7

Parabolic Flights

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7.1 Introduction

Aircraft parabolic flights are useful for performing short-duration scientific and technological experiments in reduced gravity. Their principal value 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) results obtained from space experiments. Parabolic flight experiments might also be sufficient as stand-alone, addressing a specific issue.

The levels of reduced gravity that can be attained during parabolic flights vary between 0 and 1 g (where g is the acceleration created by gravity at Earth's surface, on average 9.81 m/s^2). Near weightlessness at micro-g (μg) levels is commonly achieved during ballistic parabolic flights for microgravity research since more than 30 years. Recent years have seen more and more emphasis on partial-g flight profiles allowing to obtain gravity levels similar to those on the Moon (0.16 g) and on Mars (0.38 g) to prepare for future space exploration.

This section introduces the objectives of parabolic flights for research and the flight profiles to achieve μg and partial-g environments. The various airplanes used throughout the world to create these reduced gravity environments are introduced. These airplanes can be grouped in three categories: (1) large airplanes allowing to embark several tens of passengers and several large experiments; (2) medium-sized airplanes usually used for single experiment with several operators and/or subjects; and (3) small airplanes and jets embarking single passengers and small experiments.

7.2 Objectives of Parabolic Flights

A large aircraft in parabolic flight provides investigators with a laboratory for scientific experimentation where the g-levels are changed repetitively, giving successive periods of either 0.38 g for up to 32 s, or 0.16 g for up to 25 s or μg for 20 s, preceded and followed by periods of 20 s at approximately 1.8 g-level.

Parabolic flight objectives pursued by scientists are usually multifold: (1) to perform 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; (2) to allow experimenters to perform by themselves 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; and (3) to study transient phenomena occurring during changeovers from high-to-low and low-to-high g-phases. Additionally, for space mission experiments, preliminary results can be obtained prior to a space mission and experiments with conflicting results can be repeated shortly after a space mission, helping in data interpretation. For space human physiology experiments on astronauts, a broader data baseline can be obtained in μg prior to or after a space mission by conducting parts of the space experiments on a group of subjects other than astronauts.

From a technical point of view, in preparing experiment hardware for manned spaceflight or robotic missions, the following objectives can also be achieved: (1) test of equipment hardware in reduced gravity; (2) assessment of the safety aspects of an instrument operation in reduced gravity; and (3) training of science astronauts to experiment procedures and instrument operation.

Furthermore, aircraft parabolic flights are the only suborbital carrier to provide the opportunity to carry out medical and physiological experiments on human subjects in μg or partial gravity at Moon and Mars g-levels, to prepare for extraterrestrial planetary exploration.

Finally, other g-levels achieved during flights can be used by investigators: Pull-up and pullout maneuvers yield periods of hypergravity (from 1.8 g to several g's); spiral turn maneuvers provide for longer periods of other levels of high g's.

7.3 Parabolic Flight Maneuvers

For µg parabolic flights, the µg environment is created in a large aircraft flying the following maneuvers (see Figure 7.1, example given for the Airbus A300 ZERO-G):

- from steady horizontal flight, the aircraft climbs at approximately 45° (pull-up) (see Figure 7.2) for about 20 s with accelerations between 1.8 and 2 g;
- all aircraft engine thrust is then strongly reduced for about 20 to 25 s, compensating the effect of air drag (parabolic free fall);
- the aircraft dives at approximately 45° (pullout), accelerating at about 1.8 to 2 g for approximately 20 s, to come back to a steady horizontal flight.

Alternatively, for partial g parabolas, the engine thrust is reduced sufficiently to a point where the remaining vertical acceleration in the cabin is approximately 0.16g for approximately 25 s or 0.38 g for approximately 32 s with angles at injection of 42° and 38°, respectively, for Moon and Mars parabolas. These maneuvers can be flown consecutively (in a roller coaster manner) or separated by intervals of several minutes to allow investigators to prepare for their experiments.

For µg parabolas, the residual accelerations sensed by experimental setups attached to the aircraft floor structure are typically in the order of 10^{-2} g, while for a setup left free floating in the cabin, the levels can be improved to typically 10^{-3} g for 5 to 10 s.

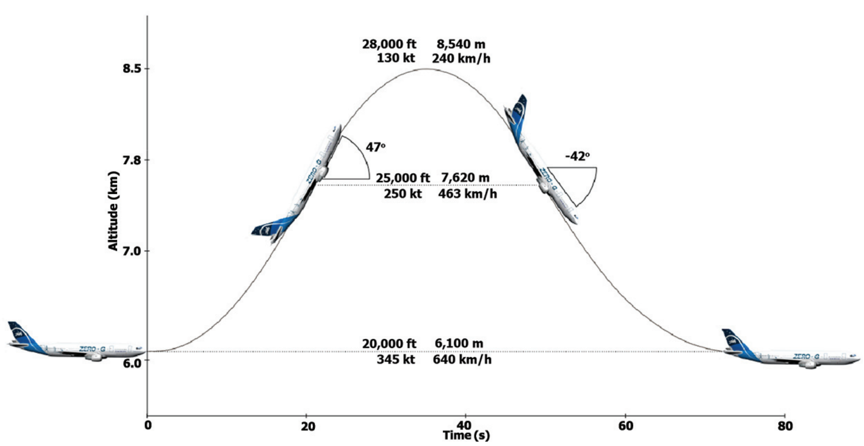

Figure 7.1 Airbus A300's parabolic flight maneuver (Credit: Novespace).

Figure 7.2 The Airbus A300 in pull-up (Photo: Novespace - Eric Magnan/Airborne Films).

7.4 Large Airplanes Used for Parabolic Flights

Large airplanes used for parabolic flights are defined as those aircraft used for flying several (typically ten or more) experiments and embarking several tens of passengers, either for research purposes or for discovery reduced gravity flights for paying passengers.

7.4.1 Europe: CNES' Caravelle and CNES-ESA's Airbus A300 ZERO-G

From 1988 till 1995, the European Space Agency (ESA) and the "Centre National d'Etudes Spatiales" (CNES, French Space Agency) have used a Caravelle aircraft for several tens of campaigns [1].

From 1997 till 2014, the Airbus A300 ZERO-G was used in Europe by ESA, CNES, and the "Deutsches Zentrum für Luft- und Raumfahrt e.V.," DLR, the German Aerospace Center, and industrial users for μg and partial-g flights. The Airbus A300 was the largest airplane in the world used for this type of experimental research flight.

Since 2015, an Airbus A310 is used to replace the A300 ZERO-G. The French company Novespace, a subsidiary of CNES, based in Bordeaux, France, is in charge of the organization of Airbus A300 and A310 flights.

Prior to a campaign with an Airbus ZERO-G, space agencies and Novespace provide support in the experiment equipment design and in all related safety aspects. All experiments are reviewed by experts several months before a campaign from the structural, mechanical, electrical, safety, and operational points of view. Technical visits are made to the experimenters' institutions to review equipment. A safety review is held one month before the campaign. A safety visit is made in the aircraft prior to the first flight to verify that all embarked equipment complies with the safety standards. The campaign in itself takes place over two weeks. The first week is devoted to the experiment preparation and loading in the aircraft. During the second week, on the Monday, a safety visit takes place to assess that all safety recommendations have been implemented and a flight briefing is organized in the afternoon to present the flight maneuvers, the emergency procedures and medical recommendations, and the experiments on board. The three flights of 30 parabolas each take place on the mornings of the Tuesday, Wednesday, and Thursday followed each time by a debriefing during which the 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 typical flight duration with the Airbus ZERO-G is about two and half hours, allowing for 30 parabolas to be flown per flight, in sets of five with two-minute intervals between parabolas and with four to six minutes between sets of parabolas. Parabolas are flown in dedicated air zones over the Gulf of Biscay or the Mediterranean Sea.

Since 1984, a total of 132 European campaigns were performed (61 ESA, 48 CNES, 23 DLR) for more than 1500 selected experiments in human physiology and medicine, biology, physics, astrophysics, technological tests, and launcher technology proposed by researchers and students [2–5] (see Figure 7.3). In addition to μg campaigns, two joint European partial-g campaigns were organized by ESA, CNES, and DLR in 2011 and 2012 for experiments at μg and lunar and Martian gravity levels [6].

Figure 7.3 Experimenters during μg parabolic flights on the airbus A300 (Photograph ESA).

Since 2013, the Airbus A300 and A310 ZERO-G are used for discovery flights open to the public.

7.4.2 USA: NASA's KC-135, DC-9 and Zero-G Corporation

A review of the aircraft used by NASA for parabolic flights since the early 1950 is given in [6].

NASA has operated several KC-135 aircraft (modified Boeing 707 jet aircraft) for reduced gravity research and astronaut training. The KC-135A/930, named "Weightless Wonder IV" (and nicknamed "Vomit Comet"), was the longest operated aircraft (1973–1995) [7]. ESA used the KC-135A aircraft for its first six µg research campaigns (1984–1988) [8], and DLR conducted nine campaigns (1987–1992) in preparation for the German Spacelab D2 mission. The replacement aircraft, the KC-135A/931, was used until its retirement in 2004 [9].

NASA operated also a DC-9 to allow researchers to perform their experiments in a reduced gravity environment. A flight lasts typically 2.5 h, with 40–60 parabolas, during which µg and partial gravity levels (0.16, 0.38 g) and sustained hyper-g (1.6 g) can be achieved according to researcher requirements [10].

The private company Zero Gravity Corporation operated a modified Boeing 727-200, named "G-FORCE ONE" in the USA from 2004 until 2014 for discovery flights open to the public. NASA had a microgravity service contract with Zero Gravity Corporation from 2008 until 2014 to fly NASA's sponsored experiments [11]. The flight maneuver is quite similar to the one described in earlier sections. From an horizontal flight at an altitude of approx. 8000 m, the pull-up up to 1.8 g lasts about 10 to 17 s up to an altitude of approx. 11300 m, and the aircraft is injected into the parabola for a duration of approx. 20 s until the pullout takes place. A flight includes 12–15 parabolas for public discovery flights or 25–40 parabolas for research flights. Moon-g and Martian-g flight maneuvers can also be performed [12].

7.4.3 Russia: Ilyushin IL-76 MDK

The Ilyushin IL-76 MDK (MDK stands for "latest modifications" in Russian) is a four-jet-engine cargo aircraft of the last modified version [13] and operated by the Russian Yu. Gagarin Cosmonaut Training Centre (CTC) from Star City near Moscow and used for parabolic flights for astronaut training, space equipment tests, and paying passenger flights. The main aircraft features are the double-floor cockpit and a large cabin, separated into two parts: The front includes several work stations for experimenters conducting tests on large equipment, while the aft part is an empty cabin space with attachment points on the cabin floor. ESA and DLR conducted parabolic flight campaigns with this aircraft in 1992 and 1994 [14]. The Ilyushin IL-76 MDK is marketed since the nineties by several private operators for discovery flights open to the public.

7.5 Medium-Sized Airplanes Used for Parabolic Flights

Medium-sized airplanes are defined as those aircraft used for flying single experiments with several operators and/or subjects.

7.5.1 Europe: TU Delft-NLR Cessna Citation II

The Cessna Citation II is a twinjet aircraft, a research aircraft owned and operated jointly by the Technology University of Delft and the Dutch National Aerospace Laboratory in the Netherlands. It has been extensively modified to serve as a versatile airborne research platform. The flight envelope with a maximum altitude of more than 13 km allows a wide range of operations to be performed, including flying at quite low speeds. It can accommodate a maximum of eight observers in addition to the two-pilot cockpit crew [15]. Among other research flights, it is used for aerospace student practical training, for parabolic flights for single experiments, and for discovery flights open to the public.

7.5.2 Canada: CSA Falcon 20

The Falcon 20 is a twin-engine business jet, capable of relatively high-speed and altitude operations with a small complement of instrumentation and research crew. It had been modified for μg experiments requiring parabolic flight trajectories [16]. The aircraft, owned and operated by the National Research Council's Institute for Aerospace Research (NRC/IAR), was used until 2014 by the Canadian Space Agency (CSA) for Canadian investigators.

7.5.3 Japan: MU-300 and Gulfstream-II

In Japan, a MU-300 jet aircraft operated by Diamond Air Service since 1990 [18] provides parabolic flights with up to 20 s of weightlessness. Besides creating conventional μg conditions, the parabolic flight using this MU-300 has many advantages. Since only one or two research themes are conducted in this medium-sized aircraft, the flight maneuver can be customized flexibly so as to make the most suitable condition for the study. Experiments have been conducted on rodents and cell cultures since 2007, using not only Martian (0.38 g) and lunar (0.16 g) gravity levels but also 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, and 0.05 g [19]. Other unique studies were also realized by using partial gravity conditions [20, 21]. A set of original parabolic trajectories was used to avoid interference of the "pull-up" phase-induced hypergravity into the genuine response to low gravities. After a certain time in the 1 g-level flight, the aircraft enters into the "pull-up" phase that lasts approximately 20∼40 s at 1.3 g, followed by a sudden descent that generates a target partial gravity condition lasting 15∼40 s and then pulls up again into the "recovery" phase that lasts 20 s at 1.3 g (see Figure 7.4).

Diamond Air Service operates also a jet aircraft "Gulfstream-II" since 1996 in Nagoya. The cockpit crew includes two pilots and one engineer who support the in-flight experiments. A total of 5.5-hour flight is possible

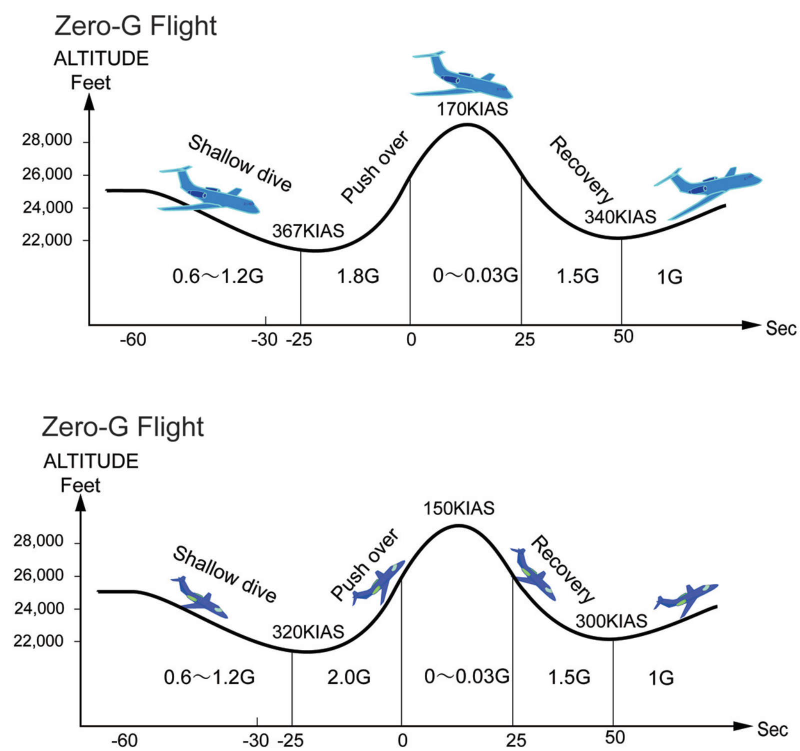

Figure 7.4 Typical μg flight trajectories of the Gulfstream-II (top) and the MU-300 (bottom) (Credit: Diamond Air Service).

with 5 or 6 researchers and up to 2.4 t of payload. To date, a total of 1480 flights with MU-300 and 350 flights with Gulfstream-II have been conducted so far, and 845 studies have been accomplished with JAXA support.

7.5.4 Other Aircraft

Ecuador: The Ecuadorian Air Force (FAE) and the Ecuadorian Civilian Space Agency (EXA) adapted jointly T-39 Sabreliner to perform μg parabolic flights [22]. In 2008, two flights took place and a fluid experiment was performed.

Austria: The company Pauls Parabelflüge organized since 2002 a series of flights in Germany, Austria, and Slovakia with several medium-sized aircraft (Casa 212, Short Skyvan SC7, Cessna Grand Caravan, Let 410) and recently with a glider (SARA-Mercury) yielding parabolas of 10 to 15 s of μg for discovery flights for paying passengers and students [22].

7.6 Small Airplanes and Jets Used for Parabolic Flights

Small airplanes and jets used for parabolic flights are defined as those aircraft used for flying single passengers and small experiments.

7.6.1 Switzerland: Swiss Air Force Jet Fighter F-5E

A jet fighter F-5E Tiger II aircraft was used in Switzerland from Emmen Air Force Base for biological research contained in a small experimental apparatus installed in the cannon ammunition box [23]. The military fighter jet aircraft Northrop F-5E "Tiger II" is a light supersonic fighter aircraft with two axial straight turbines, able to reach a maximum speed of Mach 1.64, with a maximum climb rate of 571 ft/s and a maximum altitude of 51,800 ft.

Single parabolas of up to 45 s are executed during military training flights (see Figure 7.5). After a 1 g control phase, the parabolic maneuver starts at 13,000 ft. and at Mach 0.99 airspeed, with a 22-s climb with an acceleration of 2.5 g up to an angle of 60° at an altitude of 18,000 ft., followed by a free fall ballistic trajectory lasting 45 s of 0.05 g in all axes with an apogee of 27,000 ft. at Mach 0.4 airspeed. The pullout is initiated when the aircraft reached 60° nose down with an acceleration of 2.5 g (up to 3.5 g) and lasts for approximately 13 s. Access time is 30 min before takeoff, and retrieval time is 30 min after landing.

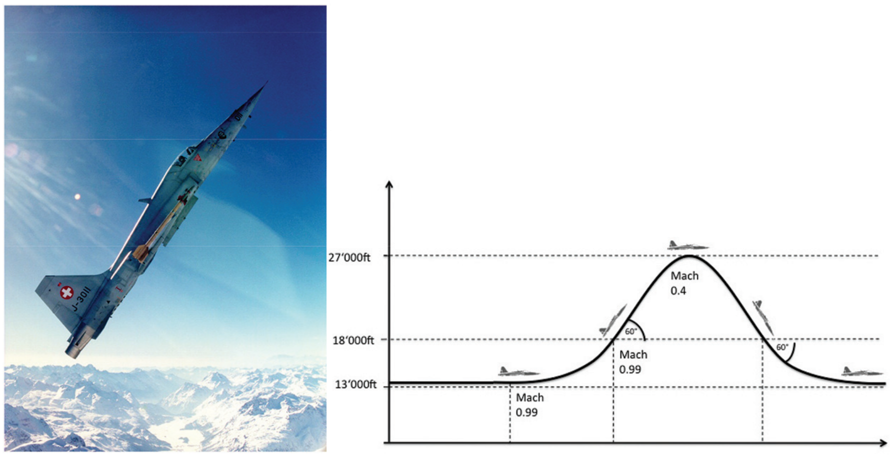

Figure 7.5 The F-5E Tiger II jet fighter aircraft and parabolic flight characteristics (from [22]).

7.6.2 Other Aircraft

Spain: In Barcelona, the Universitat Politecnica de Catalunya with the Aero Club Barcelona Sabadell proposes since 2007 parabolic flights on board a Mudry Cap10B aircraft, a two-seat training aerobatic aircraft. Up to ten parabolas of 5 to 8 s of µg each, with pull-ups and pullouts up to 3.5 g, can be performed by researchers and students with small experiments (typically $30 \times 20 \times 20$ cm, max. 10 kg).

Belgium: In the early 1990s, a two-seat Fouga Magister from the Brustem base of the Belgian Air Force was used, as part of aerobatics training, to perform parabolic flights of duration between 15 and 24 s. It was used to conduct fluid physics and technology development experiments from the University of Brussels [24].

7.7 Conclusions

Aircraft parabolic flight maneuvers are a very useful tool to investigate gravity related phenomena, whether in complete weightlessness or at partial-g levels. 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. In this respect, this section introduced the main aircraft used throughout the world to conduct research in reduced gravity. This survey is probably not exhaustive as no information could be obtained on similar parabolic flight program for reduced gravity research and practical training from emerging space-faring nations like China, India, Brazil, and possibly other countries.

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