



SPACE EXPERIMENTS BY DA RIVA'S TEAM

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ABSTRACT

The space experiments performed by the team of the late Prof. Da Riva are here revisited on the occasion of the international congress organized to celebrate Prof. Legros retirement, both of them coworkers at the European Space Agency on fluid science research under microgravity.

Emphasis is on experiment aboard the Spacelab laboratory, where the international cooperation has been at its most, but experiments performed on sounding rockets are covered in detail too.

The main theme of the experiments carried out by Da Riva's team on microgravity platforms concerns the mechanical stability of long liquid columns under the large variety of disturbances that may arise either accidentally or intentionally, both as a test-bench for theoretical developments on the behavior of capillary systems unmasked by the overwhelming gravity force, and as a contribution to the modeling of the floating-zone technique used in crystal growth.

INTRODUCTION

Space related activities at the Escuela Técnica Superior de Ingenieros Aeronáuticos of Universidad Politécnica de Madrid (ETSIA-UPM), begun in 1973, when the late Prof. Ignacio Da Riva (1931-1991) got a contract from the European Space Agency (at that time ESRO) for a compilation of spacecraft thermal control data. Prof. Da Riva got the Engineering degree in 1956 and the PhD degree in 1959; he collaborated in the 1960s on combustion research within an internationally reputed team [1-5], and got the Head of Aerodynamics at ETSIA in 1965.

Precisely at the same time, after the end of the Apollo program, NASA and ESA (at that time ESRO) agreed to build a dedicated space laboratory, Spacelab, to be launched around 1979 by the Shuttle being

designed at the same time. An international Call for Ideas for experiments on Spacelab was issued in 1974, and Prof. Da Riva made a proposal on the hydrodynamics of liquid columns, based on the Skylab-IV results reported by Carruthers et al. [6]; Prof. Da Riva had made a survey on physico-chemical problems of space relevance, and submitted to ESRO an experiment proposal on Bénard convection the year before [7]. In 1975 ESA selected Da Riva's experiment on the hydrodynamics of liquid columns, and financed an industrial Phase A contract with CASA-Spain [8], with ETSIA-UPM as advisors, to define a fluid physics module to support the experiment aboard Spacelab.

These two crucial events allowed Prof. Da Riva to nucleate a small group of young graduate students devoted to space research activities (and teaching), located at the Laboratorio de Aerodinámica y Mecánica de Fluidos (LAMF-ETSIA), while applications for an independent research institute were initiated, what was finally achieved in 1997, and named in his honour: the Instituto de Microgravedad "Ignacio Da Riva" (IDR-UPM).

SPACELAB EXPERIMENTS

Research in low-gravity fluid physics started in Europe in the 1960s with the aim of solving problems posed by fluid management in spacecraft. Typical problems were sloshing, thermal control, capillary liquid retention, gauging of partially filled tanks, etc. [9]. But the real thrust came from the 1974 Call for Ideas for experiments on the first Spacelab payload (FSLP). From the nearly eighty proposals, thirteen dealt with pure fluid physics, although several more were in the fuzzy fringe between fluid physics and material sciences [9]. Seven experiments were selected for flight (Table 1), and a multi-user facility to support all of them, the Fluid Physics Module (named the same as the precursor conception to support Da Riva's experiment), was designed and built by FIAT C.R. [10].

Table 1. Experiments performed in the Fluid Physics Module during Spacelab-1 mission, 1983.

1-ES-326	Oscillation of semi-free liquid spheres in space	Rodot, H. (F)
1-ES-327	Kinetics of spreading of liquids on solids	Haynes, M. (UK)
1-ES-328	Free convection in low gravity	Napolitano, L.G. (I)
1-ES-329	Capillary forces in a low-gravity environment	Padday, J.F. (UK)
1-ES-330	Coupled motion of liquid-solid systems in near zero gravity	Vreeburg, J.P.B. (N)
1-ES-331	Floating zone stability in zero gravity	Da Riva, I. (E)
1-ES-339	Interfacial instability and capillary hysteresis	Haynes, M. (UK)

Most of these experiments were concerned with capillary-dominated liquid behaviour when gravity forces are negligible (weightlessness, or microgravity). Space flight brought a revival on capillarity research, which had languished after the classical 19th century studies by Young, Laplace, Poisson, Plateau, Kelvin, Gauss, Poincaré, Rayleigh, and others (the first paper by Einstein, in 1901, was on capillarity). Capillarity research is of interest in many practical problems in science and industry: capillary rise, seepage in porous media, wetting, spreading, nucleation, soldering, bubbling, etc.

The experiment proposed by Prof. Da Riva was centred on the analysis of the mechanics of a liquid column, as a simplified model of the molten zone in the floating zone technique of crystal growth and

other containerless material processing operations. The term liquid bridge is more general, but most of the experiments here presented concern nearly-cylindrical liquid bridges, i.e. liquid columns. The equilibrium shapes and stability limits of the floating zone melt under the large variety of disturbances that could arise either accidentally or intentionally during the growing process is a matter of great concern. The study of the problem involves a formidable task both because of the material characteristics of the melt, whose properties are strongly temperature dependant, and because of the complexities associated to the disturbances that could be imposed on the molten zone. Several simplifications must be introduced in the model to make it workable. The simplest approach consists in disregarding phase changes, temperature gradients, electromagnetic fields, and so on, and considering just an isothermal liquid bridge spanning between two inert solid supports. For this liquid column, equilibrium shapes and their stability limits are investigated, as well as the effect of rotation (imposed on real floating zones to render the heating uniform), and vibration (induced by such a flexible structure as a space platform).

In the simplest configuration, shown in Fig. 1, a liquid bridge consists of an isothermal drop of liquid (held by surface tension forces) spanning between two parallel solid-discs, to the edges of which the liquid attaches by wetting and canthotaxis (contact line pinning at a border). Only cylindrical support discs were envisaged for the first flight, because of simplicity (axial symmetry) in theoretical developments. The equilibrium interface shape and hydrostatic stability limits of such a fluid configuration are determined by the geometry and the stimuli. The first choice on geometry is the overall size of the experimental volume; previous Skylab-IV experiments used a small water column; for Spacelab-1 much larger liquid masses were envisaged, to better control uncertainties in configuration, stimuli and diagnosis, and characteristic sizes of 100 mm for the liquid column and field of view, were requested. It has been sometimes questioned the need to go to space to achieve a given microgravity level, since, on non-dimensional terms, the same microgravity level can be achieved using large liquid bridges in space than using millimetric liquid bridges under a microscope on ground. The answer is that uncertainties in the uncontrolled variables do not scaled down, as was demonstrated in Spacelab-1 with the 0.5 mm protrusion of the supporting discs, which turned out to be too small. The initial proposal by Da Riva asked for water as the natural working liquid (as in the Skylab-IV demonstrations), but the international team adopted silicone oil as working fluid to avoid sample contamination. In Skylab-IV, liquid columns of various volumes were formed by placing a liquid drop on each disk with a syringe and bringing the disks together to form a single column.

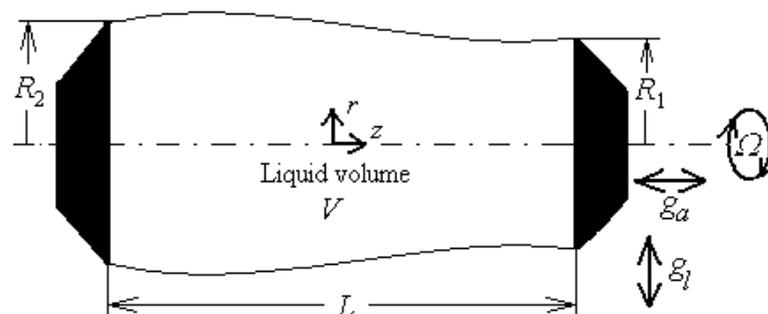


Fig. 1. Geometry and stimuli for an axisymmetric liquid bridge of volume V , spanning a length L between circular coaxial discs of different radii, R ; the stimuli can be some rotation, Ω , and residual gravity or inertial forces, g , (axial and lateral).

Some early stability studies concerning this basic configuration were published before the Spacelab era [11-15], much remained to be done. The multiple delays of Spacelab-1 flight (from 1979 to 1983), provided good time for ground trials with liquid columns in a Plateau Tank Facility built at LAMF to mimic the Fluid Physics Module, and a wide theoretical development (even an animated-drawing film in 1976 and a PTF-video film in 1982).

The basic geometrical parameters of a liquid bridge are the slenderness, $A=L/(2R)$, where L is the distance between the supporting discs and $R=(R_1+R_2)/2$ is the mean radius; the ratio of the radius of the smaller disc, R_1 , to the radius of the larger one, R_2 , that is $K=R_1/R_2$, or the equivalent parameter $h=(1-K)/(1+K)=(R_2-R_1)/(R_2+R_1)$; and the dimensionless volume, defined as the ratio of the actual volume V_f to the volume of a cylinder of the same length (L) and diameter ($2R$), $V=V_f/(\pi R^2 L)$, all of them assumed constant (i.e. fixed by the experimenter; notice that other possibilities can be of interest, as when fixing the feeding pressure instead of the volume, or the disc pulling instead of the length [16]); other geometrical parameters have been also considered, as a dimensionless eccentricity in two concentric disc, non-circular discs (ellipsoidal, square [17]).

The basic stimuli considered are: a residual axial acceleration, g_a , quantify in non-dimensional terms by the Bond number, $B_a=\Delta\rho g_a R^2/\sigma$, where $\Delta\rho$ is the difference between the density of the liquid and the density of the surrounding medium, and σ is the surface tension; the lateral Bond number, $B_l=\Delta\rho g_l R^2/\sigma$, where g_l stands for the lateral component of the acceleration acting on the liquid, which forms an angle β with respect to the plane defined by the axes of the discs, the Weber number (assuming that the liquid bridge is rotating as a solid body with angular velocity Ω), $W=\Delta\rho\Omega^2 R^3/\sigma$, with a possible dimensionless eccentricity for rotation, $e=E/R$, E being the distance between disc axis (assumed coaxial) and rotation axis (assumed parallel to the former).

The nominal 1-ES-331 configuration envisaged was a liquid column 100 mm long, spanning between equal circular discs of 40 mm in diameter ($h=0$) and with cylindrical volume ($V=1$). The liquid, a silicone oil five times more viscous than water (DMS-5 seeded with 0.15 mm Eccosphere-tracers), was injected and removed through a 6 mm in diameter central hole in one disc. No relevant information on microgravity levels both in the axial and lateral axes on board orbital laboratories like Spacelab was available at that time, so that in early studies, zero-gravity conditions were assumed [18-20]. In the nominal experimental sequence, once the cylindrical liquid column formed, several stimuli were to be applied, involving the axial vibration of one of the supporting discs, rotation of one of the discs, rotation of both discs either in iso-rotation or in counter-rotation, disalignment of the disc-axes with the liquid bridge in solid body rotation, and liquid bridge breakage. Since two runs were foreseen, two different breaking sequences were scheduled. In the first one the breaking should be accomplished by adding liquid and stretching the zone as to maintain the cylindrical shape, and in the second, by just withdrawing liquid at constant disc-separation.

Spacelab-1 was launched on 28-11-83 in the boot of Columbia Shuttle (STS-9, 250 km altitude, 57° inclination), and landed 10 days later. Actual operations of all the experiments scheduled for the Fluid Physics Module in Spacelab-1 suffered large deviations from the nominal conditions: it was the maiden flight for the whole lab and its first payload, FSLP; the FPM itself contributed with many infancy problems, already detected during crew familiarization before flight, but frozen in the project due to the understandable stiffness of FSLP; the worse problem being lack of visual access to the liquid volume (Fig. 2).

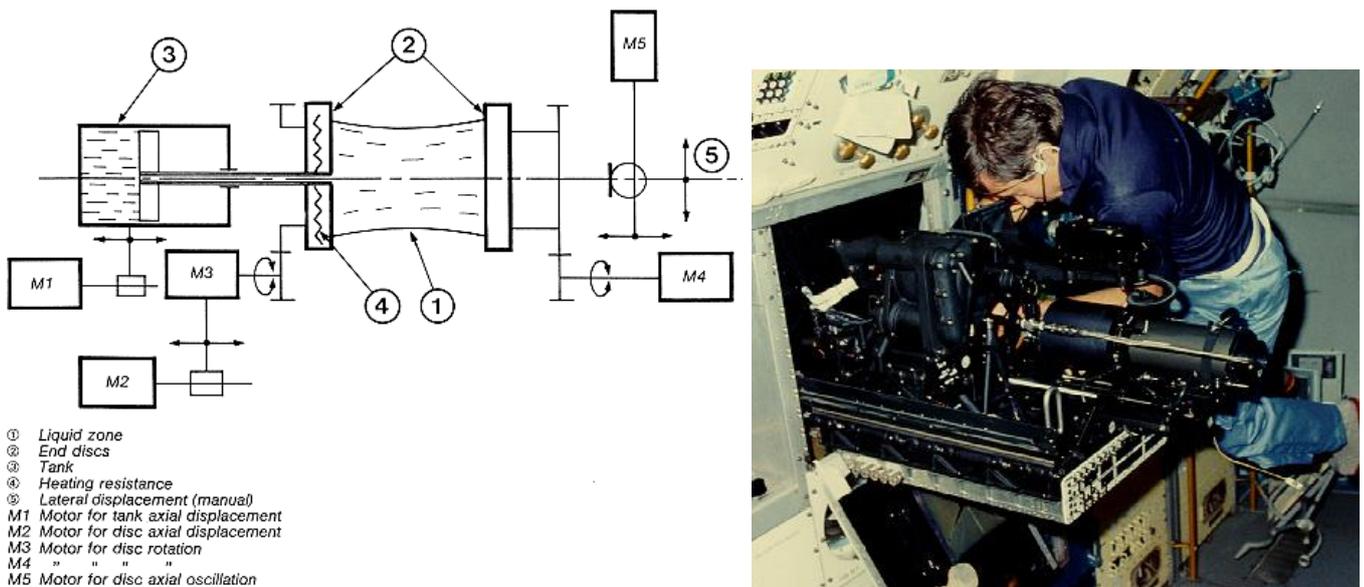


Fig. 2. Sketch of Fluid Physics Module variety of stimuli capabilities. Ulf Merbold during FPM operations aboard Spacelab-1.

In the case of the experiment 1-ES-331 [21] the nominal liquid column could not be reached; at every trial, the liquid being injected spread beyond the edges of the discs. Only the invaluable creativeness of the crew operators, Ulf Merbold and Byron Lichtenberg, avoided full failure and managed to form liquid columns between unconventional supports (by manual refitting of hardware items on site). In that way, some quasi-cylindrical columns (badly anchored), and non-cylindrical bridges (like the one shown in Fig. 3), were realised. These circumstances, a poor visualisation set-up, and scarce off-line data handling (one 16 mm film cassette with 2000 photo-frames available, mal-functioning during flight, and recovered 6 months after), strongly reduced the possibilities for a deep analysis of available results, besides the lack of appropriate theoretical background to perform such analysis: the first mathematical model for the liquid bridge dynamics was published in the same year than Spacelab-1 flight [22], and theoretical results concerning the stability of liquid bridges between unequal discs appear in the next year [23]. In any case, 1-ES-331 results were spectacular, as judging by the mass-media interest shown for the few minutes (non-allocated) of direct TV-link: large free liquid masses, controlled in space (Fig. 3) were broadcasted for the first time. Besides, fruitful collaborations blossomed with researches on real floating zones [24].

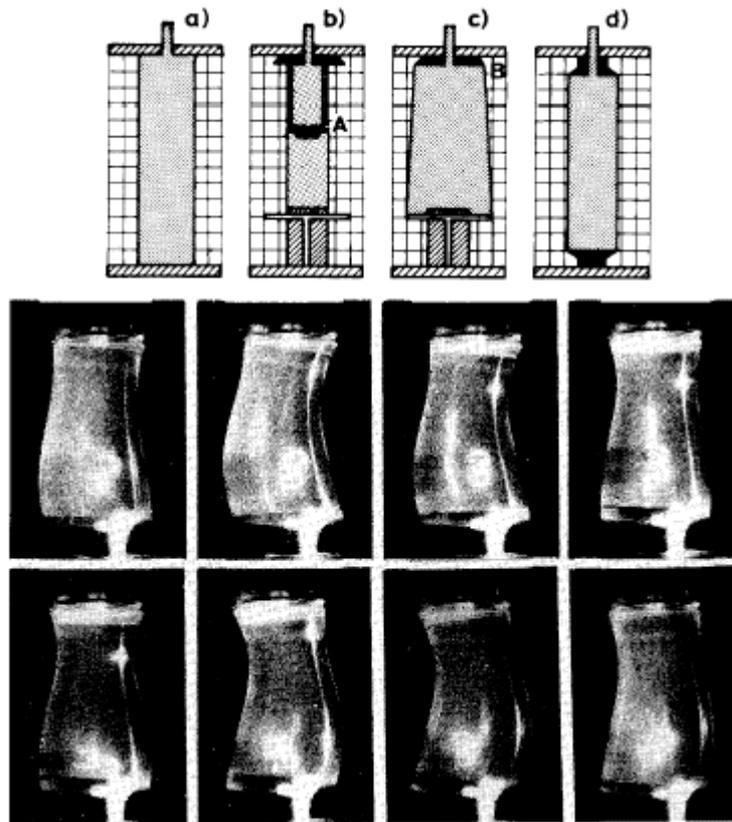


Fig. 3. a) Nominal liquid bridge configuration in Spacelab-1 (failed); b) Off-nominal cylindrical liquid column 30 mm in diameter, built with spare hardware (inefficient liquid canthotaxis); c) Off-nominal liquid bridge 100 mm long between unequal discs of 50 mm and 60 mm, built with spare hardware, to which all the nominal stimuli were applied (a picture sequence, at 1 s interval, of a liquid bridge in rotation is shown); d) Configuration proposed for Spacelab-1 (already used in our previous Texus-12 flight).

Because of the many difficulties met in Spacelab-1 many of the experiments performed in the FPM in Spacelab-1 in 1983 were repeated again in 1985 during the Spacelab-D1 mission (Table 2), in spite of more ambitious goals for this follow on (Spacelab-D1 proposals were submitted before Spacelab-1 flight). For our new experiment (FLIZ), the nominal procedure was similar to the one proposed for Spacelab-1, where due to wetting problems only partial success was allowed. The same Fluid Physics Module was used, refitted with new-design end discs (to enhance canthotaxis) and a manual operated syringe for liquid injection (to avoid cross-coupling of piston motion and cylinder motion).

Table 2. Experiments performed in the Fluid Physics Module during Spacelab-D1 mission, 1985.

FLIM	Forced Liquid Motions in partially filled containers	Vreeburg, J.P.B. (N)
MAFL	Marangoni Flows	Napolitano, L.G.; Monti, R. (I)
CAPS	Capillary experiments in low gravity fields	Padday, J.F. (UK)
STEM	Surface Tension Induced Convection around a Surface Tension Minimum	Legros, J.C.; Limbourg.C., Petre, G. (B)
FLIZ	Floating Zone Hydrodynamics	Da Riva,I., Martinez, I. (E)
MISE	Mixing and separation of immiscible liquids	Langbein, D. (D)
BUDY	Separation of fluid phases and bubble dynamics in a temperature gradient	Nahele, R. (D)
MACO	Marangoni Convection in gas-liquid mass transfer	Drinkenburg, A.H., Lichtenbelt, J.H. (N)

Spacelab-D1 was launched on 30-10-85 aboard Challenger (STS-22, 330 km altitude, 57° inclination), and landed 7 days later. The overall result for our FLIZ experiment, operated by Reinhard Furrer (1940-1995) and Erns Messerschmid, see Fig. 4, was excellent [25], dissipating all the worries the experimenters got from Spacelab-1.



Fig. 4. FPM operations in Spacelab-D1. Reinhard Furrer pulling the Fluid Physics Module out of the rack.

Discs of 35 mm in diameter, with 30° cutback to enhance canthotaxis, were used, with a nominal column length of 95 mm (up to 100 mm when stretched). The working liquid was silicone oil DMS-5 seeded with 0.15 mm Eccosphere-tracers. Both, the old film camera and a new video camera were used, with meridian light and white background. It was a most rewarding experiment execution, with several hours of direct TV link, where one could see perfect oscillation, iso-rotation and stretching, with several foreseen liquid-column breakages, which could easily be recovered (not so on later flights). Video coverage showed a permanent-wobbling long liquid column, with an unusually high residual axial acceleration. In spite of the major improvement on liquid-bridge visualization from Spacelab-1 to Spacelab-D1, some difficulties remained, mainly due to usage of a mirror box for background illumination in the Fluid Physics Module (and a misunderstanding with a raster background), as can be appreciated in Fig. 5, where a video-frame and some film-pictures are presented. It was not possible at the time, from these images to implement an automated analysis, and some 500 images had to be enlarged and digitized manually with painstaking effort (one should remind of the great changes in video and computer technology in the last few decades).



Fig. 5. Film pictures of the breaking sequence of a 100 mm long liquid column in Spacelab-D1-FLIZ experiment (times, relative to the last one, are 0, -2, -4, -10, and -50 s). Notice the difficulties for accurate edge detection in the liquid bridge because of the bright background (the video frame with less contrast shown last is even worse for the purpose).

The next flight was Spacelab-D2, scheduled for 1988, delayed until 1993 because of the Challenger disaster (it is sad to realise that the two shuttles supporting these experiments had ended in such a way). In Spacelab-D2 aboard Columbia (the same carrier as in Spacelab-1, launched on 26-04-93, at 300 km altitude and 28° inclination, and landing 10 days later), five experiments were carried out in the newly designed Advanced Fluid Physics Module (Table 3); Prof. Legros was elected facility scientist, and Da Riva's team participated in two of them (STACO and LICOR).

Table 3. Experiments in the Advanced Fluid Physics Module during Spacelab-D2 mission, 1993.

ONSET	Onset of Marangoni Flows	Napolitano, L.G.; Monti, R. (I)
STACO	Capillarity. Adhesion Forces in Liquid Films	Martinez, I., Meseguer, J. (E)
LICOR	Liquid Column Resonances	Langbein, D., Meseguer, J., Sanz, A. (D,E)
BENAR	Bénard-Marangoni Convection	Legros, J.C.; Petre, G. (B)
HIMOD	Higher Modes Oscillating Marangoni Convection	Chun, Ch.H., Siekman, J. (D)

In Staco we used discs of 30 mm in diameter with 30° cutback (the same as in our Texus experiments), with a nominal column length of 85 mm, and silicone oils DMS-10 for Staco runs 1 and 2 (and Licor run 1), and DMS-5 for Staco run 3 and Licor run 2), with 0.1 mm Eccosphere-tracers. A video camera and a 35 mm film camera were used, with illumination based on a diffuse white background (9·8 leds) and a special raster with lines, ticks, and squares. Images obtained were faultless, if not for minor distortions due to the complicated optical path (three mirrors, eccentric camera pivoting), with perfect recording of vibrations (Staco-1), stretching (Staco-2), and a bizarre wobbling during three minutes until breakage (Staco-3; see Fig. 7), although the foreseen breakages of the liquid column turned to be unrecoverable, contrary to Spacelab-1 experience. The skilful operators were this time Ulrich Walter and Hans Schlegel.



Fig. 6. A-FPM being operated by Ulrich Walter in Spacelab-D2, 1993.

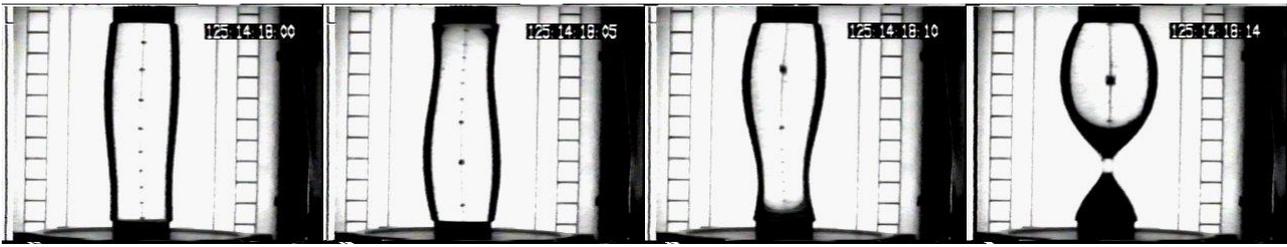


Fig. 7. Unexplained breakage of a liquid bridge in Spacelab-D2 experiment Staco (run 3). A similar quasi-cylindrical liquid column as in runs 1 and 2 of the experiment was established a week later, but this time the astronaut reported stronger g-jitter on the liquid (the recordings of the solid-state accelerometers didn't explained that) and, notwithstanding the fact that the everything was left idle not to be perturbed, in a few seconds a necking developed, moved to the other side, and the liquid bridge broke down.

TEXUS EXPERIMENTS

There is a great difference between the crew-operated Spacelab experiments, lasting typically one hour, and the one-shot six-minutes experiments in Texas sounding rockets. On one hand, the result may be full failure as in our Texas-10 experiment, or full success as in our Texas-33 experiment. On the other hand, specific hardware can be developed for a one-shot experiment, what has been advantageously used by Da Riva's team to carry out specific experiments on Texas, not only on the main theme of the mechanics of liquid columns, but on some thermal aspects too.

For Texas, size constraints were tighter than in Spacelab, and discs of 30 mm have always been used. The first launch, Texas-10 in 1984, already with a 45° cut-back-shape, aimed at finding the maximum injection rate to establish a long liquid column, but the hardware failed (did not inject the liquid). The re-flight on Texas-12 in 1985 (after Spacelab-D1) worked perfectly, and we learnt that a 10 cm long column can be safely established in a minute from scratch (it takes much longer in Spacelab), allowing for some 5 minutes of experimental time in a sounding rocket flight. The residual motion on the established column, with DMS-5 as working fluid, takes another minute or so to decay (the half-damping time is some 35 s).

On Texas-18 (1988), unidirectional solidification of a cylindrical liquid column made of water, 30 mm in diameter and 86 mm in length, was initiated (13 mm of ice were obtained in the 5 minutes of microgravity time). The aim was at finding a receding growing angle for water, as had been found for silicon and germanium, but not such an angled could be measured. On the other hand, a crucial finding was the perfect liquid-anchoring to the growing solid, observed during the rocket re-entry.

Texas-23 (1989) was the first time a well-controlled skipping-rope motion of the liquid column was achieved. Once a perfectly cylindrical liquid bridge was established, both discs were rotated eccentrically around an axis parallel to their centre-line, at increasing rate until breakage. In spite of some synchrony problems in the video transmission (no video storage on board), this was the first of our space experiment where automatic edge extraction was applied.

Texus-29 (1992) was a joint endeavour with a materials science team [26], where we intended to make an automated image analysis of a real silicon crystal growth by the floating zone technique. We had foreseen the problems of unsteady ends of the zone (it was a travelling rod within an ellipsoidal mirror furnace), but not the very poor visualisation that resulted from such high temperatures, which made the molten zone invisible except for the expert human eyes.

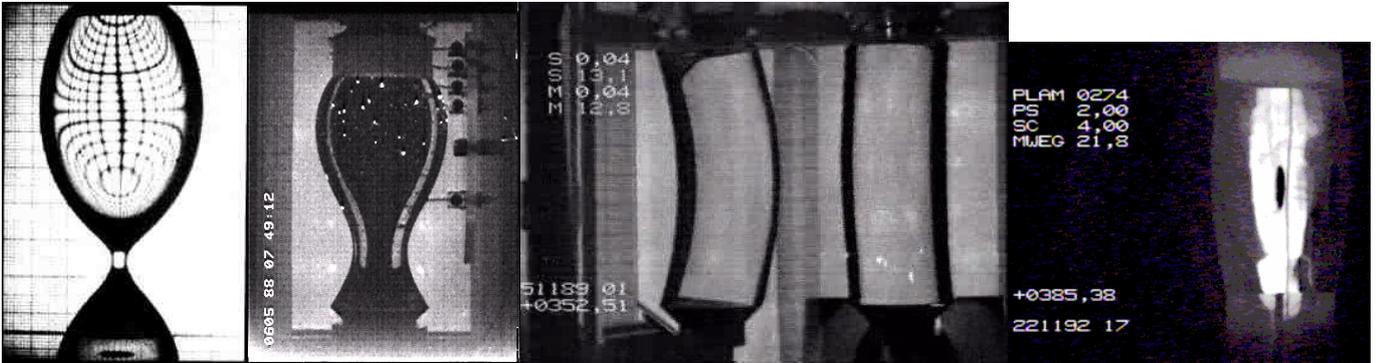


Fig. 8. Images from our Texus experiments: a) Breaking column in Texus-12; b) Freezing column in Texus-18; c) Rotating column in Texus-23; d) Molten silicon rod (at 1800 K) in Texus-29.

Texus-33 (1994), proposed in 1991 as precursor to Spacelab-D2, finally supplied plus-quam-perfect experiment data, but surprising results, only understood a decade later. Extra redundancies were taken to guaranty success; i.e. several simultaneous data acquisition channels, data and video recording aboard, plus real-time transmission and recording on ground of both data and video. This experiment aimed at checking if the liquid bridge deforms according to available theory when subjected to a prescribed axial acceleration. It was not a trivial question, since, according to liquid-bridge theory, residual acceleration were $70 \mu\text{g}$ as from Spacelab-D1 deformation measurements, and $5 \mu\text{g}$ as from Spacelab-D2 data, for the same sensor (liquid bridge) in the same platform (Spacelab orbit); furthermore, residual acceleration in Spacelab must be around $1 \mu\text{g}$ according to well-established orbital mechanics. A controlled axial acceleration of a whole liquid column, 30 mm in diameter and 85 mm long, was performed by oscillating up and down the whole test cell with 100 mm peak-to-peak amplitude, and a period of 45 s. Rocket constrains dictated a sinusoidal acceleration instead of a constant value acceleration, that would require controlled thrust or a very large platform, see Fig. 9.

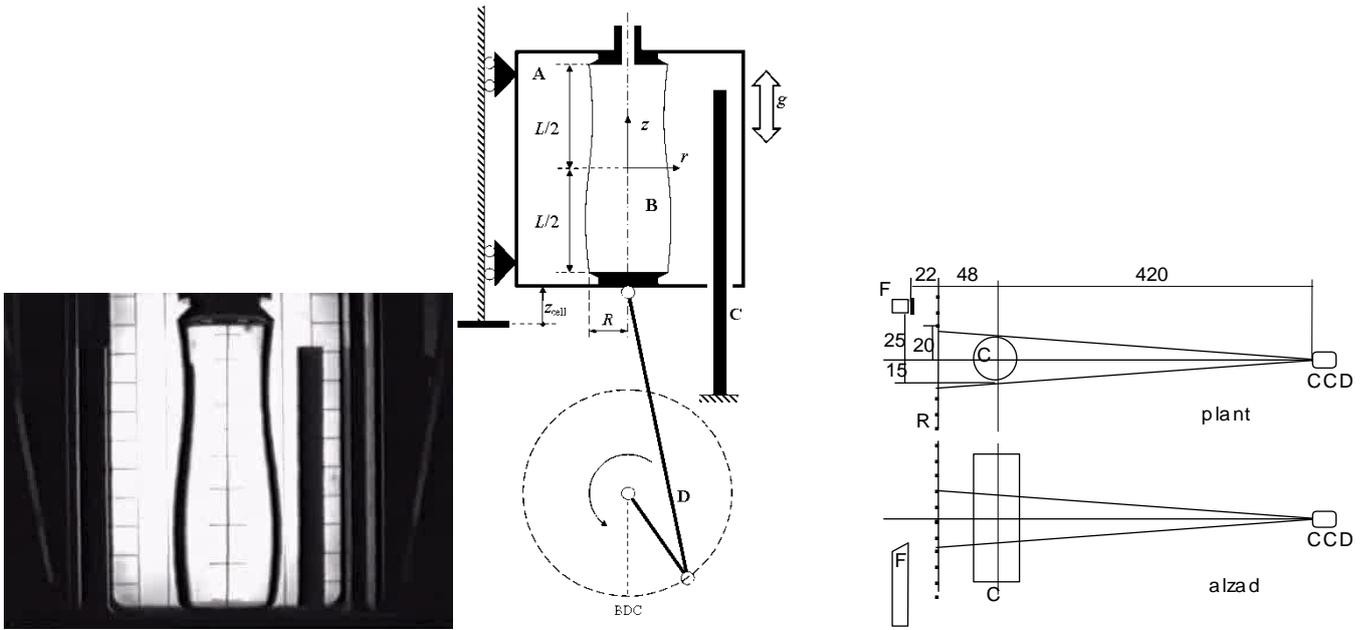


Fig. 9. Texas-33 experiment (1994): *a*) a typical image (at 166 s flight-time; first pushing); *b*) configuration; *c*) optical path. The liquid bridge B (surrounded by air A), is held between two connected solid discs being oscillated in phase. The whole liquid bridge cell is moved up and down, starting (160 s after lift-off) from the bottom-dead-center of a crank-shaft mechanism, D. The CCD-camera moves with the cell, but, in the FOV there is a bar C fixed to the rocket.

Results from Texas-33, the last and more accurate until now, are as follows. The large excitation chosen (to have a large response), introduced an unaccounted non-linear effect on the response (a softening cubic term in the rigidity of the equivalent spring) that, although small (the equivalent spring is just 8% softer than predicted), generates a third harmonic in the dynamic response, precisely coincident with the first natural frequency of the liquid column. Viscosity, although small (just 10 times that of water), would have dumped this effect to make it barely noticeable in case of the nominal pure-harmonic excitation, but the actual crank-shaft excitation implemented in Texas-33 greatly amplified it, to the extent that the free-surface deformations nearly reached the stability limit. Fortunately, a non-linear-dynamics-model has fully explained the greater than 100% deviation in expected (quasi-static) amplitude, and the bizarre quiescence observed after the forcing stopped, before rocket re-entry. This model retains just the amplitude of the first eigen-mode of the liquid-column deformation a (the deformation is $R(z,t)=a(t)\cdot\sin(\pi z/\Lambda)$), and predicts how it evolves with time t for a given axial forcing $B(t)$, as a function of the column slenderness $\lambda=L/p-1$, liquid volume $v=V/(pR^2L)-1$, and liquid viscosity parameter C :

$$m \frac{d^2 a(t)}{dt^2} + mC \frac{da(t)}{dt} + \left(\lambda - \frac{v}{2} \right) (1 - 8\lambda) a(t) + \frac{3}{4} (1 - 5\lambda) a(t)^3 = B(t) \quad (1)$$

with $m=25/8$ being an analytical non-dimensional inertia-term coefficient (deduced considering the simplified inner velocity field given by the so-called Cosserat model), $C=Oh^{1/2}=\nu\rho/(\sigma R)^{1/2}$ the square root of the Ohnesorge number accounting for viscous dissipation ($C=0.0175$ for Texas-33, with $\nu=10\cdot 10^{-6}$ m²/s, $\rho=920$ kg/m³, $\sigma=0.020$ N/m, $R=0.015$ m), with $\lambda=\Lambda/\pi-1=-0.067$ being a normalised slenderness, and $B(t)$ being the non-dimensional forcing acceleration as before. Equation (2) is a

Duffing's equation, typical of soft springs (the cubic term softens the linear rigidity, introducing the non-linear effects).

OTHER RELATED EXPERIMENTS

Experiments under microgravity conditions can be carried out on free fall towers, aircraft parabolic flights, sounding rockets, and orbiting platforms, depending on the microgravity-time required. All these recourses have been experienced by Da Riva's team. Besides the already commented experiments on Spacelab and Texus, some other experiment also dealing with liquid bridges have been performed in drop towers (in a small 15 m one at IDR premises, and in the 100 m ZARM tower in Bremen), others on board NASA KC-135 parabolic aircraft (1984-5), and some others in Spanish satellites UPM-Sat and MINISAT. The experiments performed both in orbital platforms and in sounding rockets are summarized in Table 4.

Table 4. Chronological summary of space experiments performed by Da Riva's team.

<u>Year</u>	<u>Orbital platforms</u>	<u>Sounding rockets</u>
1983	Spacelab-1	
1984		TEXUS 10
1985	Spacelab D-1	TEXUS 12
1988		TEXUS 18
1989		TEXUS 23
1992		TEXUS 29
1993	Spacelab D-2	
1994		TEXUS 33
1995	UPM-Sat	
1997	MINISAT	

Publications on this research can be grouped into static and dynamic studies. Concerning equilibrium shapes and their stability, the influence of disc separation, relative disc size, relative liquid volume, axial and lateral acceleration, and rotation, have been developed.

Besides, numerous papers on liquid bridge dynamics have been also published. Leaving apart early studies on the onset of disc rotation [27-28] and on surface tension driven flows [29], the nonlinear dynamics and breakage of liquid bridges were first studied, using inviscid, one-dimensional models [22]. An historical review of on the breaking of liquid bridges can be found in [30].

A list of other publications by members of Da Riva's team, related to these space experiments, is included in the references [31-81]. Most of the Doctoral Thesis by its members was also on the subject of liquid bridge research (Martínez, Meseguer, Sanz, Perales, González, Laverón, and Zayas). The subject has also been approached by other colleagues at the same School in Madrid (ETSIA-UPM), and by a prominent group at University of Seville, too (with important contributions on electric effects on liquid bridges).

Concerning experimentation on ground, most research teams working on liquid bridges under microgravity conditions have developed some kind of Plateau tank for their experimental work. A Plateau tank is just a reservoir filled with liquid inside which another liquid, immiscible with the former and with the same density ($\Delta\rho \rightarrow 0$), can be studied as in weightlessness (in some respects). Of course this method does not simulate completely orbital conditions because of the presence of the outer liquid, which affects the dynamics of the fluid column, but seems to be very appropriate to hydrostatic analyses, and helps in gaining experience on liquid bridge experimentation. Other method of minimizing gravity effects can be to reduce the size of the experiment to a very small scale ($R \rightarrow 0$), say a millimetre or less. Different Plateau tank and millimetric facilities have been developed at IDR/UPM; the description of these facilities can be found in [82].

As a consequence of the above described space-related activities, by the end of the eighties some more technology-oriented projects were accomplished by Da Riva's team; some of them were the preliminary study of the fluid science module for Columbus [83], and the development for ESA of a liquid bridge experimentation module which simulated zero gravity using the neutral floatability technique, and was used by the Agency in mission specialists training [84-85].

Another relevant space project performed by the group headed by Prof. Da Riva was the micro-satellite UPM-Sat, a small scientific, in-orbit demonstration, educational satellite which was designed, built, tested, integrated, and operated by a team of professors, post and undergraduate students, and auxiliary personnel belonging to the Universidad Politécnica de Madrid.

The last space experiment with liquid bridges by this team has been on board the Spanish satellite Minisat-01 [86].

CONCLUSIONS

The basic aim of these experiments is to investigate the deformations and internal motions of nearly-cylindrical liquid columns under several mechanical disturbances, controlled (oscillation of the supports, stretching, rotation), and uncontrolled (g-jitter). Although the interest of this research is basically theoretical (i.e. scientific), liquid bridges are of great practical interest in some applications as containerless materials processing. Other teams have aimed at studying thermal, solutal, electrical, or magnetical effects on similar fluid configuration.

This is a fluid mechanics problem, and the scientific content is basically stored in the image-recording of the experiment, basically the liquid contour, helped by the ancillary data recording (for redundancy). On Spacelab there was also the operator's voice record commenting the performance. Experiment definition is based on available analytical models. The analysis of results is based on image sequences, which are simplified to get only the liquid edges (and the position of the discs), and then interpreted as slice radii amplitudes and lateral departures from the centre-line. Finally the sequence of radial and lateral

deformations are analysed in amplitude and frequency, and compared with available analytical models, to check for discrepancies in the initial prediction.

In spite of the extended period of time devoted to this research at IDR-UPM (more than 30 years), the actual experimental time in space has been only of several hours, including all the time spent in debugging hardware malfunction and infancy problems on experiment procedures.

Experiment success is difficult to evaluate objectively: there are experimenters who are satisfied with any result (there are always some lessons learnt), and experimenters who are so perfectionist that they are never satisfied (in spite of achievements). It is often said that scientific relevance is not found on answers found, but on questions opened.

We have found several unexpected, and yet to be explained, results:

- In Spacelab-D2, the averaged deformation of the idle column did not match with theory or among other Spacelab flights.
- In Spacelab-D2 run 3, a liquid bridge between unequal discs of 30 mm and 28 mm, broke after some oscillations, while idle, without any apparent disturbance.
- In Spacelab, the liquid column is laterally oscillating with a component perpendicular to the viewing direction. It is not rotating, because there is no dioptrical effect between two extreme images in counter-phase. It must be some non-linear coupling from the larger axial motion, because lateral oscillations are at the first lateral eigenfrequency, but quantitative explanation is still lacking.

We are willing to follow on this research line in the new era to be opened by the Columbus laboratory aboard the International Space Station. Table 4 tries to give a summary of the liquid-column research by Da Riva's team.

Table 4. Summary of the project.

Subject	Behaviour of liquid columns under microgravity.
Field	Capillarity, Fluid Mechanics, Physics.
Objective	Analysis of liquid bridge shape and their stability, shape deformation and inner motion due to several mechanical stimulation. Experimental conception based on a sound theoretical background.
Interest	Basic research (public funding); no industrial interest yet. Application to crystal growth by the floating-zone technique.
Configuration	Liquid column anchored to the border of solid discs and held by interfacial forces.
Achievements	Analytical predictions developed, compared with numerical simulations, and experimentally confirmed. Application to crystal growth demonstrated. Experimental program developed (in international multi-user space facilities). Telescience operation developed. Unexpected g-jitter effects detected and quantified (not yet explained). Last experimental results fully explained with non-linear dynamic theory, with

	accurate prediction capability.
Theory developed	Equilibrium shapes and stability limits for a parametric set (L, V, B_a, B_r, W, H) : L , length; V , volume; B , Bond number (linear acceleration, axial and/or radial); W , Weber number (rotation); H , disc size difference. Linear and non-linear analytical stability limits for the parametric set. Linear dynamics of oscillation and breaking. Non-linear dynamics of oscillation and breaking.
Experimental setup (basic)	Liquid filling under microgravity through a centre hole (6 mm in diameter) in a disc (30 mm in diameter).
Experimental procedure	Establishing the column (small drop or small bridge, followed by cylindrical stretching). Oscillating one disc. Oscillating the whole liquid cell. Rotating both discs in iso-rotation (preferably eccentric). Stretching (at constant volume or cylindrically). Removing liquid at constant disc separation.
Experimental execution (telescience)	Field work for investigators (PI). Shared scenario: 1 voice channel for several crew-persons, on a multi-loop configuration. Coordination of multi-task operations by the payload-specialist crew on board, the crew-assistants on ground, system surveyors, manufacturers teams, etc. Integration of disperse information links (computer data, video image, switched voice link, ambient TV). Drop-outs in communications (incomplete orbit coverage, and malfunctions). Non-transparent voice and command chain (PI-FPM-WL-APS-CIC-PS).
Experimental results	Solved problems in establishing the liquid column (two methods available). Solved problems in recovering broken bridges (however, uncontrolled breakages occurred in later experiments). It is found that zero-g stability limits can only be approached up to 90% due to g-jitter. Unexplained shape deformation in SL-D1 (one order of magnitude larger than expected). Unexplained breakage in SL-D2. Good agreement between vibrational behaviour of columns with theory. High-precision automated image analysis developed (a tenth of a pixel).
Open problems (theory)	G-jitter characterisation and response. Coupling of axisymmetric perturbations (e.g. vibration and isorotation). New axisymmetric perturbations (thermal or solutal deformations). Non-axisymmetric perturbations.
Open problems (experiment)	Better bubble control during column formation. Better anchorage control during column formation and after bridge rupture. Video-recording was of poor quality (new digital video will solve it). Field-of-view clipping, zooming, tilting and slant by software, to simplify optical path. Parallax and depth of field should be avoided (go to parallel viewing). Lack of redundancy in past experiments (go to two sides viewing). Automatic synchronous merging of all data sources (video as the master data). Better uniformity of illumination and background contrast with liquid column. Quantification of diffraction effects on edges. Effects of experimental simulation in immiscible baths (Plateau tank), and with microzones (e.g. cleanliness control, measurement uncertainties).
Publications	References related to this work can be found at ESA Erasmus Experiment

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