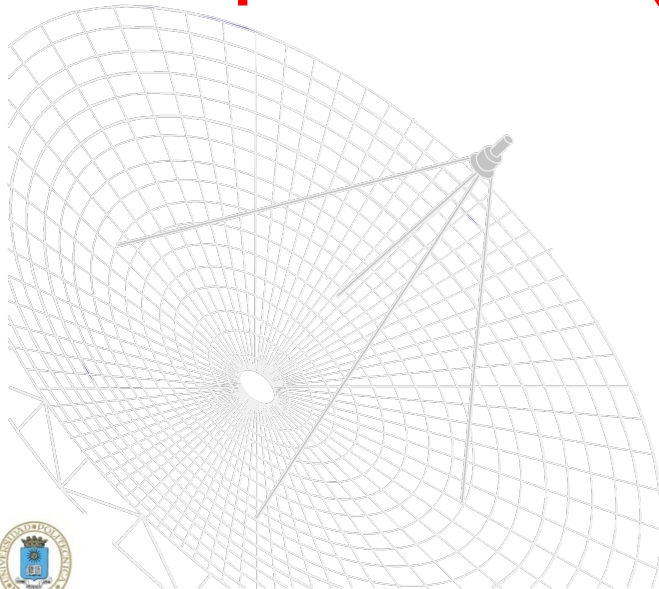


# Master in Space Technology

## Liquid bridge experiments in Spacelab (SL-1, SL-D1, SL-D2)

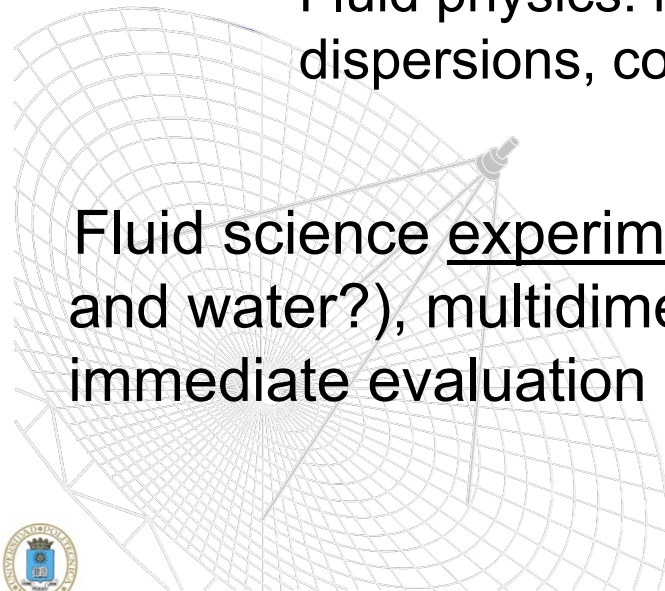
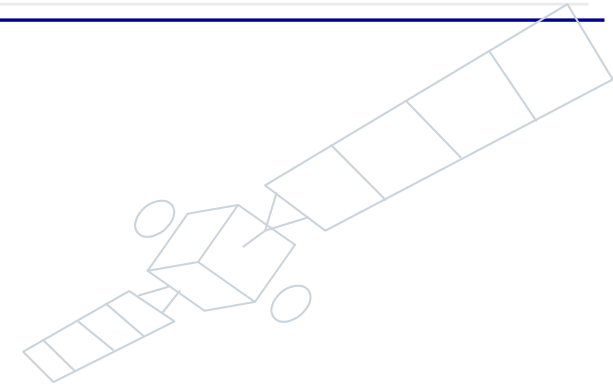
*Isidoro Martínez*



# What kind of scientific mission?

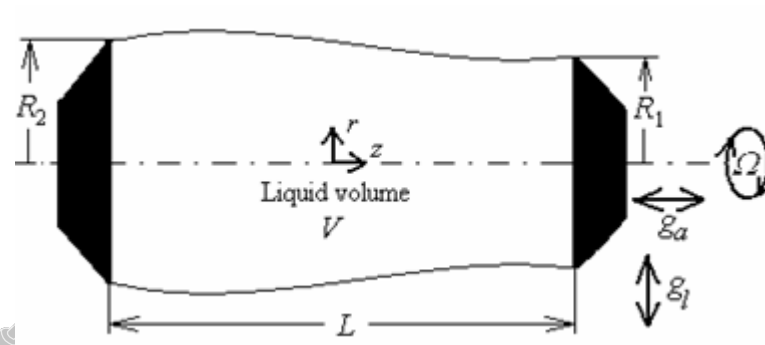
- **Astronomy and astrophysics**
- **Earth observation and communications**
- **Microgravity**
  - Life sciences
  - Materials sciences
    - Fluid physics: interfaces (drops, bubbles, **liquid bridges**), dispersions, continuum (thermal effects, solutal effects...)

Fluid science experiments use a model transparent fluid (air and water?), multidimensional geometry, repeatable, immediate evaluation by visualization, etc.



# What is a liquid bridge?

- Liquid bridge: a blob of liquid bridging the span between two solids
- Liquid column: a nearly-cylindrical liquid bridge
- Floating zone: a liquid column or liquid bridge formed by melting a portion of the support material



- The liquid mass is held in position by cohesive forces at the free surface, and by adhesive forces to two solid supports.
- Capillary forces are so small that the liquid drains under normal gravity, and a microgravity ( $\mu g$ ) platform is required: orbiting station, sounding rocket, parabolic flight, or drop tower.

# Why liquid bridges?

- **Precursor experiments**
  - 1974, Skylab IV. Interest in liquid handling in space, and in material science (floating zone technique of crystal growth)
- **Spacelab experiments**
  - 1983, Spacelab-1 (FSLP), on Columbia, from Houston (USA)
  - 1985, Spacelab-D1, on Challenger, from Oberfaffenhofen (G)
  - 1993, Spacelab-D2, on Columbia, from Oberfaffenhofen (G)
- **Other experiments**
  - TEXUS
  - Parabolic flights
  - Drop towers
  - Micrometric bridges.

# Purpose of liquid bridge research

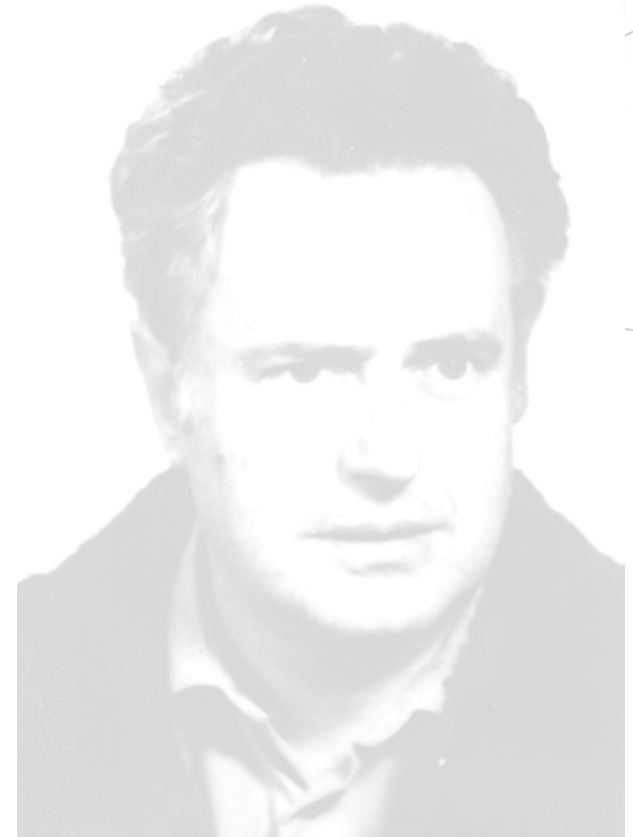
The basic aim of these experiments is to investigate the deformations and internal motions of nearly-cylindrical liquid columns under several mechanical disturbances, controlled (oscillation of the supports, stretching, rotation), and uncontrolled (g-jitter).

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 magnetic effects on similar fluid configuration.

# The research team

- **Ignacio Da Riva (†1991)**
  - 1974, Initial proposal to ESRO (ESA)
- **Isidoro Martínez**
- **José Meseguer**
- **Ángel Sanz**
- **José Manuel Perales**
- **and many other contributors on theoretical aspects, numerical simulation, and non-Spacelab experimentation.**



# The FSLP fluid physics group

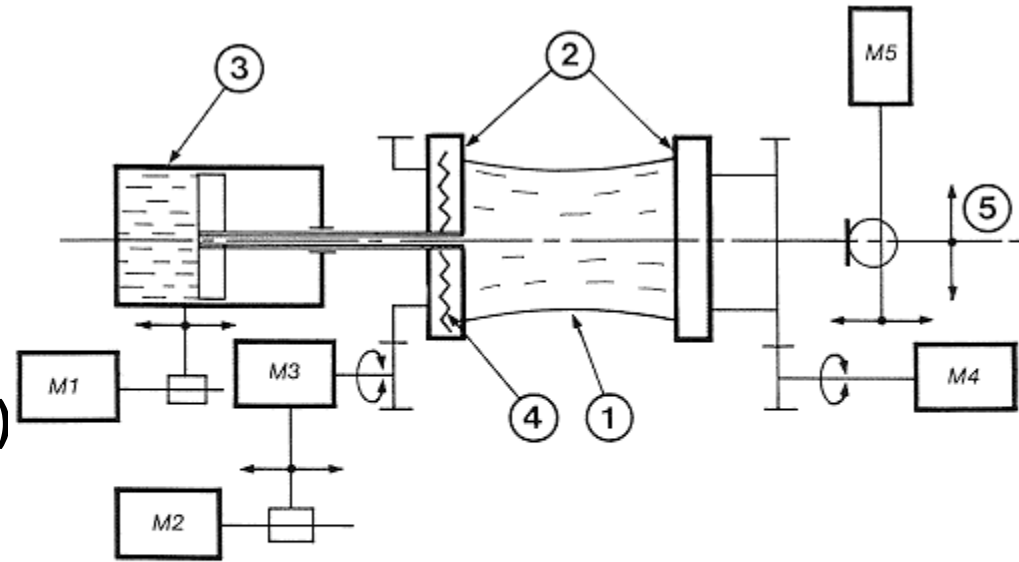
1-ES-326	Oscillation of semi-free liquid spheres in space	Rodot, H. (F)
1-ES-327	Kinetics of spreading of liquids on solids	Haynes, M. (UK)
1-ES-328	Free convection in low gravity	Napolitano, L.G. (I)
1-ES-329	Capillary forces in a low-gravity environment	Padday, J.F. (UK)
1-ES-330	Coupled motion of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

# The Fluid Physics Module

- **Preliminary design**
  - 1975, CASA-ETSIA

- **FPM (Fluid Physics Module)**

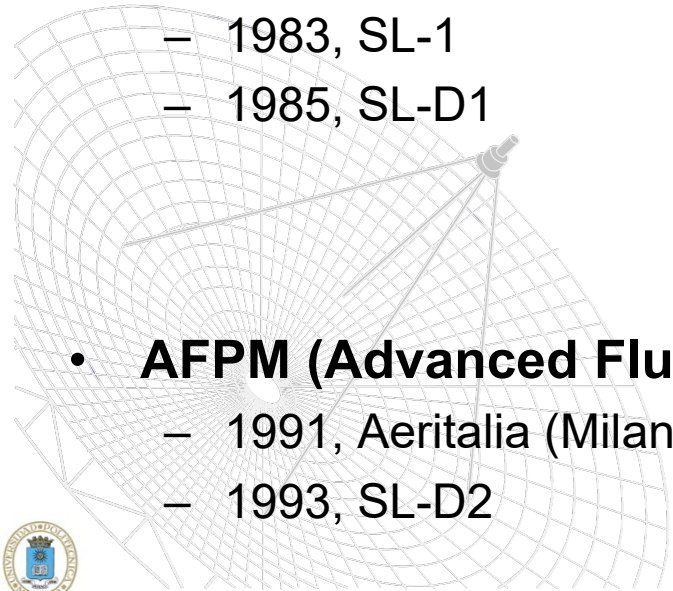
- 1979, Fiat (Torino)
- 1983, SL-1
- 1985, SL-D1



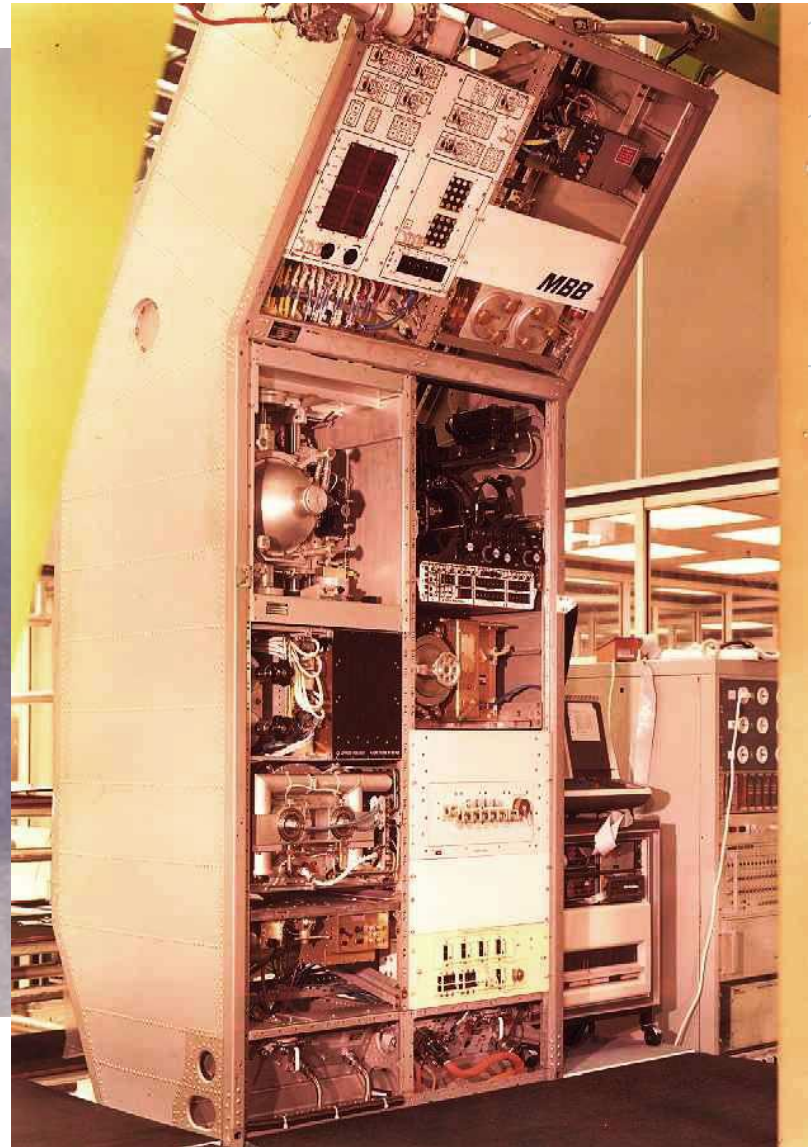
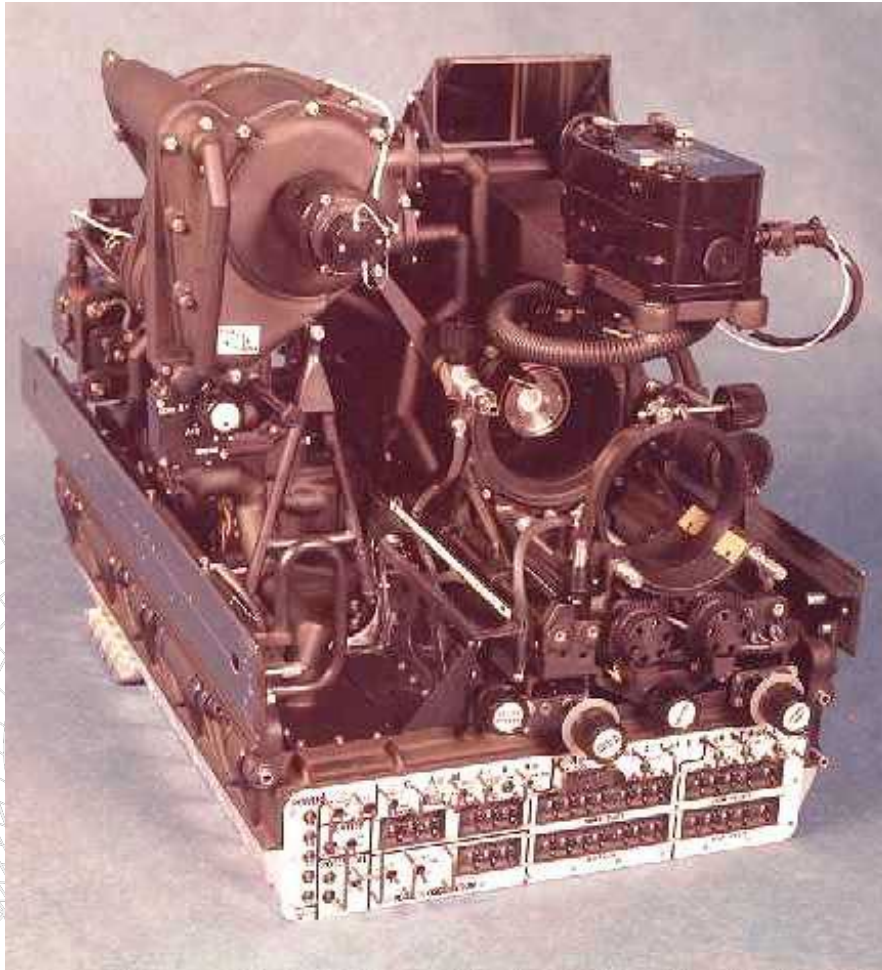
- ① Liquid zone
- ② End discs
- ③ Tank
- ④ Heating resistance
- ⑤ Lateral displacement (manual)
- M1 Motor for tank axial displacement
- M2 Motor for disc axial displacement
- M3 Motor for disc rotation
- M4 " " " "
- M5 Motor for disc axial oscillation

- **AFPM (Advanced Fluid Physics Module)**

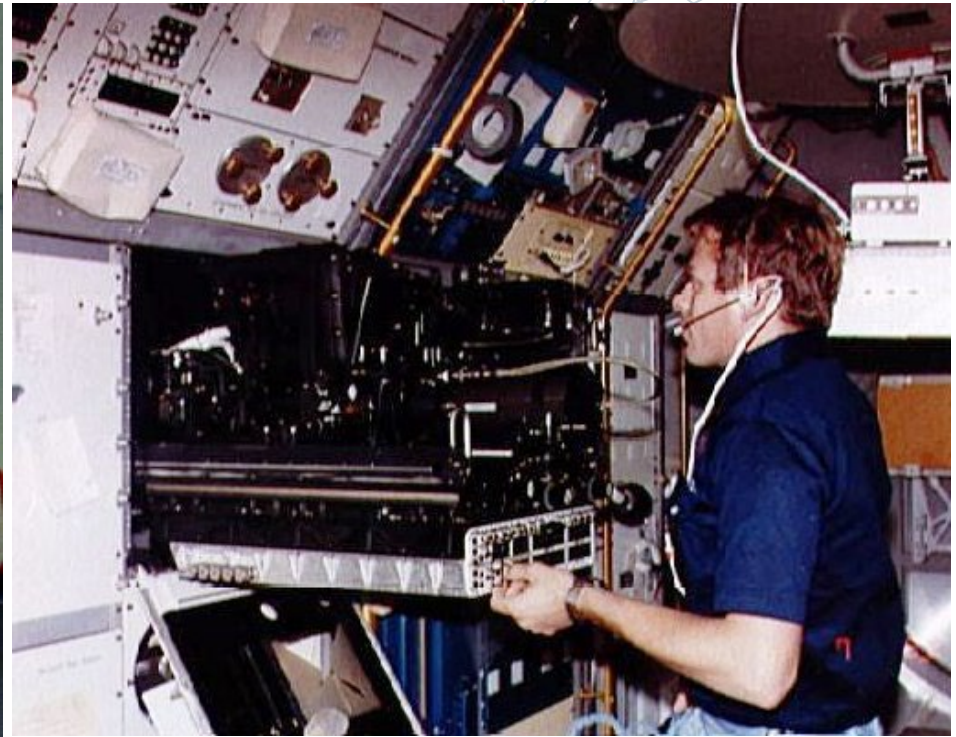
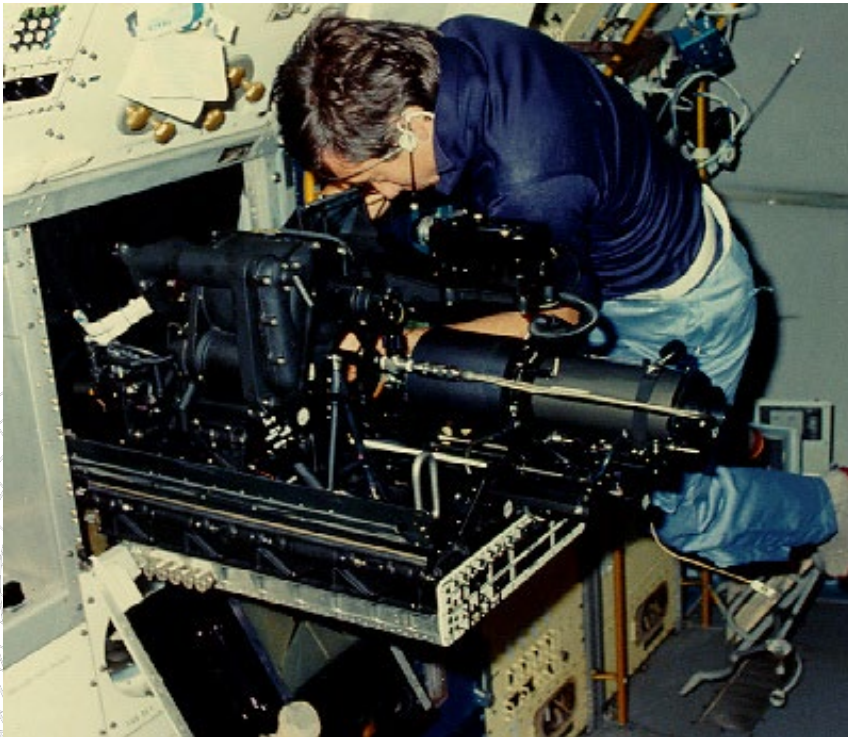
- 1991, Aeritalia (Milano)
- 1993, SL-D2



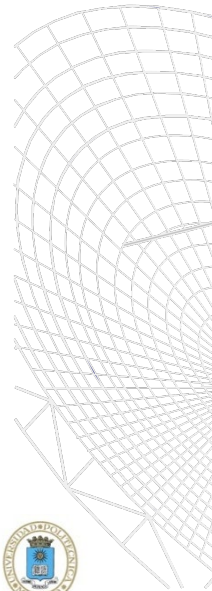
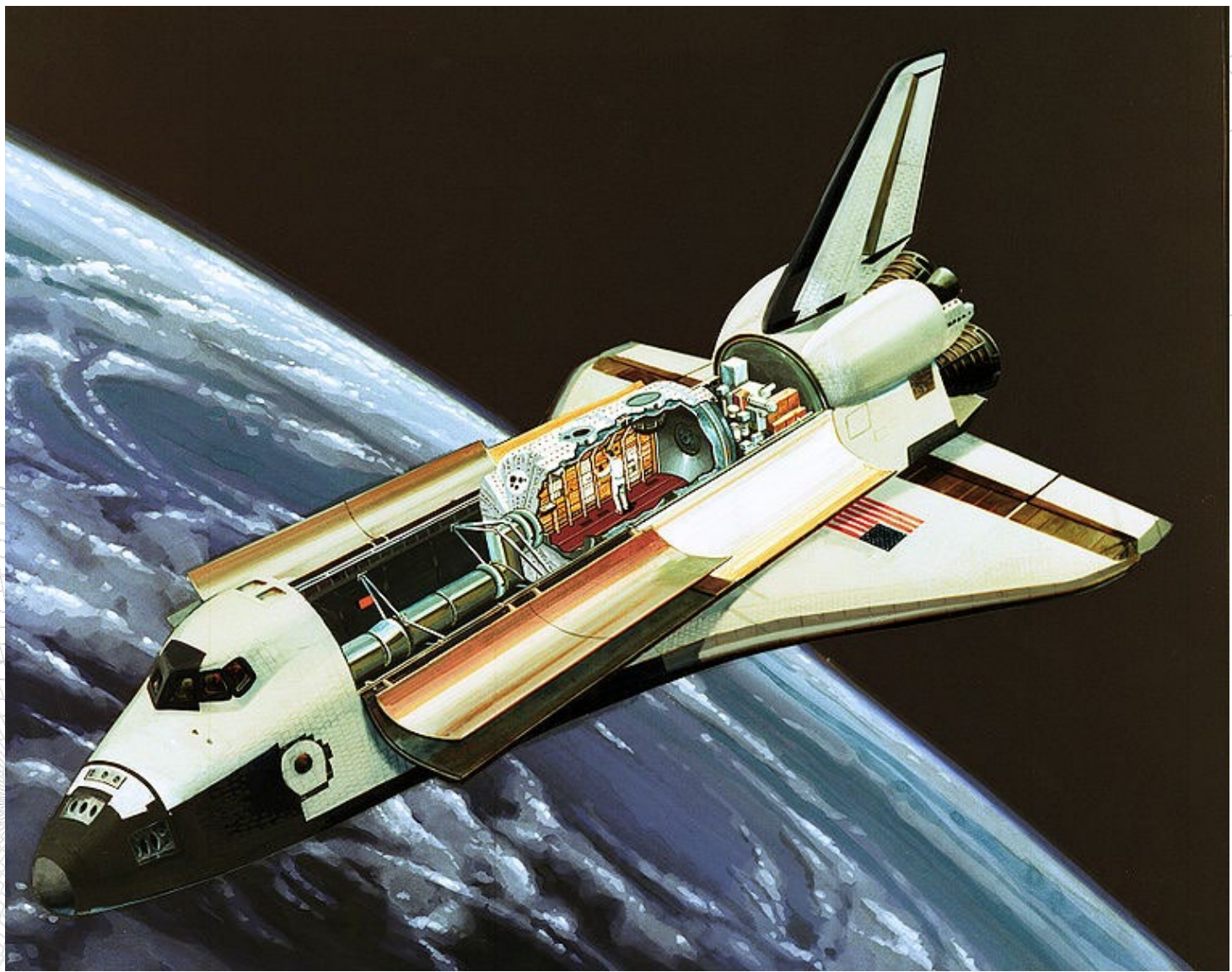
# FPM (on ground)



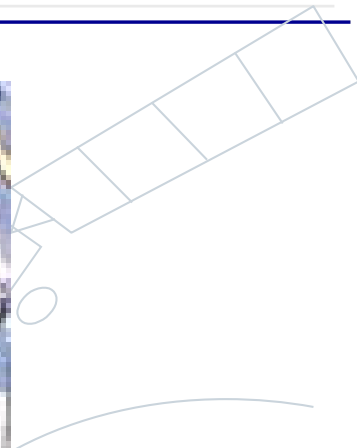
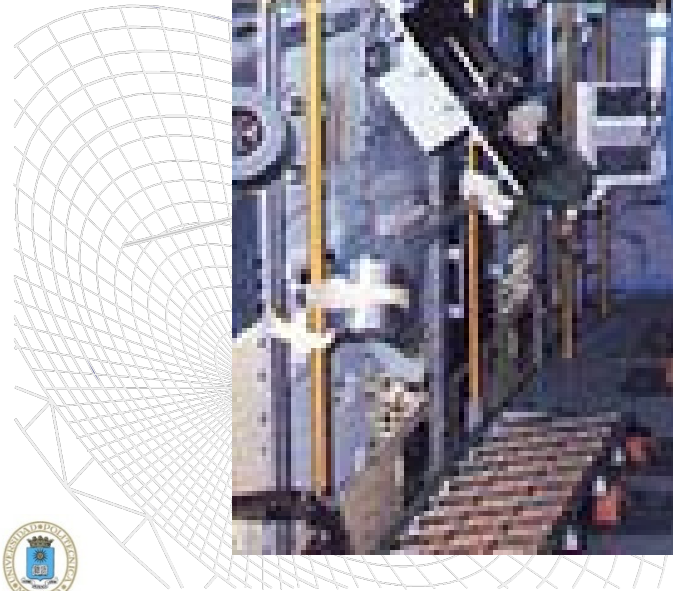
# FPM in Spacelab (SL1, FSLP)



# Spacelab in orbit

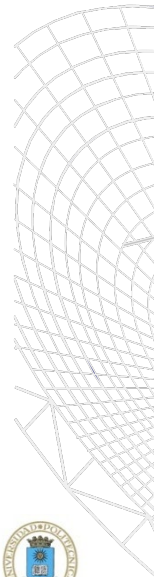
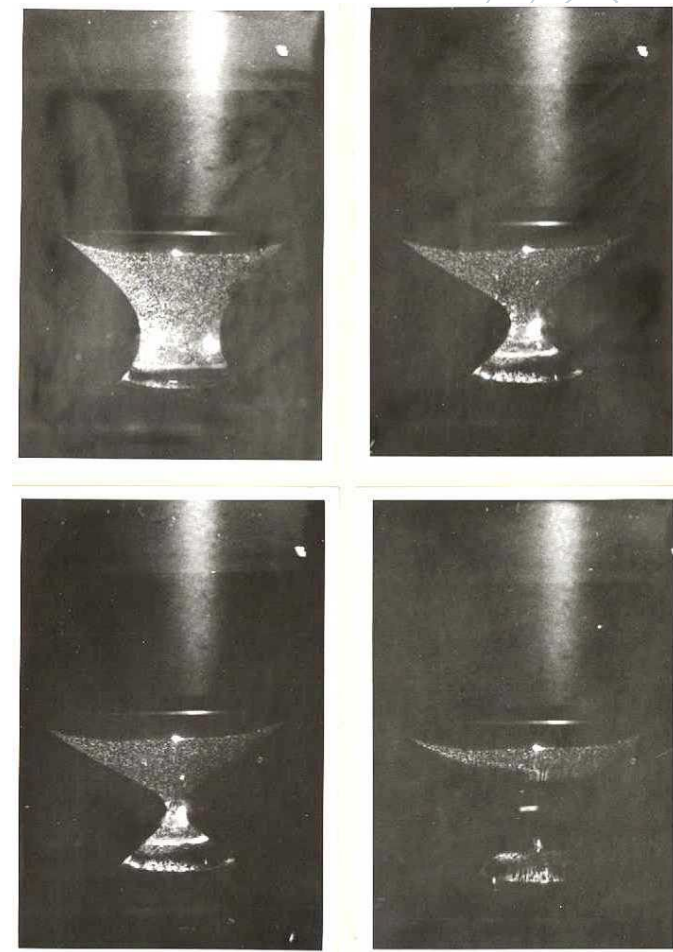
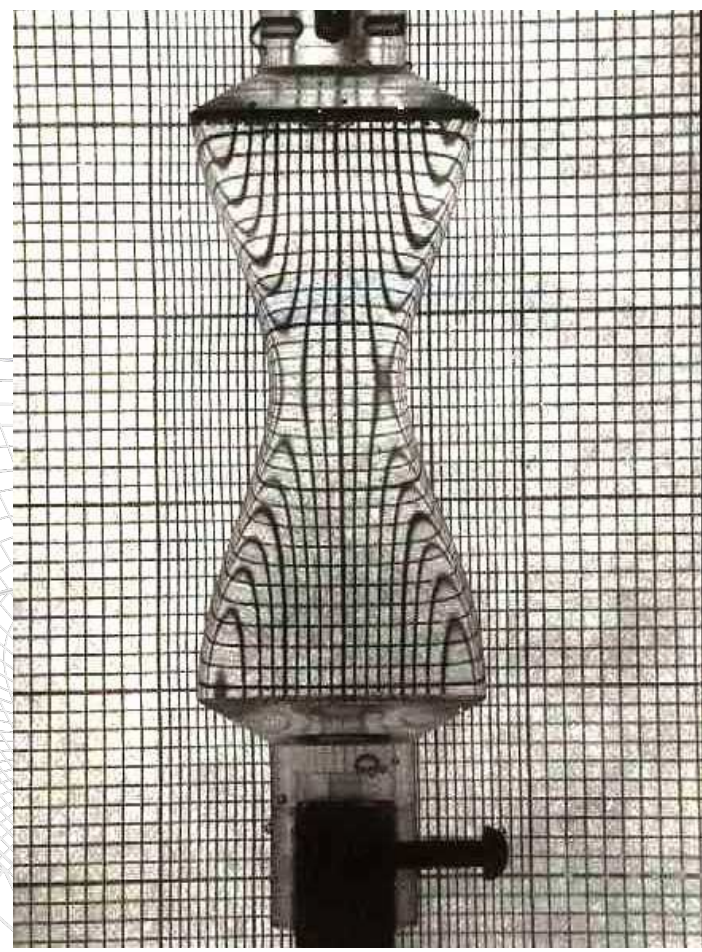


# FPM in Spacelab (SL1, FSLP)

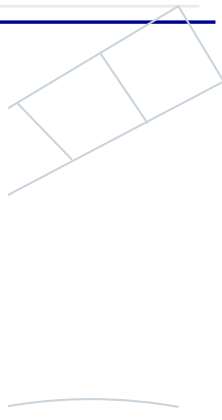
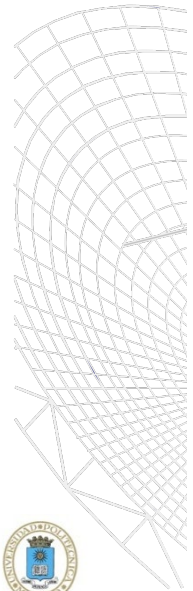
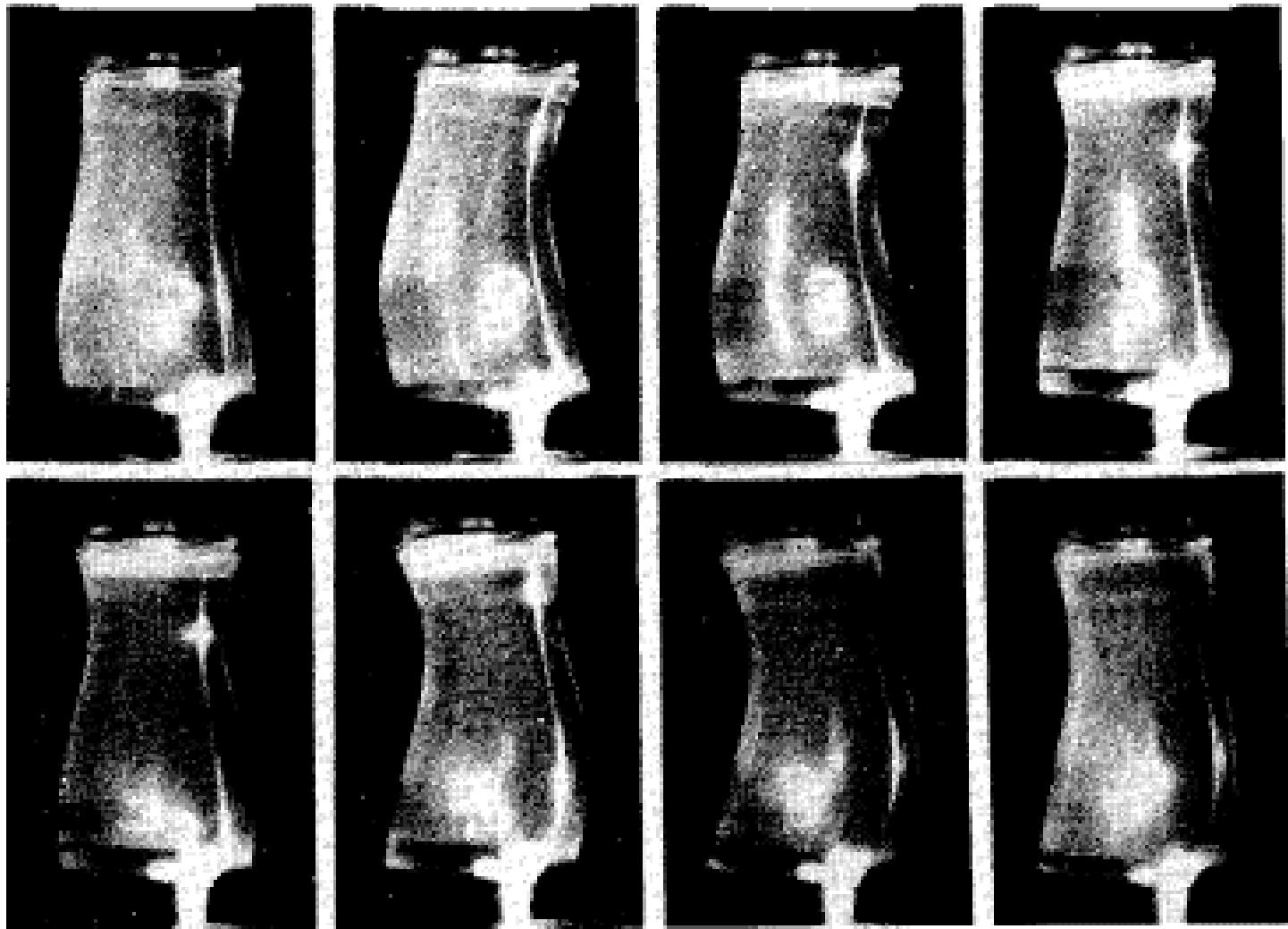


# What we expected and what we got

- The long liquid column is built inside the FPM, once in flight, by injecting liquid from a reservoir between two coaxial discs.

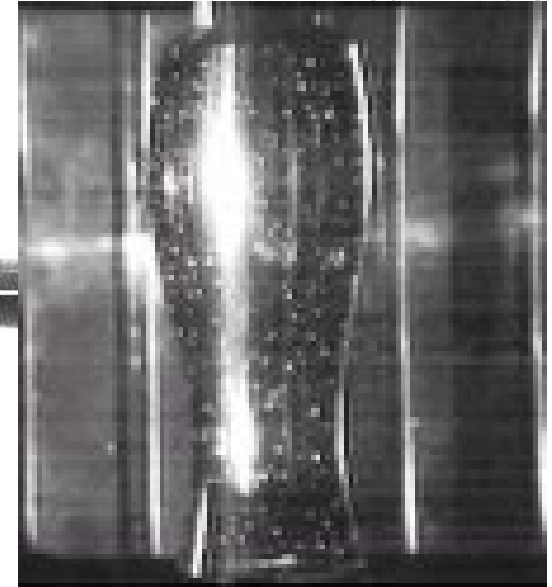
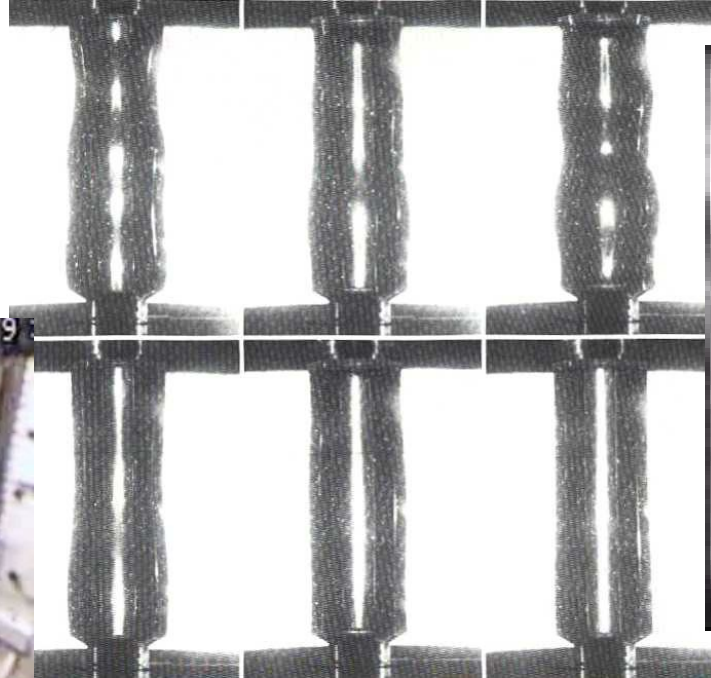


# SL-1: 1-ES-331



# SL-D1: FLIZ

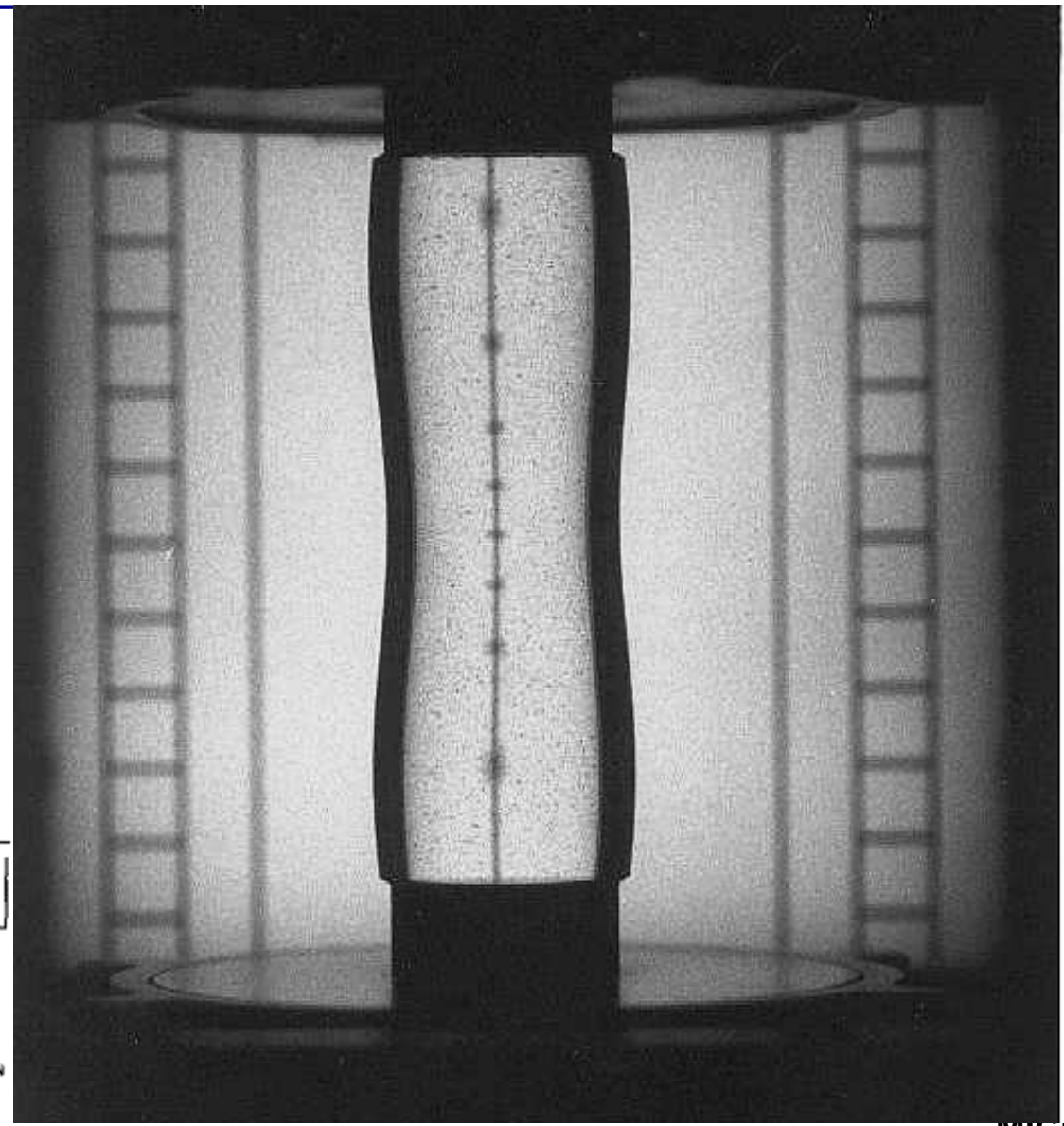
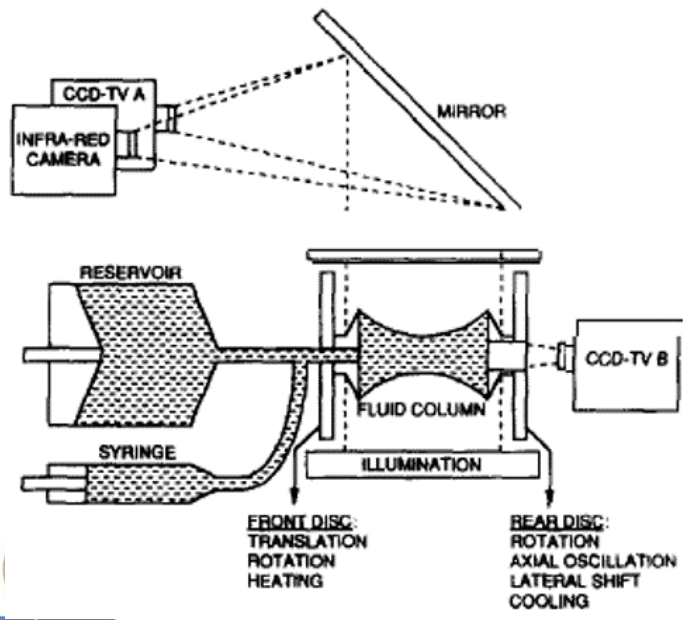
Vibration at several frequencies



Controlled breaking

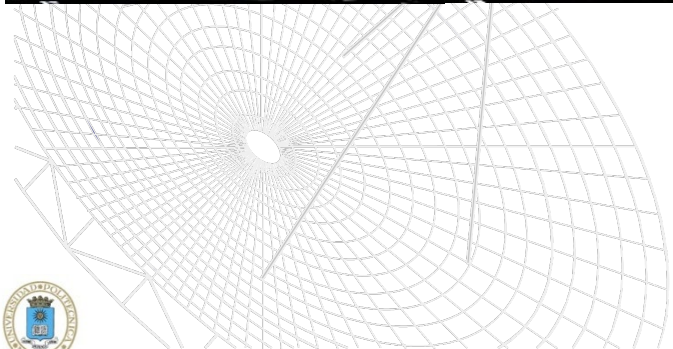
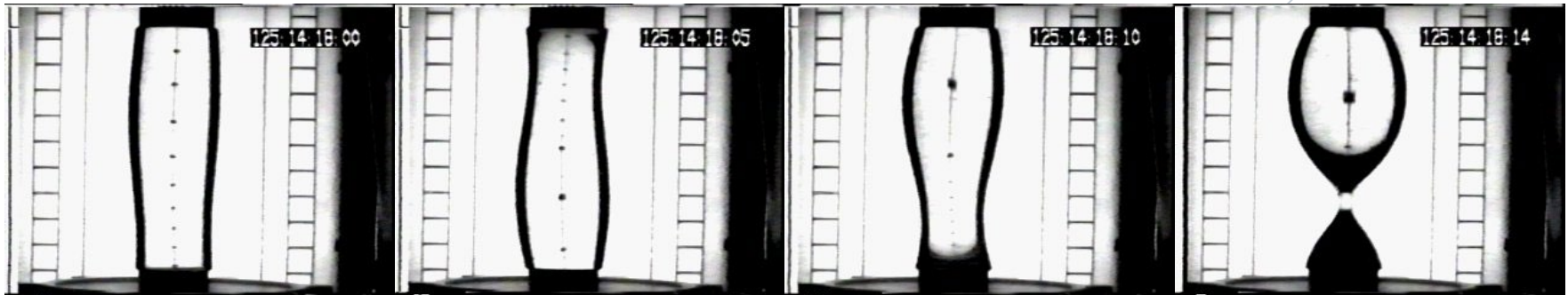


# SL-D2: STACO



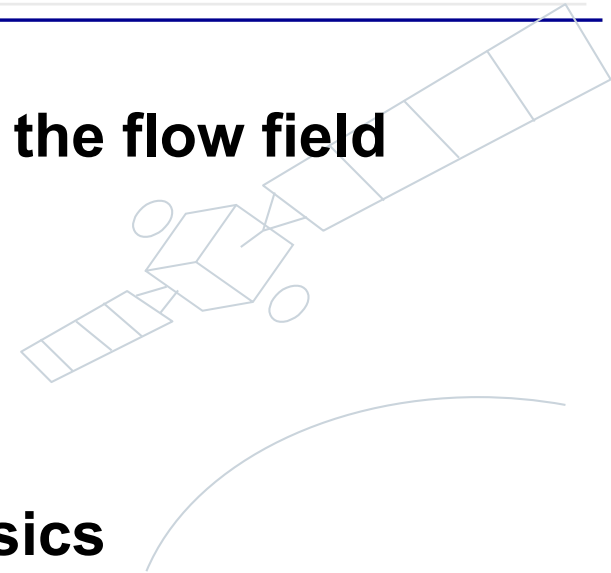
# SL-D2: STACO

**Unexpected breakage in the 3rd run of STACO**  
(the column was idle during the 150 s of wobbling)



# Fluid science research in space

- **Not just the classic problem of finding the flow field**
- **Related to the structure of matter**
  - Fluid critical point
  - Exotic fluids (e.g. ferrofluids)
  - Wetting and spreading
- **Related to other problems in fluid physics**
  - Equilibrium and stability of interfaces
  - Onset of free convection
  - Boiling
  - Drop and bubble coalescence
- **Applications to materials and life sciences**
  - Crystal growth
  - Electrophoresis...



# Microgravity relevance

- The only change is in the momentum equation
- Most cases explained with the hydrostatic equilibrium equation:

$$\Delta p = -\Delta \rho g \Delta h$$

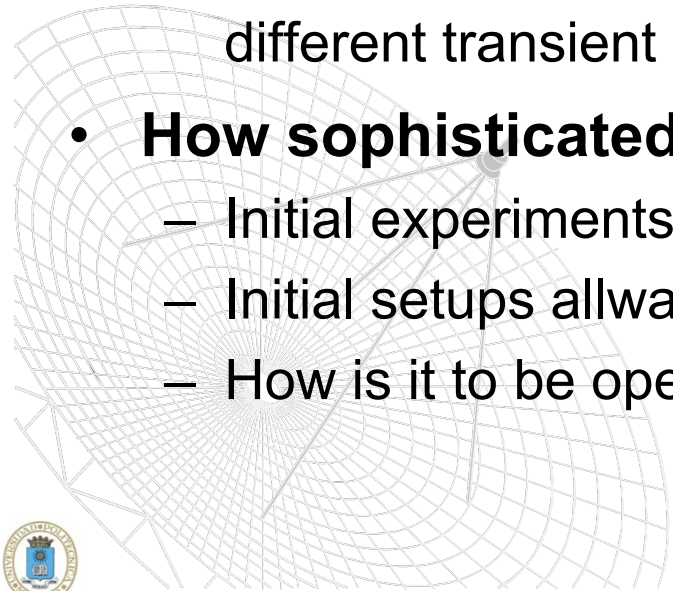
- $\Delta p$  is the pressure difference inside the fluid through a vertical height  $\Delta h$ ,
- $g$  is the constant-gravity acceleration on ground (vertical),
- $\Delta \rho$  is the density difference between the fluid of interest and the surrounding fluid
- **Weight reduction (where does the liquid sit?)**
- **Natural convection reduction**
- **Sedimentation reduction (no segregation).**

# Fluid relevance

- Particular fluids are irrelevant; only non-dimensional parameters are important:  $Re=vL/\nu$ ,  $Pr=\mu c/k$ ,  $Bo=\rho g L^2/\sigma\dots$
- Only time is consumed; fluid sample is free or low-valued, and might be recovered; experiments can be easily repeated
- Diagnosis is based on visualization (fluids are transparent), and it is multi-dimensional ( $t,x,y,z$ )
- The analysis can be evaluated real-time (no batch processing)
- Field of view and resolution may be tunable in time and space.

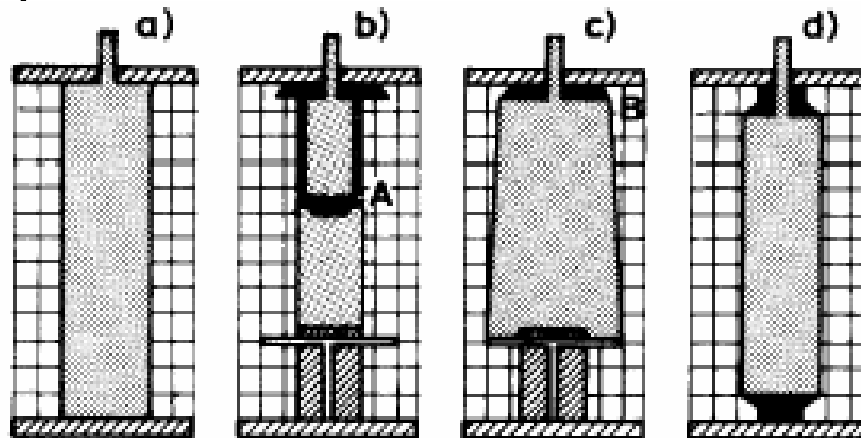
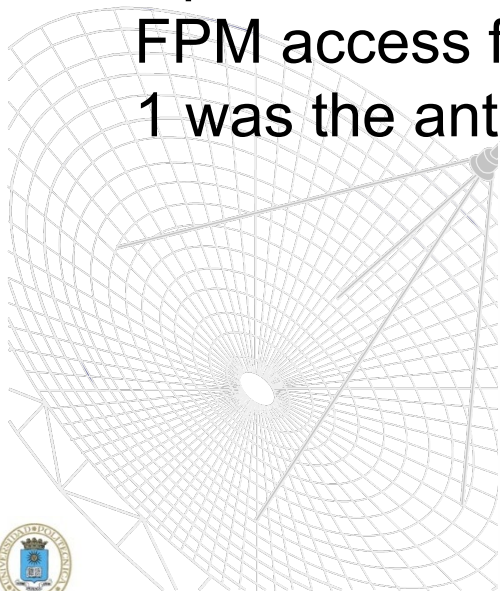
# Experiment relevance

- **Objective may be:**
  - Check for expected response to applied stimuli
  - Check for new theoretical predictions
  - Get data from new phenomena already detected
- **Why large liquid columns?**
  - Micrometric columns can be established on ground, but with different transient periods, resolution, cleanliness...
- **How sophisticated the experiment can be?**
  - Initial experiments are just look-and-see
  - Initial setups always show infancy problems
  - How is it to be operated: manually, telescience...

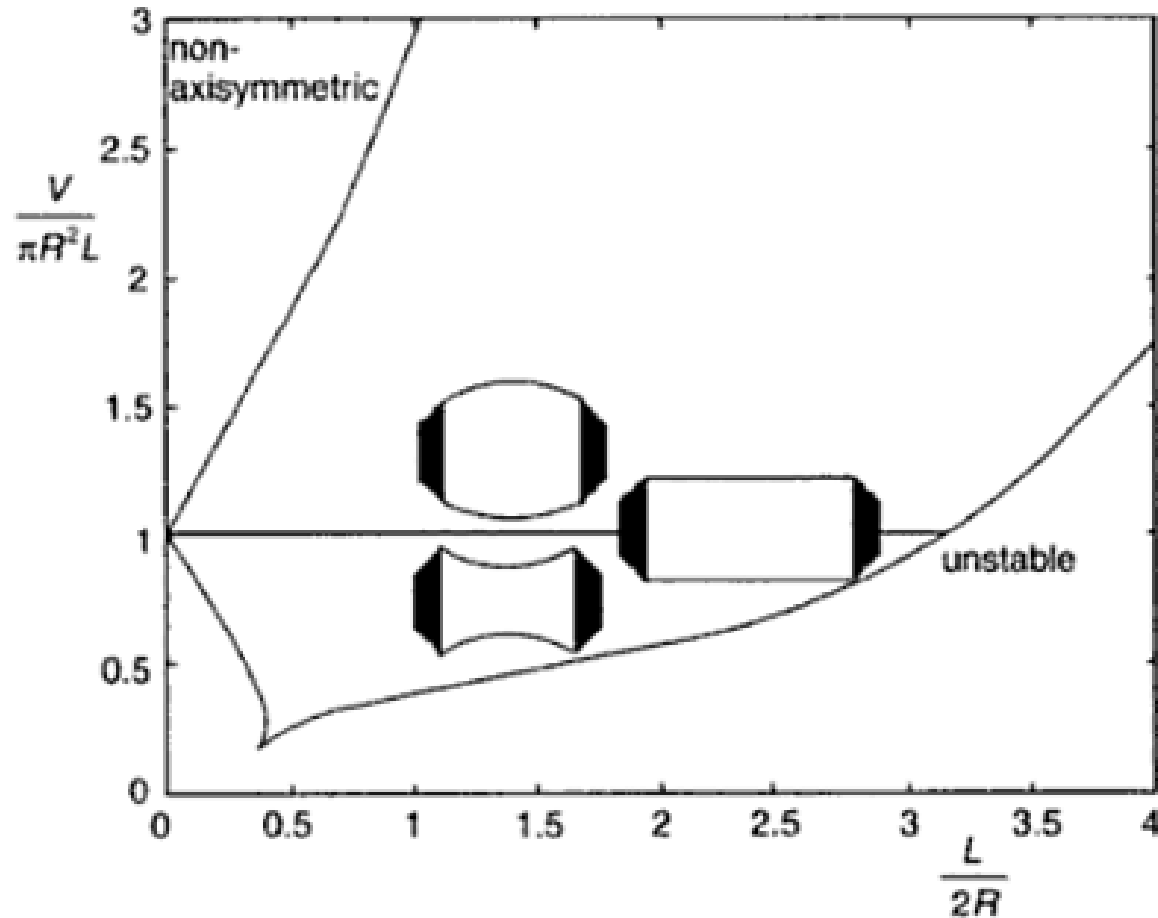


# Experiment design

- The design depends a lot on previous experience.
- On Skylab-IV it was just a manual trial with little control.
- On Spacelab-1 it was a tight procedure without ground tests on the FPM (ground trials on other setups, many times tuned to solve infancy problems like liquid filling, liquid visualization, and liquid cleaning, were made without FPM access for checking). The weakest design point in SL-1 was the antispread barrier.



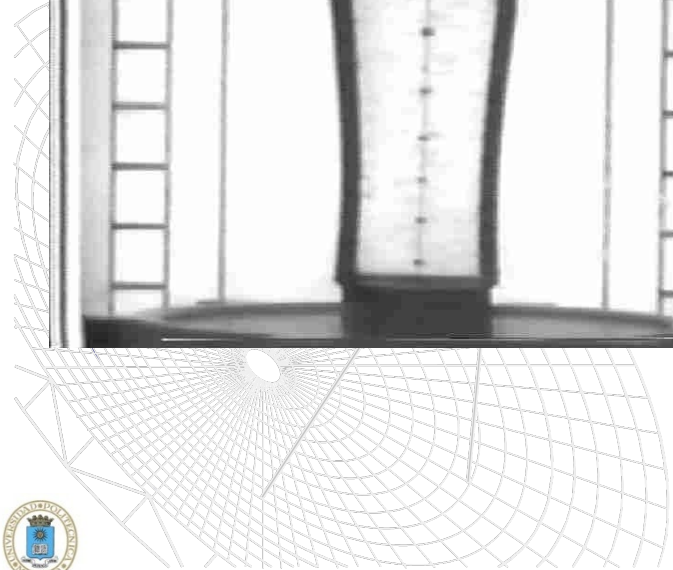
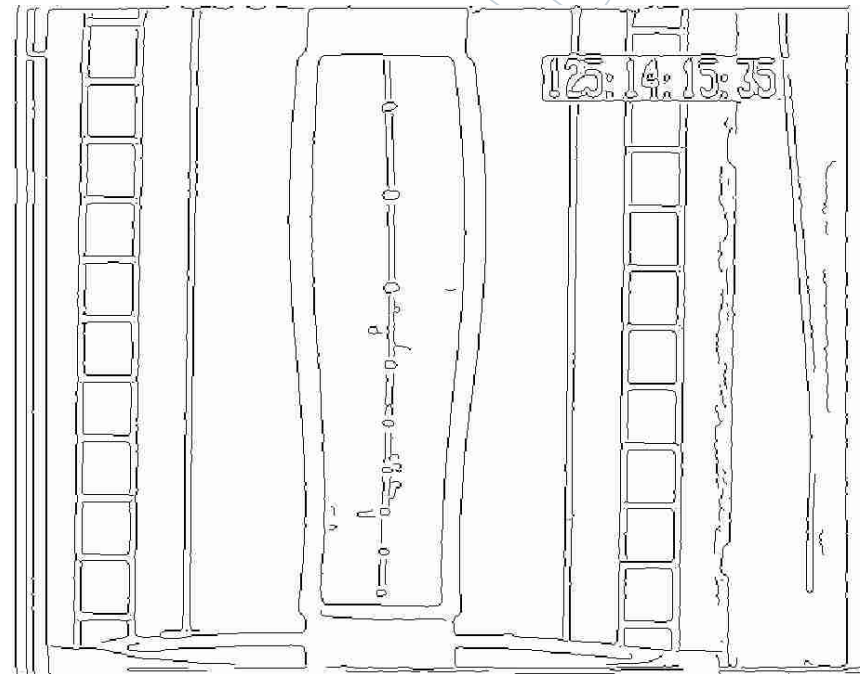
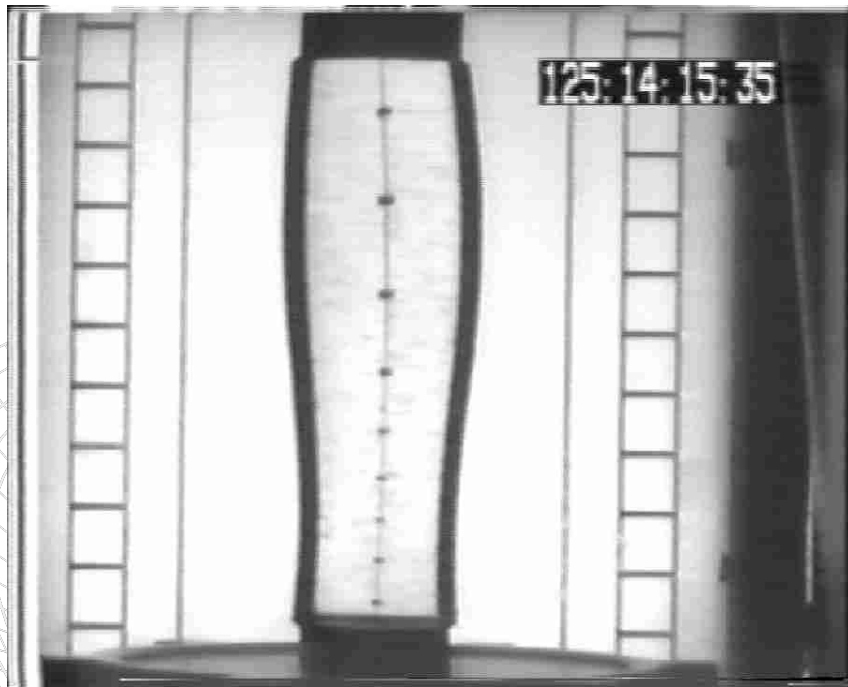
# Liquid bridge equilibrium shapes



**Figure 2.4** Stability diagram for unloaded liquid bridges of volume  $V$  between equal discs of radii  $R$  a distance  $L$  apart (Da Riva and Martínez 1979). Transitions to non-axisymmetric shapes may be quasi-static or dynamic (Slobozhanin *et al.* 1997).

# Spacelab-D2 experiment "STACO"

## Automated image edging



# Equilibrium, stability and dynamics

- Equilibrium shape

$$r(z, \theta) = 1 + h \frac{\sin z}{\sin \Lambda} + v \frac{\Lambda (\cos \Lambda - \cos z)}{2(\Lambda \cos \Lambda - \sin \Lambda)} + Bo_A \left( z - \Lambda \frac{\sin z}{\sin \Lambda} \right) + Bo_L \frac{\Lambda^2}{2} \cos \frac{\pi z}{\Lambda} \sin \theta$$

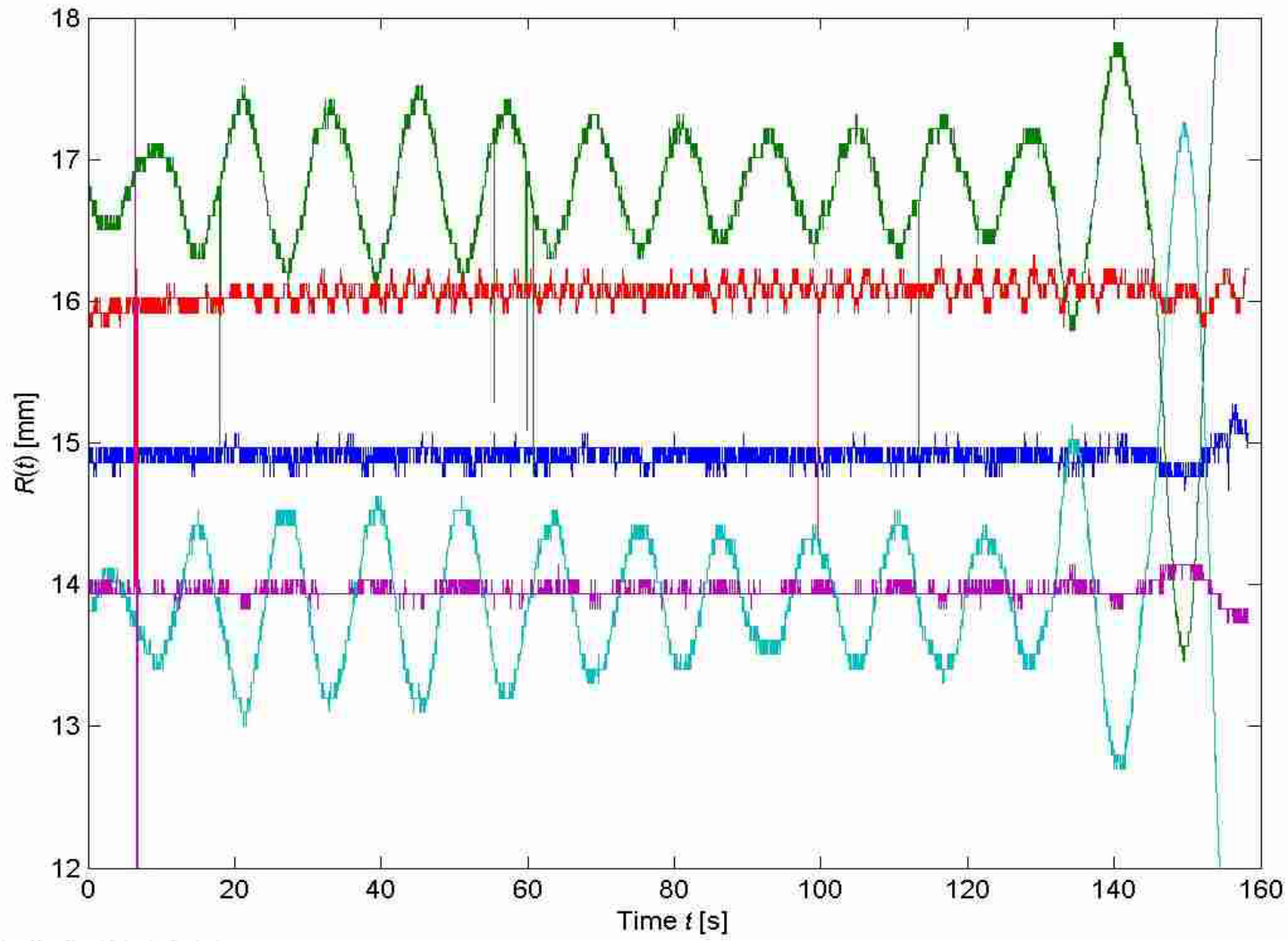
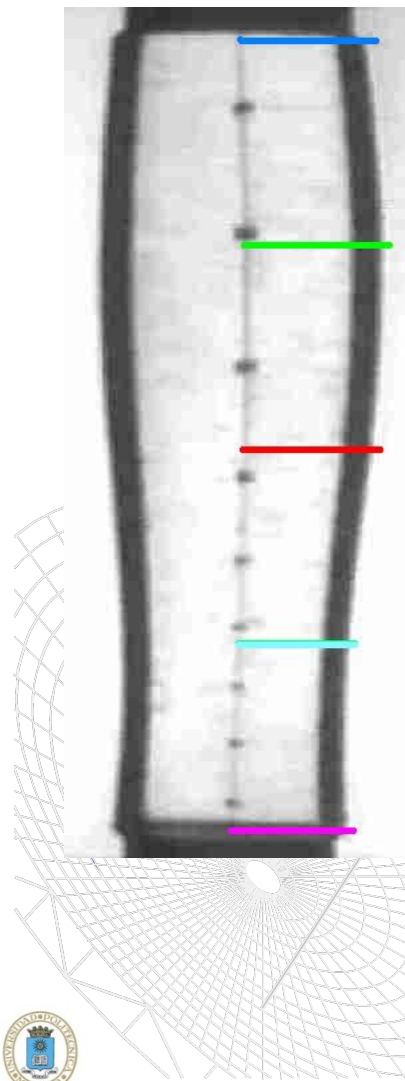
- Stability limit

$$-\lambda + \frac{v}{2} - \left( \frac{3}{2} \right)^{4/3} \left( \frac{h}{\pi} - Bo_A \right)^{2/3} - \frac{\pi^2}{4} Bo_L^2 - \frac{We}{2} - K(t) > 0$$

- Axial dynamics of quasi-cylindrical liquid columns

$$r(z, t) = r_{eq}(z) + a(t) \sin \frac{\pi z}{\Lambda} \quad m \frac{d^2 a(t)}{dt^2} + mC \frac{da(t)}{dt} + \lambda a(t) + \frac{3}{4} a(t)^3 = Bo_A(t)$$

# Time evolution of selected radii



# Achievements

- **Theoretical predictions greatly advanced on mechanical behaviour of liquid columns.**
- **Problems in establishing the liquid column solved (two methods available).**
- **It was found that zero-g stability limits can only be approached up to 90% due to g-jitter.**
- **Good agreement between vibrational behaviour of long liquid columns with theory.**
- **High-precision automated image analysis was developed (a tenth of a pixel).**
- **Unexplained shape deformation in SL-D1 (one order of magnitude larger than expected).**
- **Unexplained breakage in SL-D2 (while being idle).**
- **Record of a controlled liquid column 110 mm long.**

# Remaining problems

- **Better image capture and processing than in 1980s.**
- **Better bubble control during column formation.**
- **Better edge-anchorage control during column formation and after bridge rupture.**
- **Parallax and depth of field should be avoided (go to parallel viewing).**
- **Lack of redundancy in past experiments (go to two sides viewing).**
- **Automatic synchronization of all data sources (images and houskeeping data).**
- **G-jitter characterisation.**

# Future LB experiments?

- In spite of the extended period of time devoted to this research at IDR-UPM (more than 30 years), the total experimental time in space (Spacelab and Texas) has been only of a few hours, including all the time spent in debugging hardware malfunction and infancy problems on experiment procedures.
- The long liquid column configuration is the simplest liquid geometry (a cylinder) to control in space (planar or spherical interfaces are more difficult to build or maintain). Besides remaining mechanical problems, there are many thermal, solutal, electrical... interesting problems to benefit from this configuration.
- At present, there aren't any experiments on liquid bridges foreseen for the FSL in the ISS.

# Evolution of the space segment

**1980s**

**Space shuttle**

**Spacelab**

**WL (Werkstofflabor)**

**Fluid Physics Module**

**Manual operations**

**2010s**

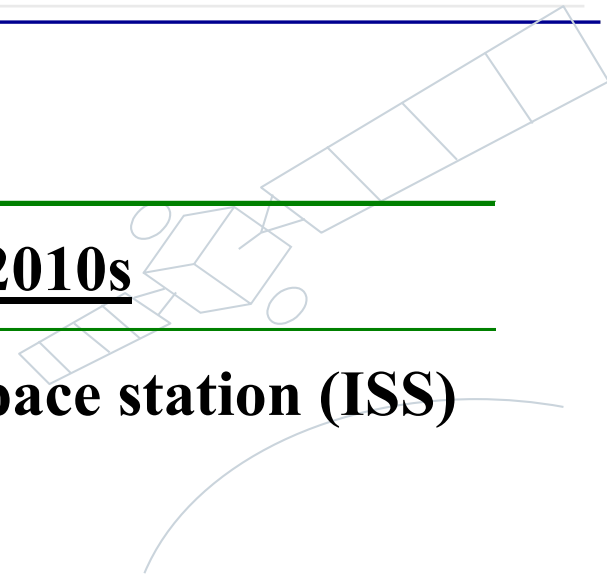
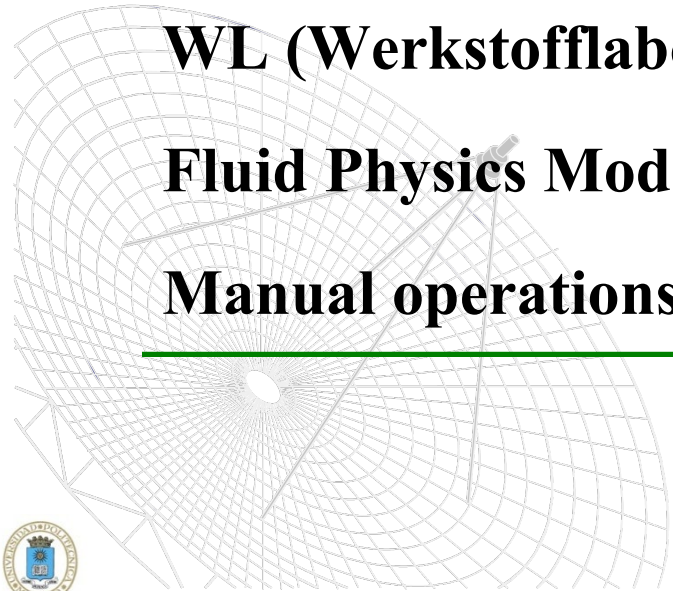
**Permanent space station (ISS)**

**Columbus**

**FSL (Fluid Science Lab)**

**Experiment Container**

**Telescience**



# REFERENCES

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- **Martinez, I., 1992, Fluid Science Requirements for Columbus, Space Technol, Vol. 12, No. 2, pp. 135-144**
- **Martínez, I., Perales, J.M., Mesequer, J, 2004, "Non-linear response of a liquid bridge to a sinusoidal acceleration under microgravity", Experiments in Fluids 37, pp. 775-781.**
- **Martínez, I., Mesequer, J, Perales, J.M., 2005, "Wobbling of a liquid column between unequal discs", Advances in Space Research 36, pp. 26–35.**
- **Martínez, I., Sanz-Andrés, A., Mesequer, J, 2007, "Space experiments by Da Riva's team", [http://imartinez.etsiae.upm.es/~isidoro/lc1/Da Riva's team research.htm](http://imartinez.etsiae.upm.es/~isidoro/lc1/Da_Riva's_team_research.htm)**