-14 mission (Credit: NASA).

Laboratory aircraft flights allow also to generate partial-g levels between 0 and 1 g. Typically Moon and Mars gravity levels are created during flight manoeuvres that are not exactly parabolic flights but that are still called (albeit erroneously) Moon and Mars parabolas. This approach allowed to answer the growing request of the scientific community to perform complementary research at partial-g levels, and to conduct studies and tests to prepare for future human and robotic exploration missions. The interest in partial-g parabolas is multifold. It allows to complement microgravity experiment results in providing additional data points at intermediate g levels in a variety of scientific fields in physical sciences (e.g., fluid and soft matter physics), life sciences (cell, plant and animal biology, human physiology) and technology. In particular, in Life Sciences, investigations can be conducted on living systems to understand how humans, small animals, cells and plants are affected by a low gravity environment similar to those on the Moon and Mars. Many issues of relevance for the preparation of future human space exploration that includes stays on the surface of planetary bodies can also be investigated (**Figure 5**). Some experiment results of European partial-g campaigns can be found in [8, 9].

Other gravity levels are also achievable during flights and can be used by investigators: e.g., during pull-up and pull-out manoeuvres, periods of 20 s of 1.8–2 g are achieved, and spiral turn manoeuvres provide for longer periods or other levels of high g. These hypergravity periods can be used for certain type of gravity dependent investigations, e.g., in combustion or physiology areas.

Finally, since a few years, parabolic flights are also used in the USA, Europe and Russia to allow the general public to discover the 0 g environment and to enjoy for a few moments the sensations that astronauts experience during their spaceflights.

3. Parabolic flight manoeuvre

For microgravity flights, let us recall first that a body is in free fall if it is subjected to the only force of gravity in an inertial reference frame and this body and all its content are in a state of weightlessness in the non-inertial reference frame attached to the body. Weightlessness thus appears in a non-inertial reference frame, which is in a state of free fall with respect to an inertial reference frame. Weightlessness is a dynamical state that requires a free-fall movement [10]. Note as well that any kind of movement of a vehicle that is subjected to the action of the sole force of gravity is a free-fall movement, and weightlessness is then generated in the vehicle.

Consider now an aircraft flying in Earth's atmosphere, assumed to be quiet. There are usually four forces acting on the aircraft in a straight and level horizontal flight (**Figure 6**):

- its own weight, oriented vertically downwards,
- the aerodynamic lift, induced by the shape of its wings, oriented vertically upward,
- the aerodynamic drag, created by air resistance, oriented horizontally backward,
- the aircraft engine thrust, oriented horizontally forward.

At steady state (dynamic equilibrium), the lift equilibrates the weight and the thrust should be larger than the drag for the plane to move forward.

To come to a free-fall configuration, the pilot should nullify all forces acting on the aircraft other than gravitational forces, i.e., the weight. Therefore, the resulting force along the aircraft velocity vector should be null, i.e., the thrust should exactly balance the drag for the duration of the free-fall manoeuvre. On the other hand, the lift must also be brought to zero. The lift is due to the shape of the wings and to the angle of attack, which is the inclination of the chord line of the wings with respect to the direction of the air flow. To nullify the angle of attack, the pilot must lower the nose of the aircraft to bring the wing chord line parallel to the air flow direction. However,

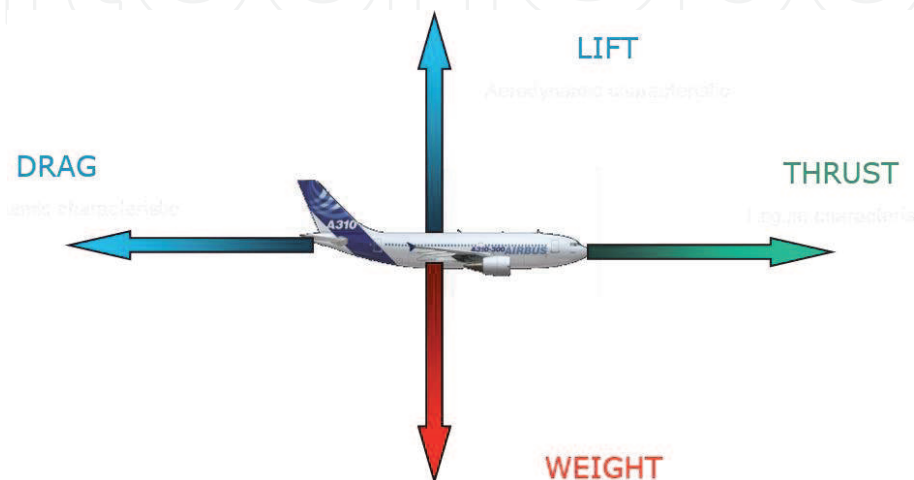


Figure 6.
The four forces acting on an aircraft in a straight and level horizontal flight.

the natural shape of the wing is such that there is always a small remaining lift, even for a zero angle of attack. Therefore, the pilot has to lower the nose a little bit more to bring it to a slightly negative angle of attack, called the zero-lift angle of attack, to completely nullify the aircraft lift. The aircraft is now in a real free-fall state, and as one can imagine, it is not an easy configuration to fly an aircraft.

The microgravity environment is then created in an aircraft flying the following manoeuvres (**Figure 7**):

- from steady horizontal flight, the aircraft climbs at approx. 45–50° (pull-up) for about 20 s with accelerations between 1.8 and 2 g;
- the thrust of each aircraft engine is then significantly reduced for about 20–25 s, compensating the effect of air drag (parabolic free fall);
- the aircraft dives at 45–50° (pull-out), accelerating at about 1.8–2 g for approximately 20 s, to come back to a steady horizontal flight.

One shows easily that the shape of the free-fall trajectory followed by the aircraft is a parabola. Assuming a constant and parallel gravity field and no resistance of the atmosphere, the aircraft at the moment of injection has a certain speed v_0 inclined on the horizontal by an angle α . Gravity being the only acting force on the aircraft, the horizontal component v_x of the velocity is constant throughout the free-fall manoeuvre while the vertical component v_z of the velocity varies with time t

$$v_x = v_0 \cos \alpha \quad v_z(t) = -g t + v_0 \sin \alpha \tag{1}$$

Integrating the two velocity components and replacing the time t between them gives the trajectory

$$z(x) = \left(\frac{-g}{2 v_0^2 \cos^2 \alpha} \right) x^2 + (tg \alpha) x \tag{2}$$

which is a parabola equation, yielding the horizontal distance travelled during the free-fall manoeuvre

$$x_{max} = \frac{\sin v_0^2 \sin 2 \alpha}{g} \tag{3}$$

The duration T of the free-fall phase is found from (1) and (3), yielding

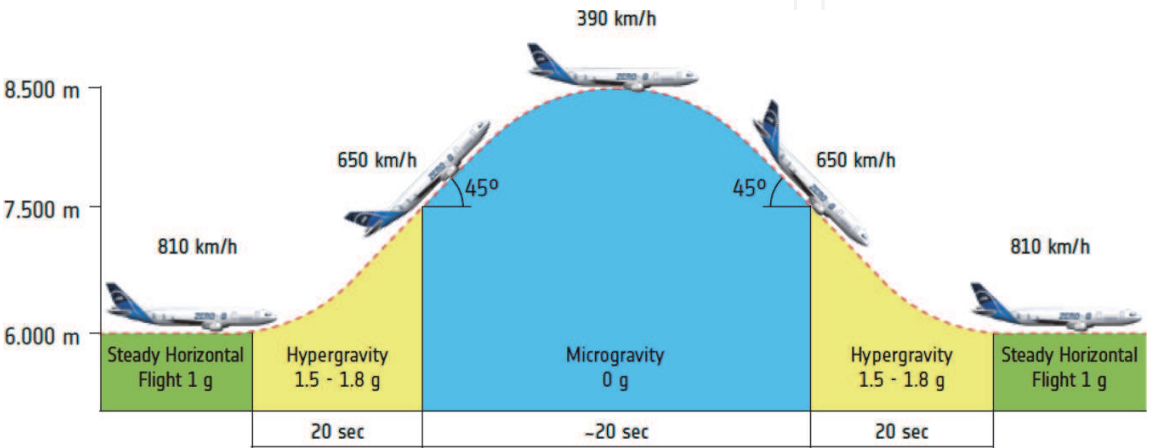


Figure 7.
The parabolic flight manoeuvre of the Airbus A310 (Credit: ESA).

$$T = \frac{2v_0 \sin \alpha}{g} \tag{4}$$

which depends only on the velocity vector at injection, i.e., its norm v_0 and its direction given by the angle α . With typical parameter values for aircraft flying parabolas (velocity at injection $v_0 = 500$ km/h and $\alpha = 45^\circ$), one obtains $T = 20$ s.

In reality, this parabolic arc is an approximation of an elliptic arc which is a part of an elliptic orbit that would intersect the Earth's surface. The relative error committed by this approximation is in the order of 10^{-4} , which justifies that these flights are still called parabolic flights (see [11]).

For partial-g parabolas, the engine thrust is reduced sufficiently to a point where the remaining vertical acceleration in the cabin is approximately 0.16 g for approximately 25 s or 0.38 g for approximately 32 s with angles at injection of approximately 42 and 38°, respectively, for Moon and Mars parabolas.

These manoeuvres are flown separated by intervals of several minutes. The duration of intervals between parabolas can be arranged prior to the flight so as to give enough time to investigators to change an experimental set-up. A typical flight duration is about two to two and half hours, allowing for 20–30 parabolas to be flown per flight, in sets of five, with 2 min intervals between parabolas and with 4–6 min between sets of parabolas. Durations between parabolas and groups of parabolas can be adjusted to the needs of investigators. Parabolas are flown in dedicated air zones controlled by well-trained air traffic controllers. The piloting is usually done manually along the X-axis (aft to front direction) by adjusting the engines thrust, the Y-axis (right to left), and along the Z-axis (floor to ceiling) using visual references utilising coarse (+2 g to –2 g) and fine (+0.1 g to –0.1 g) accelerometers.

Typical acceleration levels are shown in **Figures 8–10** for, respectively, micro-gravity, lunar and Martian parabolas for the aircraft X, Y and Z axes, measured during a parabola with micro-accelerometers strapped down on the cabin floor structure. During the reduced gravity period of, respectively, microgravity, lunar and Martian parabolas, a transitory phase of a few seconds appears first, with variations of about 10^{-1} g around respectively 0, 0.16 and 0.38 g in the Z direction, followed by a period of respectively approximately 20, 25 and 32 s with acceleration levels of about, respectively, a few 10^{-2} , 0.16 and 0.38 g. Accelerations along the

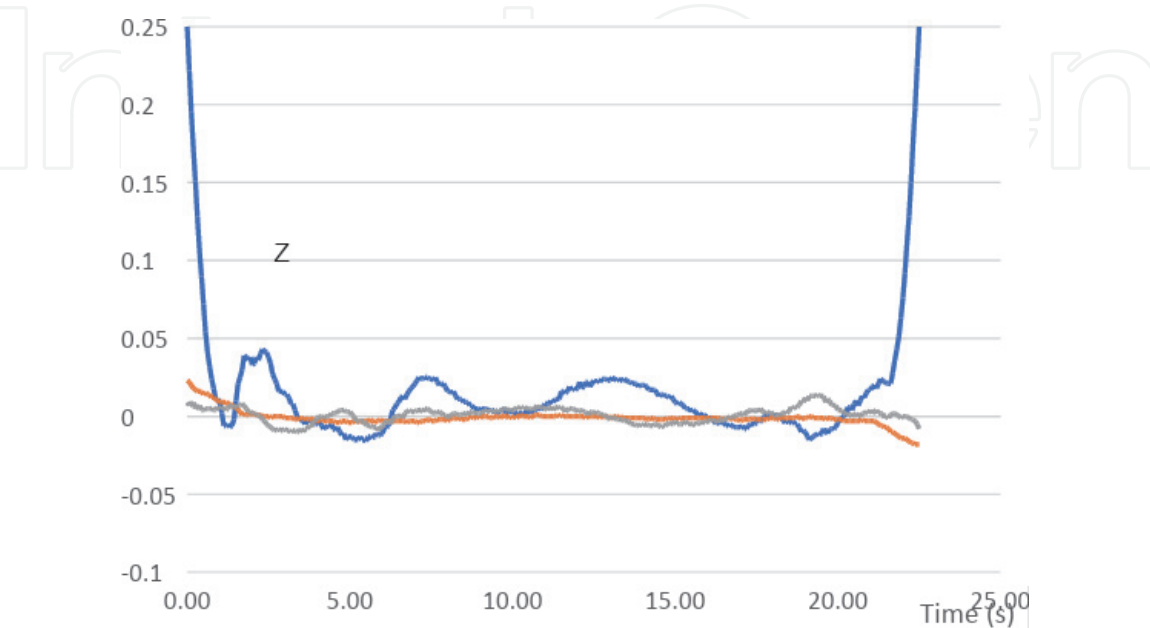


Figure 8.
Acceleration levels for a 0 g parabola.

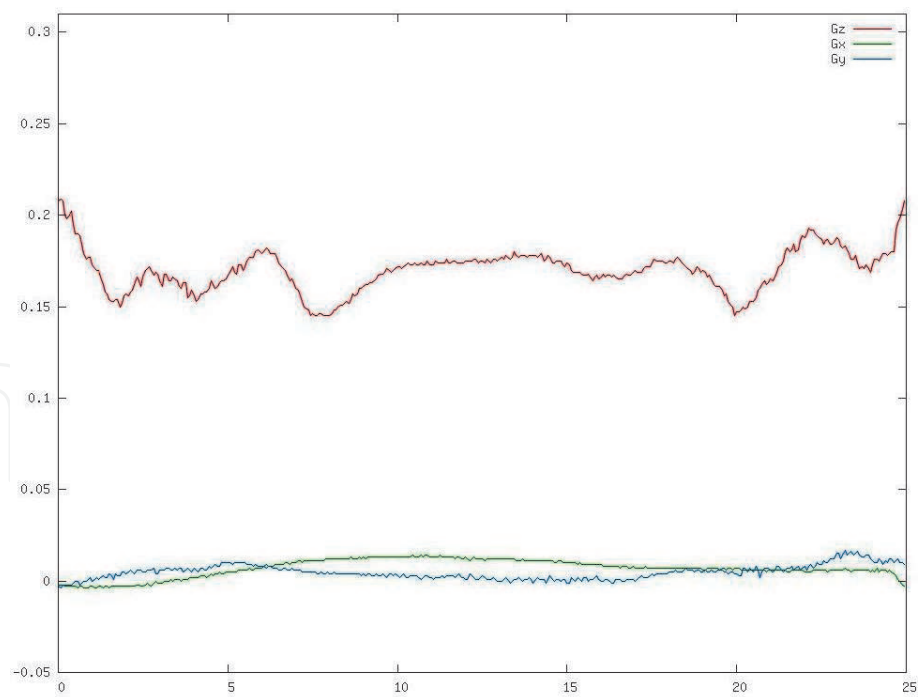


Figure 9.
Acceleration levels for a lunar g parabola for Z axis (brown), X axis (green), Y axis (blue) (Units: vertical axis: 0.05 g; horizontal axis: 5 s).

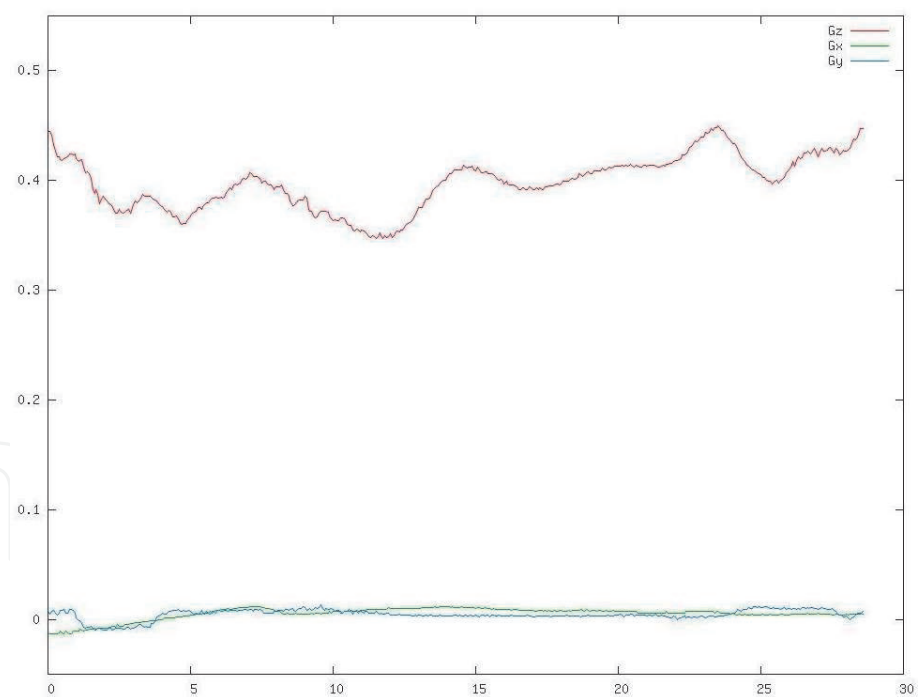


Figure 10.
Acceleration levels for a Martian g parabola for Z axis (brown), X axis (green), Y axis (blue) (Units: vertical axis: 0.1 g; horizontal axis: 5 s).

aircraft longitudinal X-axis (aft to front) and transversal Y-axis (right to left) are less than 10^{-2} g for all parabola types [12].

For microgravity parabolas, 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 left free floating in the cabin, the levels can be improved to typically 10^{-3} g.

4. Parabolic flight campaigns

As aircraft parabolic flights are considered as test flights, particular precautions are taken to ensure that all operations during flights are made safely and that flying participants are adequately prepared for the repeated high and low gravity environments. All flight participants must pass a medical examination and certifications are verified prior to the first flight. Flight participants attend a mandatory flight briefing before the first parabolic flight.

4.1 Scientific campaigns

Scientists are regularly invited by space agencies to submit experiment proposals to be conducted during parabolic flights, either in microgravity or at lunar or Mars gravity levels. These proposals are evaluated by panels of experts who review them for scientific content and for technical feasibility. Upon recommendation, scientists are formally selected by space agencies and invited to prepare their experiments to be flown on dedicated campaigns.

Prior to a campaign, support is provided for experiment equipment design and related safety aspects. All experiments to be performed and all equipment to be embarked on board the aircraft are reviewed by technical experts several months before the campaign from structural, mechanical, electrical, safety and operational points of view. Technical visits are made to experimenters' institutions to review equipment. A safety review is held approximately 1 month before the campaign. During this review, the integration of all equipment is discussed and the overall safety aspect of the campaign is assessed. Finally, a safety visit is made in the aircraft prior to the first flight to verify that all embarked equipment complies with the safety standards.

During flights, specialised personnel supervise and support the in-flight experiment operations (**Figure 11**). In addition, a Flight Surgeon participates in all parabolic flights to supervise the medical aspect of in-flight operations and to assist participants in case of sickness. Due to the association of flight phases of low and high gravity, motion sickness is quite common among participants of parabolic flights, sometimes hampering them in the conduct of their tasks. Prior to the flights,



Figure 11. Seating subjects performing the 'Sensorimotor coordination under partial gravity: movement control and adaptation' experiment (see [13, 14]) (Photo: ESA).

anti-motion sickness medication (usually based on Scopolamine) is made available on the request of flying participants.

The campaign itself takes place over 2 weeks. The first week is devoted to the experiment preparation and loading in the aircraft, culminating with a safety visit at the end of the week to assess that all safety recommendations have been implemented. During the second week, a flight briefing is organised on the Monday afternoon to present the flight manoeuvres, the emergency procedures and medical recommendations, and all experiments are shortly presented by the investigators. The flights take place on the mornings of the following days. A post-flight debriefing is organised after each flight, during which needs and requests of investigators are reviewed and discussed. Due to bad weather or technical problems, a flight can be postponed from the morning to the afternoon or to the next day. Downloading of all experiments takes place on the afternoon after the last flight.

A post campaign workshop is usually organised a few months after the campaign where investigators are invited to present their results. Investigators are further invited to publish the results of their experiments and to communicate their findings online, for example using the Erasmus Experiment Archive database of the European Space Agency, accessible on Internet [2].

4.2 Discovery flights

Since several years, the general public can participate to parabolic flights. Various private companies all over the world commercialise this type of flights.

Flight participants receive a pre-flight briefing similar to the pre-flight briefing of scientific campaigns. A discovery flight usually consists of 12–15 parabolas, including a Martian parabola and one or two Moon parabolas, followed by 10–12 0 g parabolas. A post-flight celebration debriefing is usually held, familiarly called ‘regravitation party’, where experiences are exchanged and 0 g diplomas are awarded to flying participants.

In the USA, the Zero Gravity Corporation operates a modified Boeing 727-200, named ‘G-FORCE ONE’ for discovery flights [15]. The Russian Ilyushin IL-76 MDK, located at the Yu. Gagarin Cosmonaut Training Centre at the Star City, near Moscow, is marketed since the 1990s by several private operators for discovery flights open to the public. The European Airbus A310 is also used for flights open to the general public.

5. Type of aircraft used for parabolic flights

Many airplanes are used all over the world to conduct parabolic flights. A review is given in [1, 16]. These can usually be classified in three categories: (1) the large-body aircraft, (2) the medium size aircraft and (3) the small airplanes, jets and gliders.

Large airplanes used for parabolic flights are defined as those aircraft used for flying several (typically 10 or more) experiments and embarking several tens of passengers, either for research purposes or for discovery reduced gravity flights for paying passengers. The large-body aircraft presently in use in the world are:

- a modified Boeing 727-200 of Zero Gravity Corporation in the USA,
- an Ilyushin IL-76 MDK (MDK stands for ‘latest modifications’ in Russian) in Russia, and



Figure 12.
The Airbus A310 ZERO-G during the pull-up phase (Photo: Eric Magnan/Airborne Films).



Figure 13.
The Dutch NLR Cessna Citation II in flight (Credit: NLR).

- an Airbus A310 (**Figure 12**) used in Europe by space agencies in Europe, the European Space Agency (ESA), the *Centre National d'Etudes Spatiales* (CNES, French Space Agency) and the *Deutsches Zentrum für Luft-und Raumfahrt e.V.* (DLR, German Aerospace Center).

Medium size airplanes are defined as those aircraft used for flying single experiments with several operators and/or subjects. Medium size aircraft in Europe includes:

- the Cessna Citation II (**Figure 13**) based in The Netherlands and operated by the Technology University of Delft and the Dutch National Aerospace Laboratory (NLR) [17];
- a Falcon 20 in Canada operated by the National Research Council's Institute for Aerospace Research (NRC/IAR) [18]; and
- two jets, a MU-300 and a Gulfstream-II jets in Japan, operated by Diamond Air Service [19].

Small airplanes, jets and gliders used for parabolic flights are defined as those aircraft used for flying single passengers and small experiments. These airplanes include presently:



Figure 14.

The Mudry Cap10B aircraft operated by the Aero Club Barcelona Sabadell (Credit: Universitat Politècnica de Catalunya).

- a jet fighter F-5E Tiger II aircraft of the Swiss Air Force used in Switzerland for automated science experiments [20];
- a Cessna 206, which was tested in the frame of the MiGrOp project to be used for science experiments in Germany [21];
- a Mudry Cap10B aircraft (**Figure 14**), a two-seat training aerobatic aircraft, used by the *Universitat Politècnica de Catalunya* with the Aero Club Barcelona Sabadell, in Spain for small science and student experiments [22];
- several Schleicher ASK-21 two-seat gliders have been used for students experiments in Belgium [23, 24] and Israel [25–27], with added advantages of a low-cost approach and ease of deployment at close-by geographical locations.

However, as any small or large airplane could basically be used to undergo a parabolic trajectory, it is important to choose carefully which aircraft would be best suited for scientific investigations, in terms of quality and duration of reduced gravity level but also ease of access and technical support from the integration team.

6. Conclusion

Aircraft parabolic flight manoeuvres are a very useful tool to investigate gravity related phenomena, whether in complete weightlessness or at partial-g levels. The quality and duration of microgravity obtained, the flexibility and variety of possibilities for experiments and tests and the easiness in flight preparation make aircraft parabolic flights a unique and versatile tool for scientists and engineers to perform experiments and tests at different gravity levels, from microgravity to hypergravity, including at Moon and Mars g levels. Parabolic flight campaigns for research in reduced gravity throughout the world provided a huge amount of scientific and technical data and knowledge, yielding hundreds of scientific publications, thesis or industrial applications, showing the uniqueness of this versatile tool to conduct gravity related investigations, complementing those on other microgravity carriers and preparing for space missions and for future extra-terrestrial planetary exploration missions.

In addition, opening the access of parabolic flights, traditionally reserved to scientists and astronauts, to the general public increases the perception of the public for space research and exploration, contributing to an enhanced interest for future endeavour of mankind in space.

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