The Orbital Liquid Experiment (OLE)

J.M. López, F. Mancebo, D. Meizoso & P. Valls
Universidad Politecnica de Madrid, Spain

U. Merbold
ESA Directorate of Manned Spaceflight and Microgravity,
ESTEC, Noordwijk, The Netherlands

The student Orbital Liquid Experiment (OLE), winner of the Agency's SUCCESS competition, has been built and successfully operated. OLE, which investigates the impacts of liquid drop against liquid surfaces, flew on ESA's 30th Parabolic Flight Campaign. Achieving conditions unobtainable under normal gravitational effects, valid data were recorded for 44 parabolas during the three flights of the campaign. The preliminary results show that, in microgravity conditions, there is an absence of any kind of reflection of the liquid following impact.

The SUCCESS competition

In 1998, ESA initiated a European student contest to support the early utilisation phase of the International Space Station (ISS). SUCCESS (Space Station Utilisation Contest Calling for European Student Initiatives) was officially presented at the Second Space Station Utilisation Symposium held at ESTEC on 17 November 1998. Its main aim was to have European students thinking about space and working on a proposal for an experiment aboard Europe's Columbus laboratory module of the ISS. The contest was open to all disciplines in order to stimulate new space science initiatives for the ISS.

SUCCESS was addressed to all students in more than 950 universities all around Europe – more than a million students from all disciplines. The year-long contest was organised in three phases. In the first phase, the students had to register and briefly describe their ideas; 485 proposals from 229 universities were received by the deadline of 18 February 1999. A Professional Day was organised in March 1999, when ESA experts answered online questions from the students.

In the second phase, the students had to write a proposal describing their initiatives in more detail. ESA received 103 experiment proposals from 126 students, in Austria, France, Germany, Ireland, Italy, The Netherlands, Norway, Spain and the UK, spanning the fields of technology, life sciences, physics, materials science and Earth observation.

ESA's Space Station Utilisation Panel (SSUP) served as the competition's jury and decided on the best essays to select the participants for the third phase. A Team Day was organised at ESTEC on 23 April 1999, when the participants met for the first time and worked together on their proposals. The objective was to provide first-hand information about the ISS and Columbus, as well as to encourage participants with similar proposals to form teams with members from other countries.

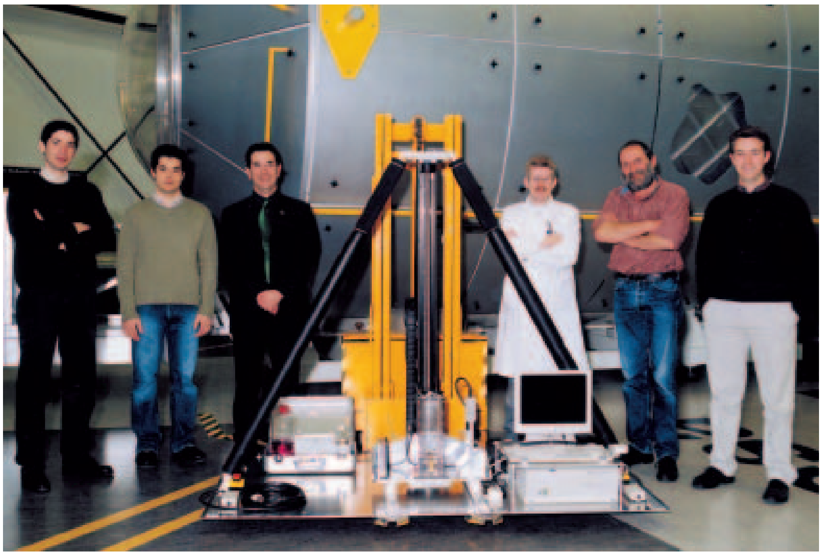
In this phase, the teams elaborated detailed proposals for flight experiments. The SSUP chose the winners. The award event was organised in connection with the 50th International Astronautical Federation congress, in Amsterdam, in October 1999. Under the aegis of ESA's Director for Manned Spaceflight and Microgravity, Mr Jörg Feustel-Büechl, prizes were awarded to:

First Prize: José Mariano López Urdiales, Fernando Mancebo Ordóñez, Daniel Meizoso Latova and Pablo Valls Moldenhauer (Universidad Politécnica de Madrid, Spain);
Second Prize: Paolo Ariaudo (Università degli Studi di Napoli 'Federico II', Italy);
Third Prize: Alexander Roger and Anna Glennmar (University of Glasgow, UK).

The First Prize was the opportunity to work on the experiment at ESTEC and test it on a parabolic flight campaign. Second Prize was a laptop; Third was a trip to Kourou to witness an Ariane launch. This article describes the activities and results that followed from the award of the First Prize to the Orbital Liquid Experiment (OLE; Figs. 1 and 2) team.

Background

Behind the beauty of the apparently simple event of a liquid drop impacting against a liquid surface lies a complex and unsolved physical system. Given the initial conditions and properties of the liquid, we are not yet able to



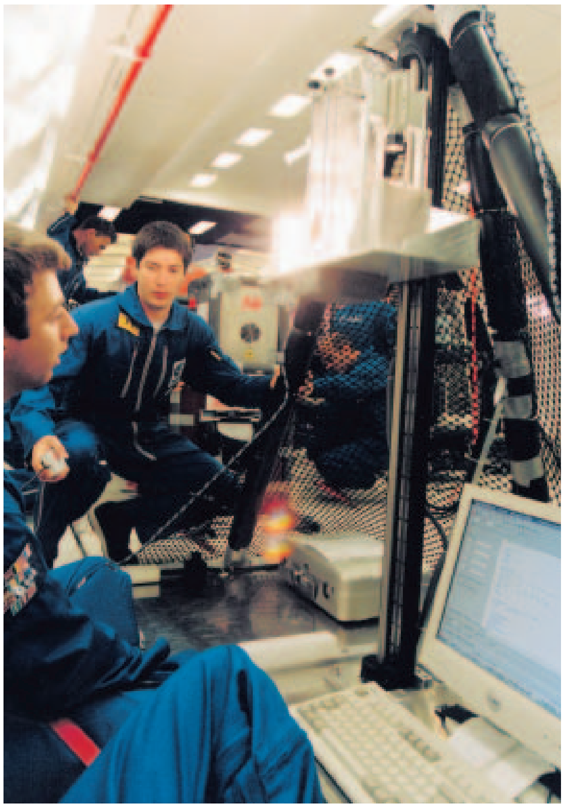


Figure 1. OLE ready for shipping to Bordeaux

Figure 2. OLE during an experiment run, poised at the top of the bearing rail

fully explain or predict what will happen. The subject has important implications for a wide variety of fields of science, including fluid dynamics, chemical engineering, space research and meteorology. It is important for many technical applications in the pharmaceutical, metallurgical and food industries. The investigation of drop collision and coalescence processes as a whole is leading to new and more efficient technologies. The main objective of this research is to gain a better understanding of liquid drop impact phenomena under a wider range of physical conditions than can be achieved in a ground-based facility.

Fluid dynamics researchers have studied impacts of liquid drops against flat liquid surfaces since the early photographic work of Prof. A.M. Worthington in the 19th Century. Many experiments of this type have been carried out using liquids of different properties (from water to superfluid helium) and drop diameters of up to 6 mm. However, they were all carried out under normal gravity, which imposed two limitations in the range of conditions that could be explored. First, the drop diameter was limited to less than 6 mm; second, the gravity in the impact reference frame was always the same. OLE was conceived to elude these limitations by providing experimental conditions in which the gravity of the reference frame of the impact was a control parameter, while being able to form drops larger than on the ground.

The outcome of the impact depends on the properties of the drop fluid, the target fluid and also of the fluid the drop travels through before it impacts. It also depends on the diameter of the impinging droplet, the impact velocity and the level of acceleration. Also, the boundary and initial conditions play an important role that may vary the results of similar experiments. The two main physical parameters on which the phenomenon depends are the Weber and Bond numbers, which are respectively the kinetic energy and the gravitational energy of the drop, both normalised to the surface energy. Using high-speed imaging, the impact can be observed and the shape and size of the impact crater can be measured to characterise the phenomenon.

Each different impact condition can be associated with a point in the Weber-Bond plane. The part of the plane already explored in ground-based laboratories is shown in Figure 3 This part can be divided into regions, each representing a different impact regime. Results so far show three different regimes: bounce, coalescence and reflection. Short descriptions of these regimes in drop-flat fluid surface collisions are given below.

Bounce
It may happen that the gas surrounding the free surfaces is trapped between them as they close in. The thin gas layer then inhibits the contact between them and the drop bounces off the flat surface. The deformation and drainage of the thin gas layer depends upon external factors such as the gas pressure, the shape of the impacting droplets and the behaviour of the trapped gas. This phenomenon is difficult to reproduce because it occurs only under very specific conditions.

Coalescence
In this case, the air layer escapes from the gap between the drop and the fluid surface. After initial contact, a liquid bridge appears between

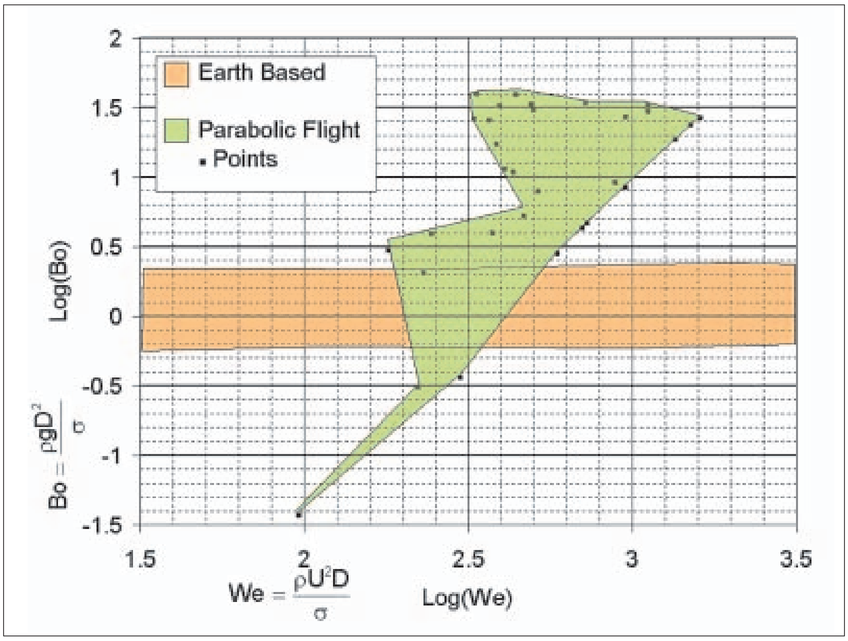


Figure 3. The Weber-Bond plane

them; the mass inside the drop joins the fluid of the target in a process called coalescence.

Reflection
The process is similar to that of coalescence – the drop merges with the target surface but then a new drop separates, of different mass. If the Weber Number of the impact is higher than about 65, a jet is reflected upwards and a new drop is pinched off at the tip of the jet (Rayleigh instability). Even higher Weber Numbers produce more complicated reflections: smaller, satellite drops are generated behind the main drop.

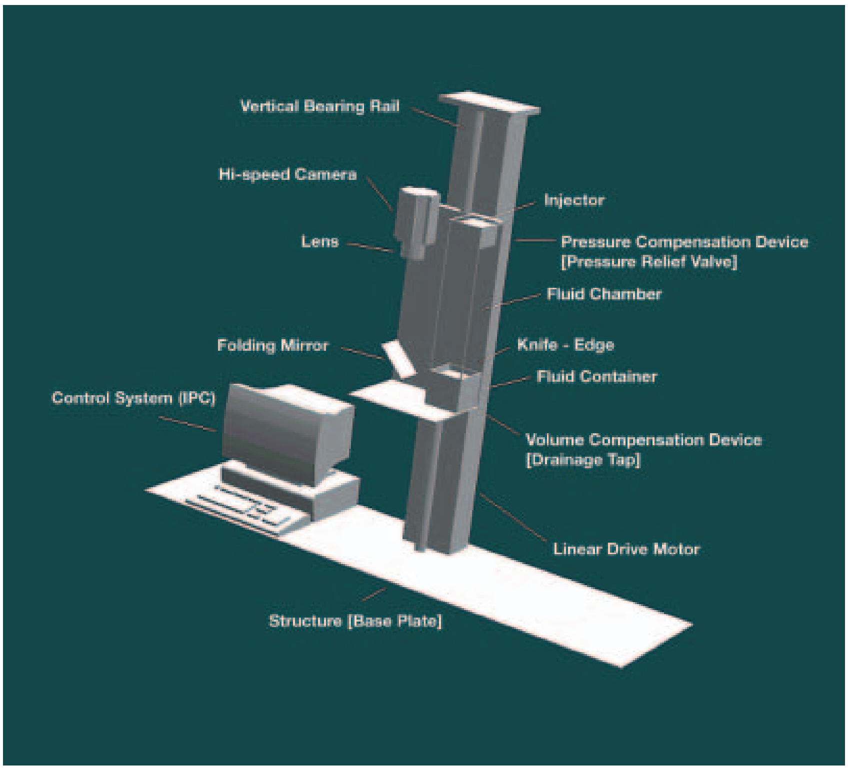


Figure 4. Schematic of the selected hardware concept

Before the OLE team's arrival at ESTEC, a series of experiments in the Universidad Politécnica de Madrid generated results in the previously known regimes and provided hands-on experience with drop impacts and high-speed imaging. This preliminary work paved the way for the project's rapid progress.

OLE was designed to study impacts of drops of various diameters in microgravity, and impacts of very large drops in conditions simulating the gravities of Titan, Mars and Earth. Figure 3 shows the impact conditions that were achieved in the experiment. All these impacts are beyond the previously explored range.

The experiment hardware
Many concepts for the experiment were studied from October to December 2000; Figure 4 shows the final version. The main hard-ware components are the:

– working fluid;
– injector system;
– fluid cell system;
– high-speed digital imaging system;
– illumination system;
– servo-controlled linear motor;
– power system;
– data-acquisition and control system;
– structure.

Distilled water was selected as the *working fluid* because it has a high surface tension and it is relatively safe and easy to handle. The *injector system* consists of a set of adapters, syringes, tubing and Teflon needles to form single drops in microgravity. Figure 5 shows the Teflon needles and an adapter. The drops were formed by pumping water manually with the syringes. Manual operation provided greater flexibility of operation than using a digitally controlled syringe. To form drops of various sizes, different drop injection sets (with needles of diameters ranging from 0.1 mm to 0.8 mm) were attached to the top of the fluid cell using custom-made adapters. The injector system was assembled at the Microgravity Laboratory in ESTEC.

The *fluid cell system* provides a watertight volume where the liquid is stored and drops can be formed and impacted against a flat liquid surface. The cell chamber is a straight prism with a square 100 mm section made of transparent polycarbonate sheets. The injection sets were attached at the top of the cell. One critical requirement for the experiment to work was to keep the surface of the liquid flat even during microgravity time. This was achieved with the aid of a laser-cut stainless steel plate 150 microns thick, its surface was treated with

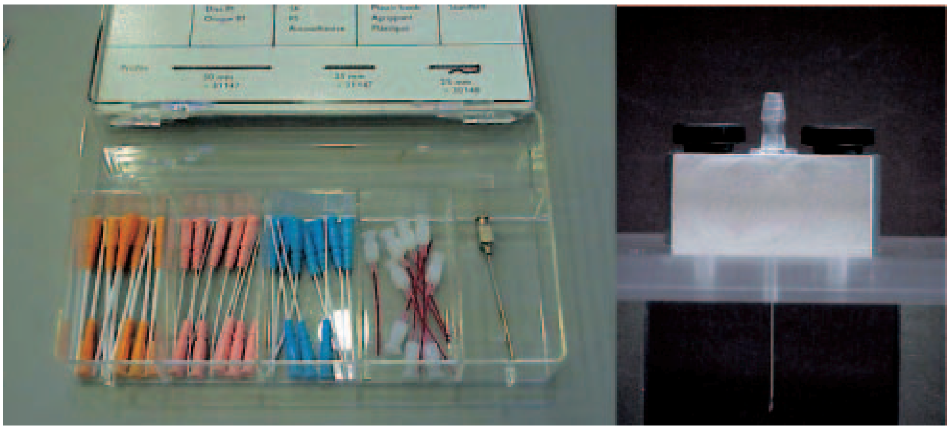


Figure 5. The Teflon needles and adapter

an experimental non-wetting coating provided by 3M (L16154). Ground tests and microscopy inspections were performed to characterise the properties of the sharp edge. However, the only way in practice to fully validate this solution was to test it in microgravity, which was obviously not a realistic option. Fortunately, this solution proved to be very effective because the surface remained pinned to the sharp edge of the plate for more than 90% of the parabolas. In the rest of the cases, the surface was probably destabilised by a small but sustained negative residual accel-eration during the first seconds of the parabola, causing the liquid to 'fall' upwards. The fluid cell was built in the main workshop in ESTEC.

The impacts were imaged by a high-speed 256-level greyscale, digitally controlled *digital imaging system.* The camera was capable of a resolution of 256x240 pixels at 1000 frames per second (fps). The camera head weighed only 1.6 kg and could accommodate different lenses via a standard C-mount. The camera and the lenses are shown in Figure 6. Up to 4 s of images, or 256 MB, were recorded in real time at each impact. The whole system was extremely compact and comprised only the CCD camera, a high data-rate cable and a PCI card plugged into a slot of the motherboard of the computer. The camera was triggered manually with a negative TTL trigger built at ESTEC. Using custom camera software, at the end of each parabola, one experimenter selected the time interval during which the impacts occurred and stored it on the hard-drive in order to free the D-RAM for the next parabola. Photon kindly loaned the camera and the PCI card. Different illumination solutions were tested; the best proved to be a white diffused background. The *illumination system* consisted of a set of four off-the-shelf 12 Vdc 50 W halogen dichroic lamps and a diffusing sheet. Together, they provided the intense diffuse background illumination that the camera required to take images at 1000 fps.

One of the requirements for OLE was to reproduce phenomena under different gravity conditions. In the original proposal for SUCCESS, intermediate gravity was to be achieved via a small centrifuge. After studying the new requirements (shorter microgravity time than aboard the ISS) as well as the additional opportunities afforded by the A300 aircraft (higher volume, mass and power available), a *servo-controlled linear motor* was found to be a better option to provide the required 0.01-1 *g* for 3 s. It also simplified the analysis and interpretation of the results because of the purely linear acceleration and the absence of Coriolis forces. The drop injection, fluid cell, high-speed camera and illumination systems were all rigidly mounted on a linearly moving platform. The platform was attached to the thrust block of the linear motor, which moved along a vertical rail fixed to the aircraft. The overall length reaches 1.6 m, providing 1.3 m of travel. The position of the motor was monitored constantly, with an optical linear encoder providing 5-micron accuracy. The motion profiles of the motor were pre-programmed in Mint™ language and downloaded to the NextMove™ PCI controller during the intervals between parabolas. A series of ground tests set the parameters and gains of the controller for each motion profile.

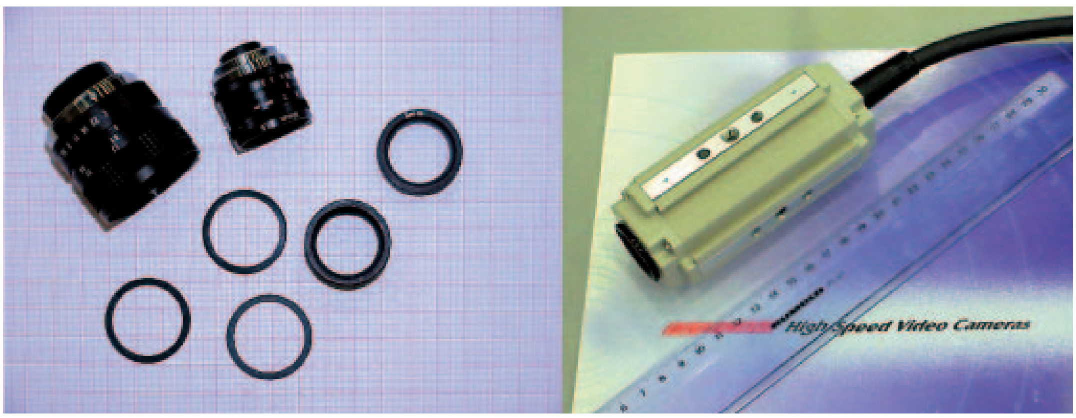


Figure 6. The high-speed camera head and lenses

The tests were performed moving the motor in a horizontal direction to simulate the conditions of motion in microgravity. In each operation cycle, there was a motion profile characterised by three values of the acceleration. The first phase was the initial acceleration, which had two different purposes. It detached the droplet from the needle and provided a certain relative velocity between the drop and the flat surface. Until shortly before impact, the motor kept moving in the same direction but at a different acceleration in order to provide the desired acceleration value during the impact process. After impact, the platform stopped in the minimum distance compatible with the loads that appear on the platform; that was the third level of acceleration. The experiment used the *power system* provided by the aircraft's electrical panel #1, which supplied up to 2 kVA of 220 V at 50 Hz. In order to obtain flicker-free illumination, a rectifier feeds the illumination system with 12 Vdc.

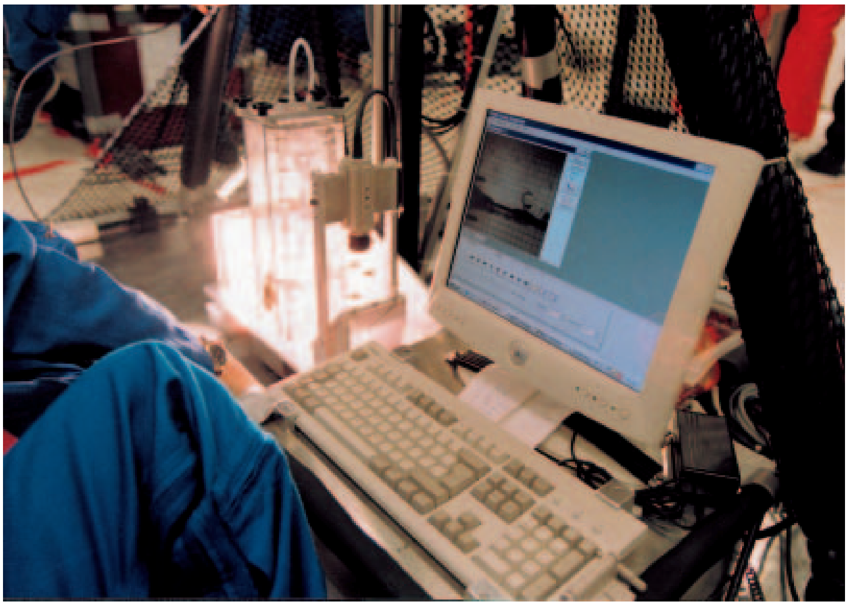


Figure 7. OLE during flight: operating the high-speed camera from the computer

The *data acquisition and control system* consisted of a PC with two dedicated PCI cards and custom software. During parabolas, the system was used to control the linear motor and imaging system simultaneously. Operated by one experimenter, the computer ran under Windows 98. Instead of a normal mouse, which would not work properly in microgravity, a Microsoft Ballpoint was used as a pointing device. This trackball proved to be very comfortable to operate and it performed flawlessly under all gravity conditions. The computer was supplied by Serco.

As with any experiment flown on the A300 aircraft, the hardware had to meet rigorous mechanical requirements imposed by the vehicle's flight profile. The most prominent is an acceleration of 9 *g* along the aircraft's main axis towards the nose. The primary structure is a set of aluminium beams of full square cross section attached to a reinforced plate of aluminium. This structure holds the linear motor bearing rail vertical. All the linearly moving items are attached to the platform. This one was built in aluminium and designed to be rigid enough to prevent any vibrations or misalignments between the camera, mirror and fluid cell. Auxiliary structures were designed and built for the electronics boxes and the computer. All the structures were built in ESTEC's main workshop.

The parabolic flight campaign

OLE (Fig. 7) was one of 14 experiments that flew on the 30th ESA Parabolic Flight Campaign from Bordeaux (F) on three flights 15–17 May 2001. Each flight included 31 parabolas, each providing about 20s of microgravity. As usual on all parabolic flights, each period of microgravity was preceded and followed by a short phase of hypergravity of about 1.8 *g*. The crew from Novespace and Sogerma, the French companies that operate and maintain the aircraft, were especially helpful in meeting the security requirements and safely attaching the experiment to the seat tracks on board.

For the first part of the first flight, the experimenters familiarised themselves with the singular and breathtaking sensation of weightlessness. These first parabolas also confirmed that the fluid surface remained flat under microgravity. Two experimenters (PV, DM) then learned the intricate art of pumping single drops of increasing size in weightlessness. To prevent jetting or, even worse, the drop staying on the tip, a fine compromise was reached between the pumping speed and duration. At the same time, JML, via the PC, operated the high-speed camera and the linear drive, and between parabolas was responsible for selecting and storing on the hard drive all useful portions of video data.

The experiment required a high degree of manual interaction, so a highly detailed procedure was devised and tested on the ground for weeks before the flights. A comprehensive set of programs for the linear drive was prepared for operational flexibility – critical for succeeding with any new experiment.

During the first flight, some drops intended for low-velocity impacts failed to detach from the needle: the initial acceleration of the moving platform was too low for those particular motion profiles. The antiwetting coating was extremely important for holding the fluid inside the container and the drop attached to the tip of the needle as long as possible. It became clear that very small drops would not detach from the needle, whereas large volumes were easily ejected even for low values of the induced acceleration. Hence, the knife-edge and each needle were carefully covered with antiwetting coating before each flight and the analysis focused on drop sizes larger than those obtainable at 1 *g*. The timing had to be precise because the longer it took to form the drop the more unstable became the fluid (inside both the container and the drop). However, the fluid had to be injected slowly into the drop in order to avoid detachment before the linear motor was triggered. Therefore, it was necessary to pump the volume slowly enough and to trigger the motor immediately after drop formation. It took several parabolas before the procedure was trimmed. The ratio of successful impacts rose from 8 out of 31on the first day, to 17/31 on the second and 19/31 on the third. An impact was considered successful if a single drop was detached and impacted in the field of view against a reasonably flat liquid surface, with the whole process recorded on the computer. During the third flight, a few bonus impacts under hypergravity were recorded between parabolas. However, the drop size could not be controlled and was always roughly the natural size of a detaching drop at 1.8 *g*.

During video processing, all of the 'Titan' (1.4 ms^{-2}) runs were found to be defective

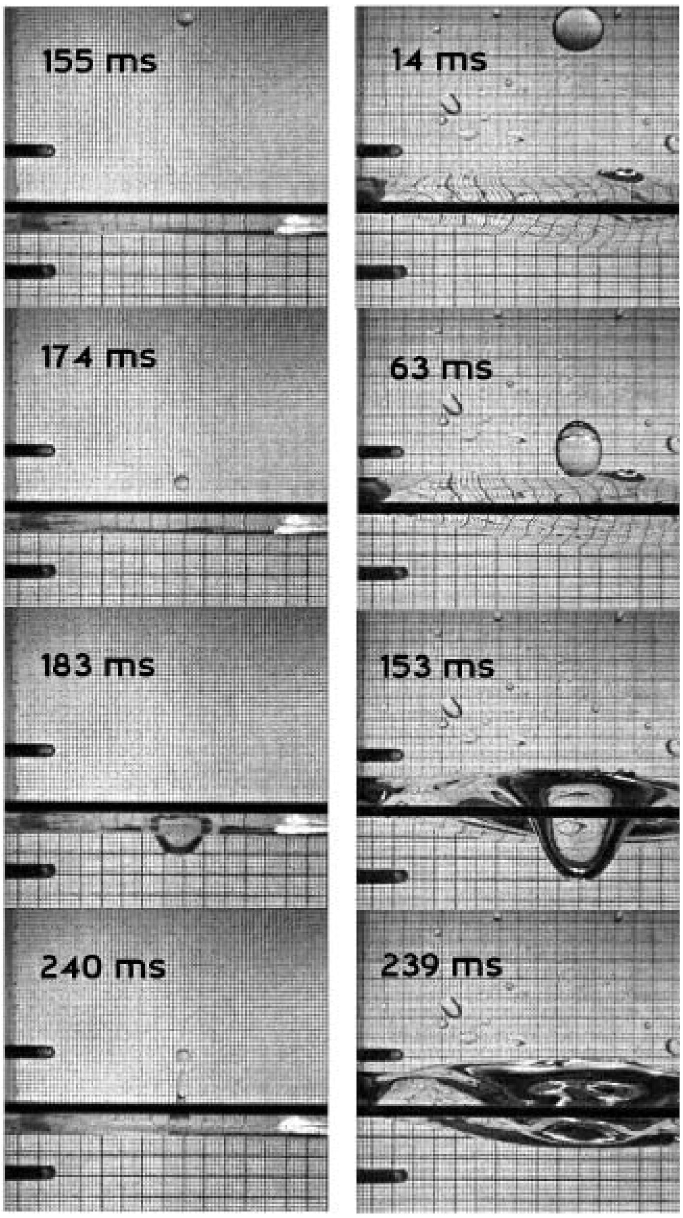


Figure 8. Comparison between two impacts of similar Weber Number: ground-based reflection (left) and pure coalescence in microgravity (right). Note the difference in the drop sizes

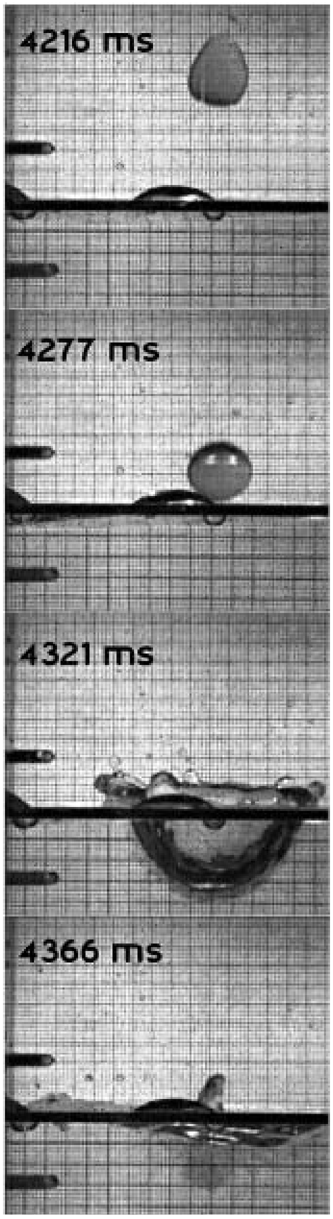


Figure 9. The impact of a 15 mm-diameter coloured drop at 1.4 ms^{-1} in Earth gravity

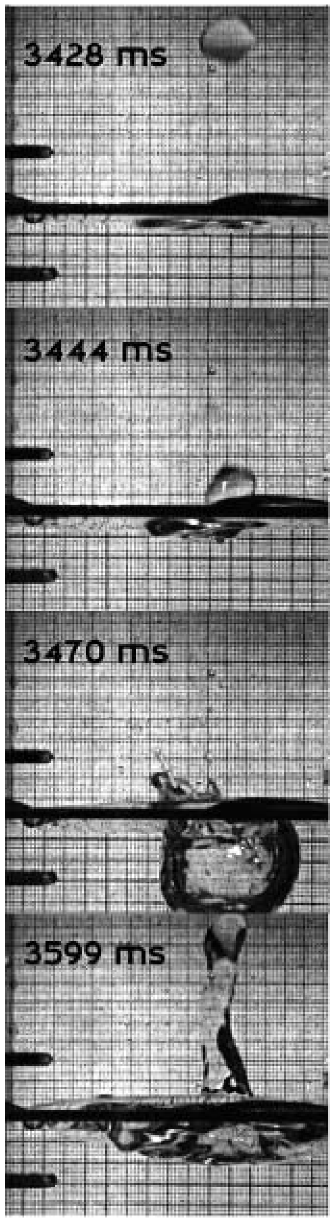


Figure 10. The impact of a 9 mm-diameter drop at 2.3 ms^{-1} in martian gravity

apparently because of an instability breaking the fluid surface just before impact. Despite this minor setback, an excellent set of successful impacts was recorded for the Mars (3.8 ms^{-2}), Earth (9.81 ms^{-2}) and pullout phases (18 ms^{-2}) for various sizes and different speeds.

During the last few parabolas of each flight a few impacts were reproduced using coloured water. The violet colouring agent was potassium permanganate, chosen because it leaves the surface tension and density almost unchanged. These impacts are useful because they allow us to see what happens to the fluid inside the drop after impact.

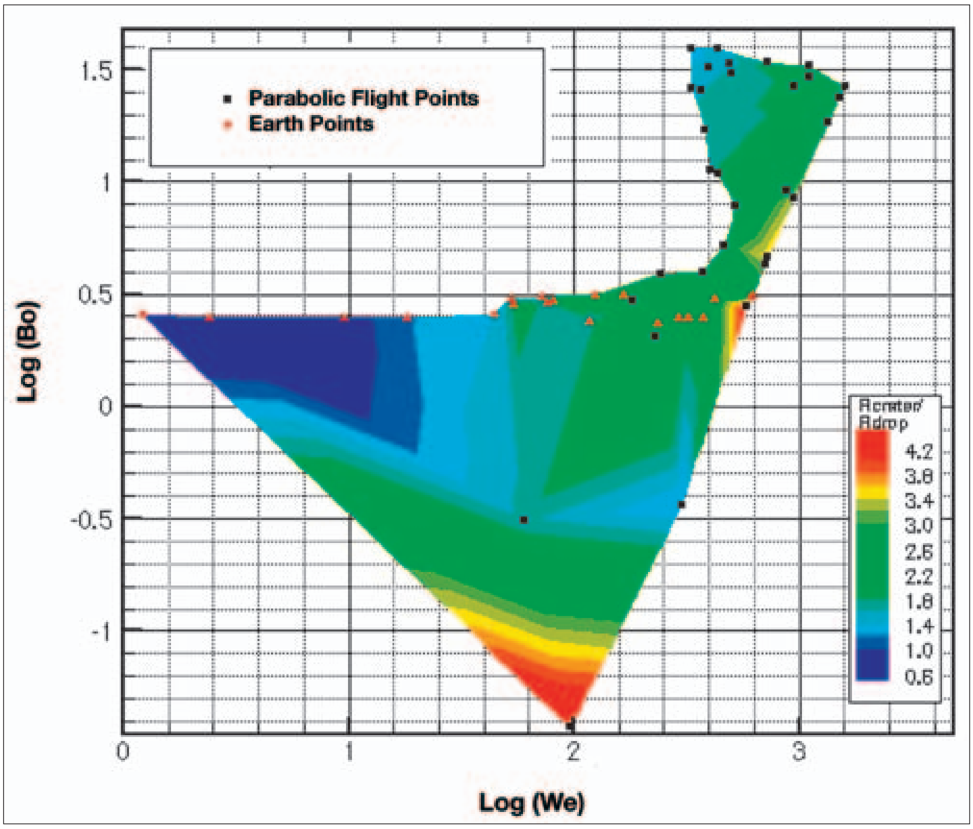


Figure 11. Radius of the impact crater, normalised to the radius of the impacting drop, as a function of the Bond and Weber Numbers

Preliminary results

One of the most striking results concerns the reflection phenomenon. In the range of explored Weber Numbers, a drop impacting a flat liquid surface in microgravity always coalesces with the target fluid, preventing reflection. Even for impacts with Weber Numbers up to 300, no drop or jet is ejected in the opposite direction. From this, we infer that the familiar phenomenon of reflection is caused by gravitational effects. This is seen in Figure 8, which compares an impact recorded on the ground with one in microgravity, with similar Weber Numbers. With gravity, there is a reflection while in microgravity the drop simply coalesces. Gravity has a strong influence on the shape of the impact crater and particularly in the way it collapses.

About half of the impacts were obtained while accelerating the platform at 9.81 ms^{-2} (1 *g*). In this case, the novelty of the experiment came from the large drop sizes: 7-18 mm in diameter. Figure 9 shows a 15 mm coloured drop impacting at 1.4 ms^{-1}.

Particularly exciting are the impacts recorded under 'martian' gravity. A series of drops 7–18 mm in diameter and at impact velocities of 1.2–2.5 ms^{-1} was made to fall and impact under martian conditions. All yielded Weber Numbers high enough for reflection. The reflected jet was always much wider and reached further than similar impacts under terrestrial gravity. If, as many planetary scientists believe, water once rained down on a martian ocean, the impacts probably looked something like Figure 10.

During June 2001, more than 50 image sequences were analysed. Emphasis was placed on determining the main features of the impact crater and its maximum size. Figure 11 combines data from the parabolic flights and the results from ground-based experiments. It graphically represents the radius of the impact crater, normalised to the radius of the impacting drop, as a function of the Bond and Weber Numbers.

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