The ESA Parabolic Flight Programme for Physical Sciences

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Abstract

Aircraft parabolic flights provide repetitively up to 20 s of reduced gravity during ballistic flight manoeuvres and are used to conduct short microgravity investigations in Physical and Life Sciences and Technology, to test instrumentation and to train astronauts before a space flight. Their use is complementary to other microgravity platforms, such as drop towers, sounding rockets, automatic orbital capsules and the International Space Station, and preparatory to space missions. Since 1997, parabolic flights in Europe are performed with the Airbus A300 'Zero-G', the world largest aircraft for this research activity. ESA campaigns are organized at a rate of two campaigns per year, usually in spring and autumn. Depending on their sizes, 12 to 14 experiments can be accommodated per campaign. ESA has organized 21 microgravity research campaigns on the Airbus, with a total of 275 experiments in various fields such as plasma physics, dust particles, material sciences, fluid physics, and heat transfer. The ESA aircraft parabolic flight programme, the Airbus A300 'Zero-G' aircraft and the safety and medical aspects of experiment operations during parabolic flights are presented. Some results from Physical Sciences experiments flown in previous ESA parabolic flight campaigns are highlighted.

Keywords: Microgravity research, Parabolic Flights, Physical Sciences

1. Introduction

Aircraft parabolic flights are a useful tool for performing short duration scientific and technological experiments in reduced gravity. 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. For these purposes, ESA has organized since 1984 in the frame of its Microgravity Programme forty five parabolic flight campaigns.

ESA has used since 1984 six airplanes to conduct its parabolic flight campaigns: NASA KC-135's, the CNES Caravelle, the Russian Ilyushin IL-76 MDK, the Dutch Cessna Citation II. Since 1997, the Airbus A300 'Zero G' is used in Europe for short microgravity investigations. The Airbus A300 is the largest airplane in the world used for this type of experimental research flight. The French company Novespace, a subsidiary of the 'Centre National d'Etudes Spatiales' (CNES, French Space Agency), is in charge of the organisation of Airbus A300 flights.

The main advantages of parabolic flights for microgravity investigations are: the short turn-around time (typically of a few months between the experiment proposal and its performance), the low cost involved (ESA provides the flight opportunity free of charge to 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.

This paper introduces the experimental objectives of parabolic flights, the parabolic flight manoeuvres, the ESA parabolic flight campaigns, the safety and medical aspects, the organisation of ESA campaigns,
and some Physical Science experiments conducted during the last ESA campaigns.

2. Objectives of parabolic flights

The microgravity environment is created in free falling carriers, where the sum of all forces, other than gravity, acting on the carrier is nil or strongly reduced. Scientific and technological experimentation in microgravity can be conducted in different carriers on Earth or in orbit. Generating a weightless environment on Earth imposes practical constraints on the level and duration of the microgravity required for investigations and on the cost at which this environment is obtained. Depending on their initial velocity, free fall trajectories are either linear vertical for drop facilities, or parabolic for aircraft flights and sounding rockets, or circular and elliptic for orbital platforms, including manned carriers such as NASA's Space Shuttle and the International Space Station (ISS).

An aircraft in parabolic flight provides investigators with a laboratory for scientific experimentation where the gravity levels are changed repetitively, giving successive periods of 20 s of microgravity preceded and followed by periods of 20 s of 1.8 g's. Parabolic flight objectives pursued by ESA and by scientists are multifold. From a scientific point of view, the following objectives can be attained:

• 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 in microgravity; and
- quantitative experiments to measure phenomena in microgravity, yielding direct quantitative exploitable results;

• to allow experimenters to perform by themselves their own experiments in microgravity 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;

• to study transient phenomena occurring during changeovers from high to low and low to high g phases.

• to achieve partial g levels between 0 and 1g, including lunar and Martian g's, by flying modified parabolas, allowing to complement results for certain investigations at different partial g levels.

These last two points were outlined by scientists as the major advantage of the experimental environment attainable during parabolic flights, for investigations in several disciplines.

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

• assessment of preliminary results for a newly proposed experiment, 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.

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

• test of equipment hardware in microgravity;

• assessment of the safety aspects of an instrument operation in microgravity;

• training of science astronauts to experiment procedures and to an instrument operation.

3. Parabolic flight manoeuvre

The microgravity environment is created in the Airbus flying the following manoeuvres (see **Fig. 1**):

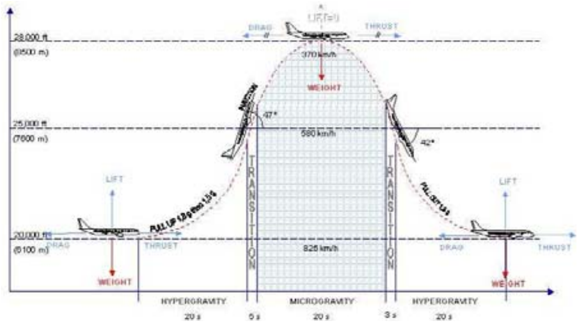

Fig. 1 The parabolic flight manoeuvre of the Airbus A300

Fig. 2 The Airbus A300 in pull-up (Photo: Novespace)

• from steady horizontal flight, the aircraft climbs at 47° (pull-up, see **Fig. 2**) for about 20 s with accelerations between 1.8 and 2 g;

• all aircraft engines thrust is then strongly reduced for about 20 to 25 s, compensating the effect of air drag (parabolic free fall);

• the aircraft dives at 42° (pull-out), accelerating at about 1.8 to 2 g for approximately 20 s, to come back to a steady horizontal flight.

These manoeuvres are flown separated by intervals of several minutes. Duration of 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 duration is about two and half hours, allowing for 30 parabolas to be flown per flight, in sets of five with two minutes intervals between parabolas and with four to six minutes between sets of parabolas. Take-offs and landings are made from the Bordeaux airport, although other airport can be envisaged. Parabolas are flown in dedicated air zones over the Gulf of Biscaye or the Mediterranean Sea.

In addition, Novespace’s ground infrastructures include hangar room for equipment set-up and check-out and office rooms for experiment preparation.

Typical acceleration levels are shown in **Fig. 3** for the Airbus aircraft X (aft to front direction), Y (right to left) and Z (floor to ceiling) axes, measured during a parabola with micro-accelerometers strapped down on the

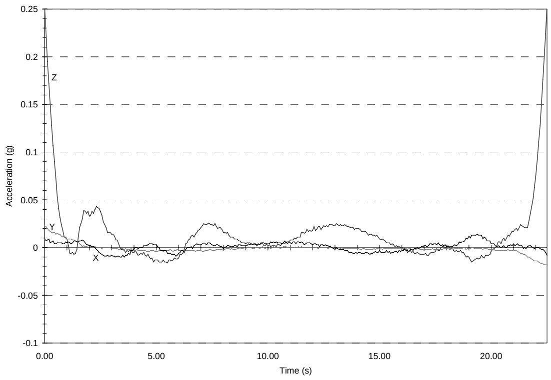

Fig 3 Acceleration levels during a parabola; accelerometers attached to the floor structure (sampling rate of 10 Hz)

cabin floor structure. During the reduced gravity period, a transitory phase of about 5 s appears first, with variations of about 10^{-1}g in the Z direction, followed by a period of approximately 20s with acceleration levels of about a few 10^{-2}g, while accelerations along the aircraft longitudinal X-axis (aft to front) and transversal Y-axis (right to left) are less than 10^{-2}g. 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.
The piloting is done manually along the X-axis (adjusting the engines thrust), the Y-axis, and along the Z-axis (using visual references of a coarse (+2 to -2g) and fine (+0.1 to -0.1g) accelerometers).
The Airbus A300 Zero-G can also be used to create hypergravity periods of up to 2 g during spiralling turns. These hypergravity periods can be used for certain type of gravity dependent investigations, e.g. in combustion or physiology areas.

4. ESA parabolic flight campaigns

In 23 years of ESA microgravity campaigns, 551 experiments were performed in Physical and Life Sciences and Technology, during 4206 parabolas, yielding a total cumulated time of 23 h 22 m of microgravity in slices of 20 s, equivalent to 15.6 low Earth orbits. In addition, ESA has organized since 1994 nine campaigns for Student proposed experiments to involve as early as possible students in microgravity and space technology research. 273 experiments were performed by students during 1201 parabolas.
Table 1 shows an overview of ESA microgravity and student campaigns.
Since 1997, ESA conducts its campaigns with the Airbus A300, the largest aircraft in the world ever used to perform parabolic flight campaigns. On Novespace instigation, new institutional and industrial customers joined ESA in using this new microgravity research tool. The French and German Space agencies CNES and DLR and private organisations from the USA, Canada and Japan organised campaigns for their own scientists and engineers. ESA conducted its 24th to 45th campaigns with the Airbus A300 from the Bordeaux-Mérignac airport with mixed payload of Physical and Life Sciences experiments. In early 1999, ESA reached an agreement with CNES and DLR to exchange experiments for reasons of experiment availability and schedule. This more flexible approach allowed to accommodate urgent experiments and to fly several time an experiment in a short time.
A majority of the experiments conducted on recent microgravity research campaigns were proposed in answer to International Announcement of Opportunities issued by ESA and selected after Peer reviewing, although the simpler 'look and see' type of experiments were still flown from time to time.
ESA's Announcement of Opportunity is permanently open for microgravity experiments to be conducted during parabolic flights. More information can be found on the Internet[1)]. Proposals can therefore be received at any time. Proposals are sent to selected external peers for reviewing from a scientific standpoint. 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 offers free of charge the opportunity of participating in the parabolic flights to selected investigators, but ESA cannot intervene in the costs of experiment preparation and in related expenses (travel costs, additional insurances, medical examinations, …). These costs must be supported either by the investigators themselves or by the national space agency or the national science research organisation.

5. Safety and medical operational aspects

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. The CEV (*'Centre d'Essais en Vol'*, French Test Flight Centre) is responsible for all in-flight operations.

Table 1: ESA Microgravity and Student campaigns

Dates	Campaign	Aircraft	Par.	Exp.
1984-88	1^{st}- 6^{th}	NASA KC-135/930	395	94
1989-94	D+7^{th}-18^{th}	CNES Caravelle	1094	119
1994	D+19^{th}	CTC Ilyushin	125	11
1994-95	20^{th}-22^{nd}	CNES Caravelle	279	33
1996	23^{rd}	NASA KC-135/931	90	12
1995-01	Supp. (6x)	NLR Cessna Citation	173	7
1997-06	24^{th}-45^{th}	CNES/ESA Airbus	2050	275
Total	45 campaigns		4206	551
1994	1^{st}	CNES Caravelle	107	20
1995	2^{nd}	NASA KC-135/931	158	24
2000-06	3^{rd}-9^{th}	CNES/ESA Airbus	936	229
Total	9 campaigns		1201	273

D: Demonstration campaign

Prior to a campaign, ESA, with the help of its Contractor Novespace, provides support in the experiment equipment design and in related safety aspects. All experiments to be performed and all equipment to be embarked on board the aircraft 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 with CEV and ESA experts 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. 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. Since October 2006, the safety approach was strengthened to guarantee an improved safe environment for experiment preparation on ground and experiment performance during flights. All technical and safety information can be found in Novespace's User Manual[2)].

All experimenters invited by ESA to participate to parabolic flights must pass a medical examination (JAR Class II, or above) and a tympanographic test replacing the previously required hypobaric chamber physiological test. All certifications are verified prior to the first flight. All participants attend a mandatory flight briefing before the first parabolic flight.

During the flights, specialized personnel supervise and support the in-flight experiment operations. In addition, CEV Flight Surgeons participate to all ESA 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 to parabolic flights, sometimes hampering them to conduct their tasks. Prior to the flights, anti-motion sickness medication (based on Scopolamine) is made available on request to flying participants.

6. Organisation of ESA campaigns

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. 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 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. Investigators are therefore advised to foresee the Friday as a potential back-up day. Downloading of all experiments takes place on the afternoon after the last flight.

Parabolic flight investigators are encouraged to present their results at microgravity symposia organised by ESA every other year dedicated alternatively to Physical Science and to Life Science research in Space. Results of previous experiments can be found in [3-12)].

Furthermore, parabolic flight investigators are requested to submit abstracts with preliminary results to be put in ESA's Erasmus Experiment Archive (EEA) database, accessible on Internet[13)], and are still encouraged to present their results in ESA's microgravity research symposia.

7. Some results of Physical Science experiments

Some of the Physical Science experiments conducted in the last few ESA campaigns with the Airbus are presented in this section, to show the diversity of investigations conducted during parabolic flights. Results, sometimes preliminary, can be found in ESA's EEA database[13)].

First of all, parabolic flights are often used by scientific teams to prepare or refine their experimental setup and experimental protocol in view of a longer flight opportunity. For example, the experiments BIOMICS (Biomimetic systems), CDIC (Hydrochemical Instabilities and Patterns at Reacting Interfaces), XRMON (Investigations of Fundamentals in Solidification of Metals) and SOURCE (Sounding Rocket COMPERE Experiment: behaviour of a liquid in a tank) are scheduled to fly on a MASER sounding rocket in 2008. They are all taking advantage of parabolic flight campaigns in 2007 for experiment fine-tuning. Experiment hardware foreseen on ISS can also be tested in parabolic flights, such as the PK4 experiment in the field of Complex Plasmas or a prototype of condensation/separation system for the CIMEX experiment.

Furthermore, parabolic flight experiments lead also often to interesting scientific results. The DOLFIN project team (Dynamics of Liquid Film/wall Interactions) has designed a modular rack that can be used for experiments on drop impacts, drop generation and film studies. A parabolic flight campaign was dedicated to the study of a water spray impact on a heated target, using high-speed, infra-red (IR) and high-resolution cameras (see **Fig. 4**).

It was demonstrated that:

- the average film thickness increases in microgravity, and decreases with an increase in flow rate;
- the spray cooling efficiency decreases in microgravity and with an increase in flow rate.

In the field of boiling, the experiment "High resolution measurements of wall temperature distribution underneath vapour bubbles under low-gravity conditions" has confirmed the theory that the highest heat transfer is reached in a micro-region located at the contact line between the wall, the liquid and the vapour (see **Fig. 5**).

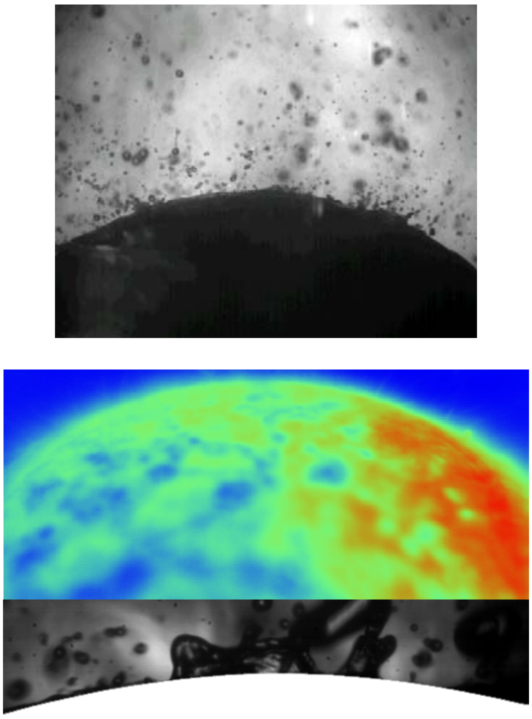

Fig. 4 Spray impact on a heated target: high-speed, IR and high-res. views (Images: DOLFIN scientific team)[14]

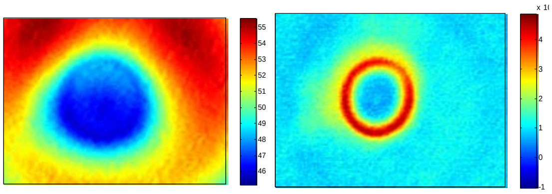

Fig. 5 Measured wall temperature and calculated heat flux under a single vapour bubble (Images: TU Darmstadt)[15)]

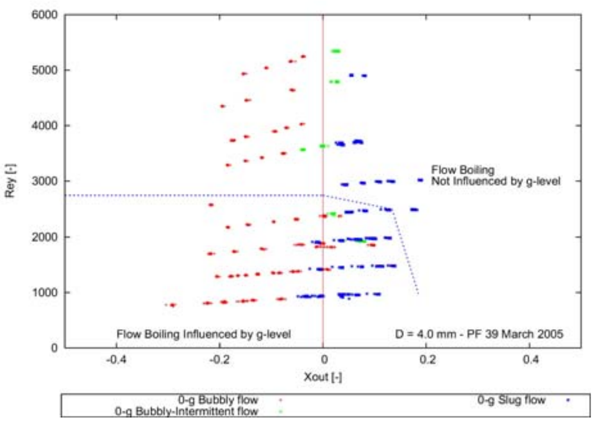

Fig. 6 Threshold map for test section of diameter 4 mm (Image: ENEA)[16)]

Fig. 7 Flow boiling in a microchannel (upward flow): left: 2g, right: 0g (Image: IUSTI)[17)]

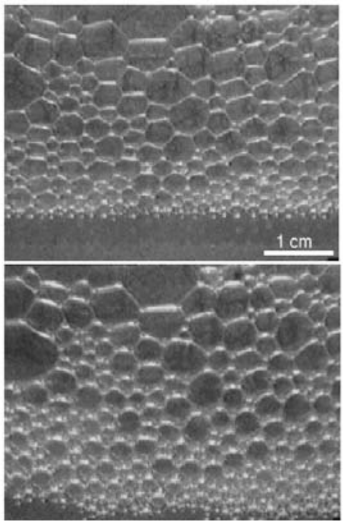

Fig. 8 Foam in 1g (top: drainage) and 0g (bottom: no drainage) (Image: GRASP)[18)]

Convective boiling is also being studied regularly in parabolic flights. Experiments on tubes with 2, 4 and 6 mm diameters have led to the establishment of flow pattern maps for microgravity conditions (see **Fig. 6**) with a threshold for microgravity influence. The effect of microgravity on rewetting velocity during quenching is also being investigated.

An experiment on flow boiling in microchannels concluded that the pressure loss by friction between phases in identical conditions is in linear proportion to gravity. **Fig. 7** shows a comparison of the microgravity phase (vapour pocket structures filling the channel) to hypergravity (classical bubble structure).

In the field of foams, the drainage of liquid and its relationship with the global stability (collapse) of the foam were investigated (see **Fig. 8**).

8. Conclusions

ESA has organized for twenty three years parabolic flight campaigns for microgravity research experiments with six different airplanes. This unique experience acquired on board the two NASA KC-135's, the CNES Caravelle, the CTC Ilyushin, the Dutch Cessna Citation and the CNES/ESA Airbus is reflected in the number of experiments successfully conducted since twenty three years.

ESA plans to continue to organize parabolic flight campaigns at a rate of two campaigns per year for the European scientific and technical microgravity communities. The ESA Announcement of Opportunity for microgravity research experiments is permanently open and proposals can be received at any time.

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 European scientists and engineers to perform experiments and tests in microgravity and at different g levels. In particular, aircraft parabolic flights are most indicated to conduct gravity related physical and life science investigations, to complement investigations on other microgravity carriers and to prepare for ISS missions.

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