ITEL EXPERIMENT MODULE AND ITS FLIGHT ON MASER 10

Olle Janson, Maurits Broxvall, Kenneth Löth, Patrik Andersson, Ylva Houltz
Space Systems Division, Swedish Space Corporation
P.O.Box 4207, S-171 04, Solna, Sweden (e-mail: kenneth.loth@ssc.se)

Pierre Colinet, Benoit Scheid
Université Libre de Bruxelles, Microgravity Research centre,
Av. Fr. Roosevelt, 50 CP 165/62, B-1050 Bruxelles, Belgium

Luc Joannes, B. Saul, B. Haesendonck, M. Heraud, Olivier Dupont
Lambda-X, Zoning II, Rue de l'Industrie 37, B-1400 Nivelles, Belgium

ABSTRACT

The Interfacial Turbulence in Evaporating Liquids (ITEL) experiment module flew in microgravity during 6 minutes and 1 second on the Sounding Rocket MASER 10 on May 2, 2005. Swedish Space Corporation and Lambda-X, Belgium, developed the ITEL module under contract from the European Space Agency (ESA).
The objective of the experiment was to observe cellular convection (Marangoni-Bénard instability) in an evaporating highly volatile liquid with a free surface.
The experiment module contains the experiment cell. An interferometric optical tomograph, with six viewing directions, measures the 3-dimensional distribution of temperature in the evaporating liquid and a Schlieren optical system visualizes the convective motions and deformations of the liquid surface.
After microgravity is achieved, the liquid is injected into the cell and a free liquid surface is established and kept flat. The evaporation rate of the free surface is controlled by regulating the gas pressure and gas flow. The two optical systems worked nominally during the flight and the scientific results are under evaluation.

1. INTRODUCTION

This project included refurbishment, modification and flight of the experiment module developed for the Sounding Rocket program MASER. The Interfacial Turbulence in Evaporating Liquids (ITEL) was built under contract from the European Space Agency (ESA) and flew for the first time on MASER 9 on March 16, 2002.
In order to perform the experiment on the first flight, several systems had to be developed, such as:

- An experiment cell with a free liquid surface including thermal control, gas flow system, liquid injection system and surface flatness regulation.

- An interferometric optical tomograph, with six viewing directions parallel to the liquid surface, in order to measure the 3-dimensional temperature distribution in the liquid. This system is to our knowledge the first interferometric tomograph to be onboard a space system.
- A Schlieren optical system to visualize the convective motions and to aid the surface regulation.

One technical objective for the MASER 9 flight was to validate the optical tomography system, which was built

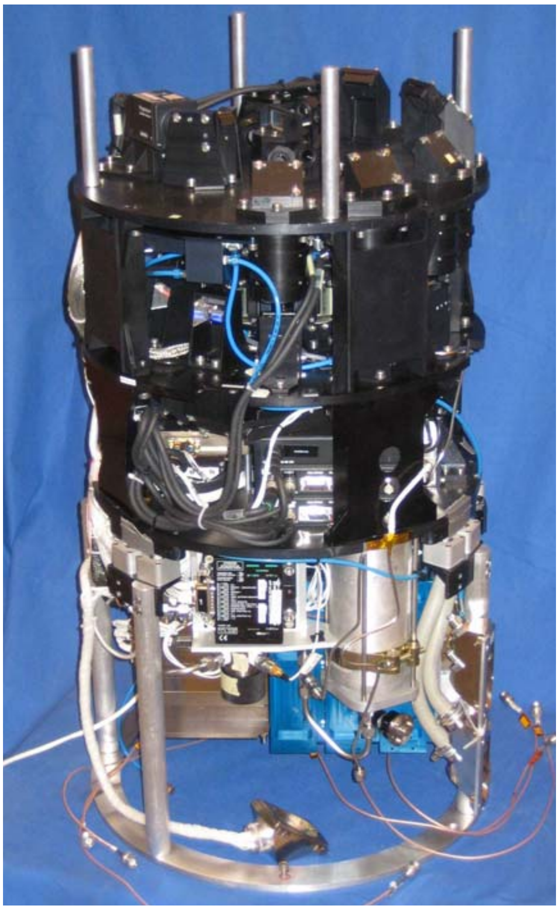

Fig. 1. ITEL experiment module on the MASER 10 without its outer structure.

Published by the 17th ESA Symposium on European Rocket & Balloon Programmes and Related Research, with permission.

for general utilisation in fluid physics experiments in microgravity.
The Swedish Space Corporation (SSC) conducted the project with Lambda-X as a subcontractor responsible for the optical systems.
For the MASER 10 flight some modifications were made. These were:

- An improved thermal control of the experiment cell and injection unit. This consisted of a separate inner loop with heat exchanger and pump.
- Better cooling of the electronics. This was achieved with an extra heat exchanger.
- Relocated N_2 vessel and Mass Flow Controller.
- New CPU.
- Modified software.
- A Digital Video System (DVS) developed by Techno System developments, Naples, Italy.

The ITEL experiment on Maser 9 & 10 was a preliminary step in the preparation of the CIMEX (Convection and Interfacial Mass Exchange) program, which will make use of the International Space Station.

2. EXPERIMENT DESCRIPTION

2.1 Experiment

The Principal Investigator (PI) of ITEL was Dr Pierre Colinet, Université Libre de Bruxelles (ULB) Belgium.
The objective of the experiment was to analyse the fluid dynamics of an evaporating liquid in microgravity. A highly volatile liquid layer was evaporated and the convection phenomenon generated in this process was observed. Due to the cooling by latent heat consumption at the level of the evaporating free surface, a temperature gradient is induced mostly perpendicularly to it. Due to the surface tension variation with temperature, thermocapillary instability is triggered which leads to cellular convection (Marangoni-Bénard). The main scientific goal was to show that, in microgravity, evaporation could drive Marangoni convection and chaotic patterns.

2.2 Experiment Set-Up

The idea was to keep the experiment cell at constant and uniform temperature, inject liquid into the cell at microgravity and to control the evaporation rate of the free surface by regulating the gas pressure and gas flow. The liquid-gas interface had to be kept flat during the experiment imposing injection of liquid to compensate for evaporation.

2.2.1 Experiment sequence during flight

Liquid was injected into the cell and when an isothermal situation (with weak evaporation rate) was

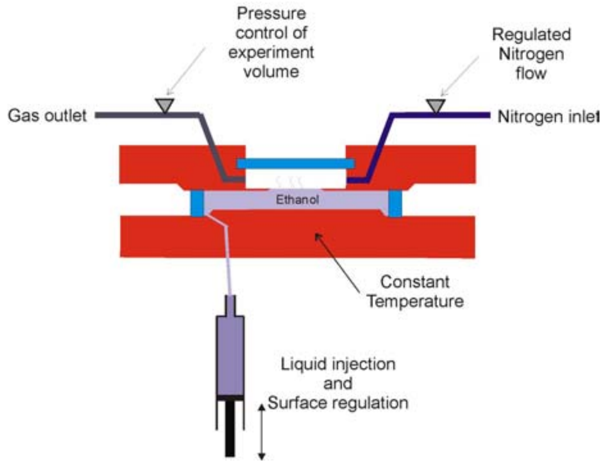

Fig. 2. Simplified sketch of the experiment cell.

obtained, the flow/pressure sequence was started. A number of experiment points were used during the microgravity phase in order to observe the interfacial motions. The pressure was changed in steps of 100 from 1200 to 500 mbars. The flow was changed in steps of 100 from 0 to 500ml/min.

3. EXPERIMENT MODULE

3.1 General Description

The ITEL-2 module has a length of 750mm and a mass of 68 kg. The mechanical system has an outer structure of Al-alloy (∅438 mm), to which the experiment deck is attached via shock absorbers. The outer structure is insulated with glass fibre insulation and equipped with lids at top and bottom. The injection unit can be taken out from the module via a late access hatch.

The ITEL module comprises:
-Experiment cell including reference volume
-Gas flow and liquid injection systems
-Schlieren Optical system
-Tomography Optical system
-Image capture and storage system
-Electronic control system
-Software
-Thermal system including cooling loops

3.2 Overall design

Due to the limited diameter of the Sounding rocket the optical systems are split in three levels, as described further in paragraph 3.5, requiring one main experiment deck and two optical decks.

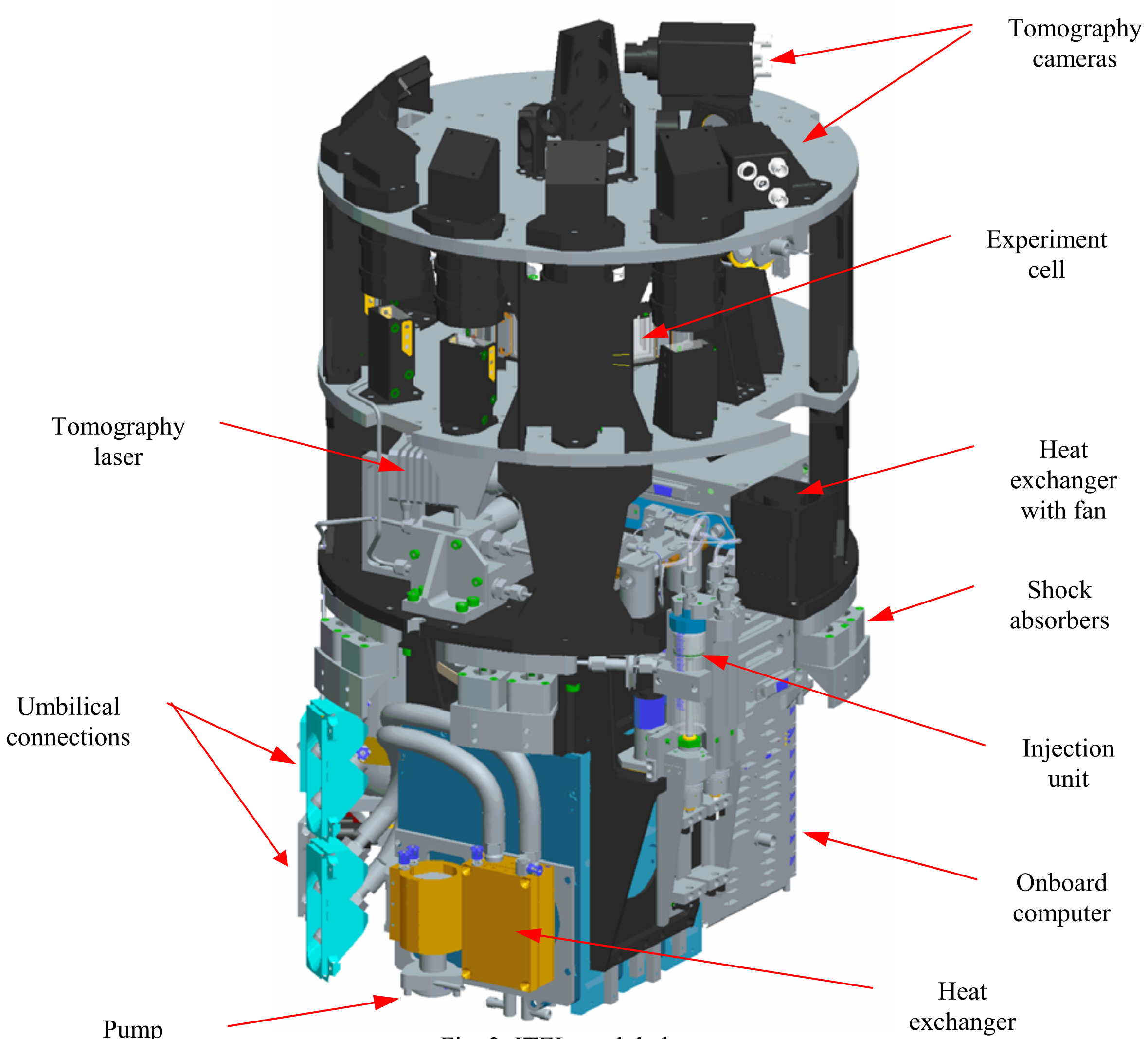

Fig. 3. ITEL module layout

The two optical decks contain the cameras and lenses for the tomographical interferometers and for the Schlieren system. On the underside of the lower optical deck the laser source for the tomography system is placed. On its upper side the experiment cell with its correction lenses and thermocouples as well as tubing for gas are positioned. On the underside of the upper optical deck the Schlieren system is placed. On its upper side the tomography cameras are placed. The two optical decks are then mounted on top of the experiment deck. On the underside of the experiment deck the electronics such as the computer, memory units, the batteries, the laser driver, the Peltier control, three Digital Video recorders and thermocouple amplifier are located as well as heat exchanger, gas vessel, pressure valve and flow meter. The DVS is placed on the underside of the bottom lid.

3.3 Thermal system

The module incorporates a thermal system consisting of two main liquid loops connected before launch via liquid umbilicals to two thermal baths. One loop transports excessive heat from the electronics and consists of a heat exchanger with fan placed on the experiment deck and a heat exchanger between the DC/DC converter unit - being the hottest unit of the electronics stack - and the experiment deck, acting as a thermal barrier. The other loop (which itself is divided in two) is used for controlling the initial temperature in the injection unit and the experiment cell. This consists of a separate, inner, loop with a pump and runs through the cell and injection unit. It is connected to the outer loop via a heat exchanger. This way the outer loop can have a larger cross section than the inner loop, allowing a larger flowrate. This arrangement gives a system that is less sensitive to temperature variations in the launch tower during countdown. There is also an electrical heater foil installed in the injection unit for fine tuning of the temperature in the fill syringe.

3.4 Experiment system

3.4.1 Experiment cell

The cell is designed in three levels (top, mid, bottom) with experiment and reference volume between. The experiment liquid volume is 12 ml with a depth of 5 mm and has a ∅15 mm active area open to the gas channel.
The free liquid surface is defined by a 0.2 mm thin foil of stainless steel. Water loops for pre-launch thermalisation are included in all three levels. Cylindrical correction lenses are mounted to the top plate
The interior design and material properties have been chosen according to the results of cell filling tests performed on a parabolic flight. The cell is pressure tight and has a gas inlet, a gas outlet and a liquid inlet/outlet.

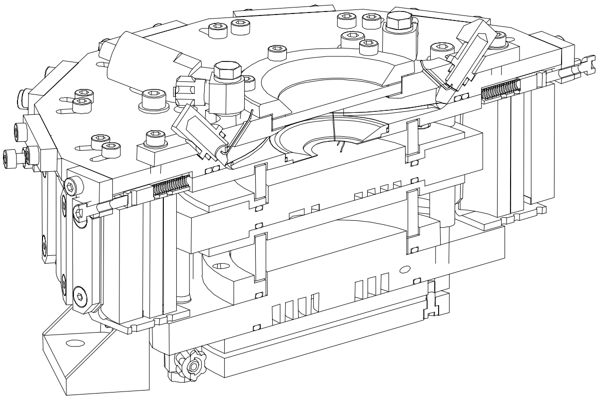

Fig. 4. Cross-section of experiment cell

The top part of the cell is designed to give a laminar flow of Nitrogen along the free ethanol surface. The cell bottom is furnished as a mirror for the Schlieren system.

3.4.2 Liquid injection unit

The liquid injection unit is assigned for initial filling of the experiment cell at microgravity as well as for dispensing small volumes to compensate for evaporation and for surface regulation during flight. It consists of 2 syringes with drive mechanisms and DC-motors, 2 zero-volume inert solenoid valves, one manual valve and Teflon tubing.
It is filled during count-down with de-gassed ethanol to avoid bubbles in the experiment cell when lowering the pressure.
The Injection unit is installed in the module via a late access hatch.

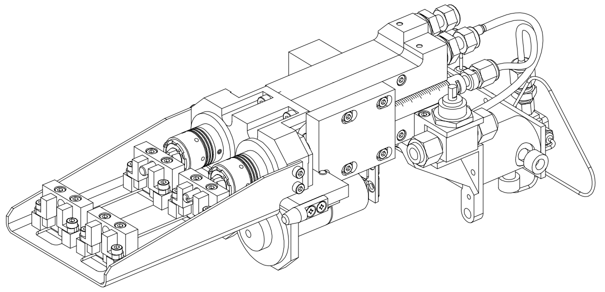

Fig. 5. Injection unit

3.4.3 Gas flow system

The evaporation rate was controlled by a gas flow system consisting of a pressure control system and a gas injection system.
During flight, the pressure regulation in the cell was controlled via an electronic adjustable pressure valve on the outlet and a pressure sensor in the cell. A software controlled PI(D) regulator registered the actual pressure in the cell and adjusted the pressure valve according to the set point.
The N_2 injection system comprised a pressure vessel, pressure reducer, primary and secondary pressure sensors and a relief valve on the inlet to the cell. The mass flow controller regulated the flow into the cell and a mass flow meter measured the outlet flow. The gas on the outlet was symmetrically distributed through outlet diffusers on the outer structure in order not to disturb the microgravity levels.

3.5 Optical systems

The optical systems developed by Lambda-X are divided around two optical decks. The Schlieren system is located on the lower side of the upper deck, above the cell. The tomography optical system is split in three levels (see figure 7). The first one from the bottom (Tomo-Source level) is the level where the laser beam coming from a single red laser diode is split into six identical collimated beams. This is done by first letting the light pass a 50/50 beam-splitter and then splitting the two beams in one ±30° holographic grating each. The second level (Tomo-Interferometers level) includes the interferometers and the experimental cell. The third one (Tomo-Imaging level) is the imaging level. Here another set of holographic gratings combine the beams 3 + 3. Afocal systems image the views into CCD cameras, and the views are combined (three on each CCD).

3.5.1 Schlieren optical system

The tasks of the Schlieren system is to:
- Visualize liquid-gas interface deformation and refractive index gradients in the liquid.

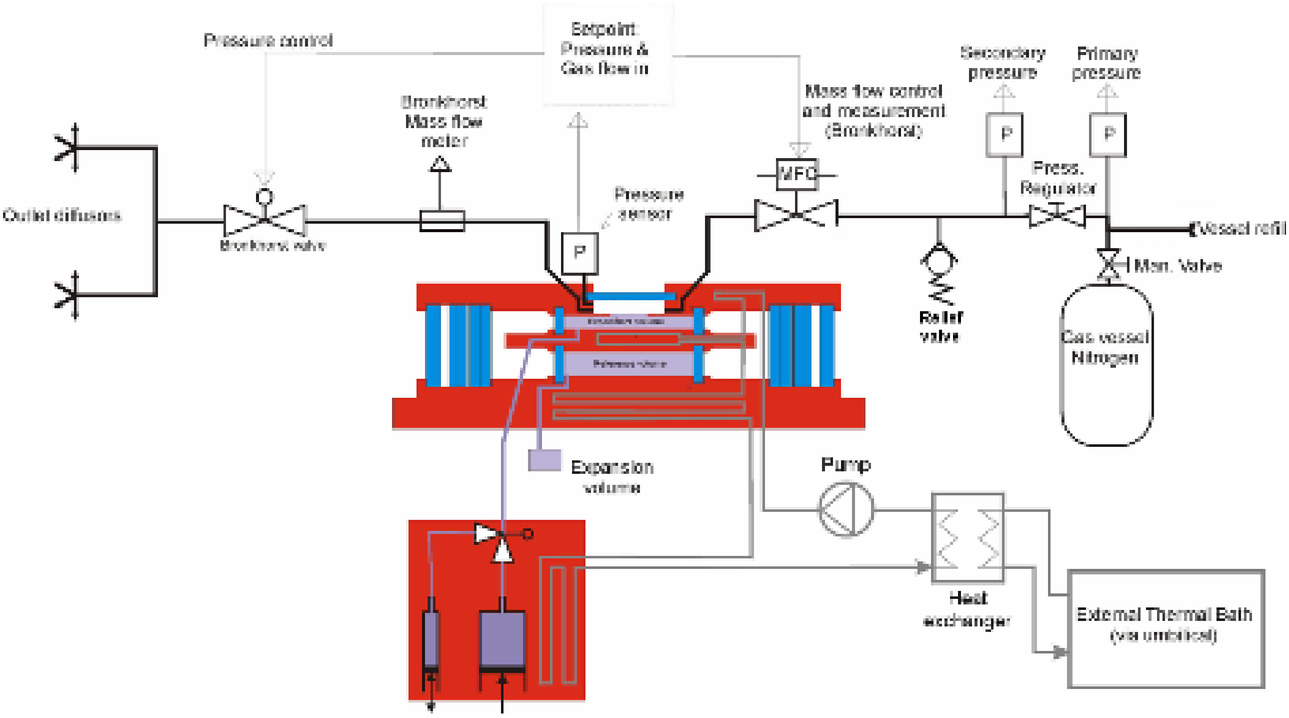

Fig. 6. ITEL Gas flow system

- Localization of convection cells to be used for tomographic reconstruction
- Interface flatness control

The Schlieren system uses a LED source and is used in transmission mode with a mirror at the bottom of the cell. It has a variable sensitivity by a variable iris diaphragm and modulation of LED intensity.

3.5.2 Tomographic system

Interferometric tomography is a technique that allows measuring the 3 dimensional (relative) refractive index distribution in a typical volume. Multiple interferometer paths are crossing the volume at different angles and each measures the integrated refractive index distribution in the experimental volume. The views are lying in a plane and the central part, called 'Common Volume', crossed by all the views, is the volume in which the refractive index distribution can be retrieved. The arrangement design for the 6 views in ITEL can be seen in Fig. 8.

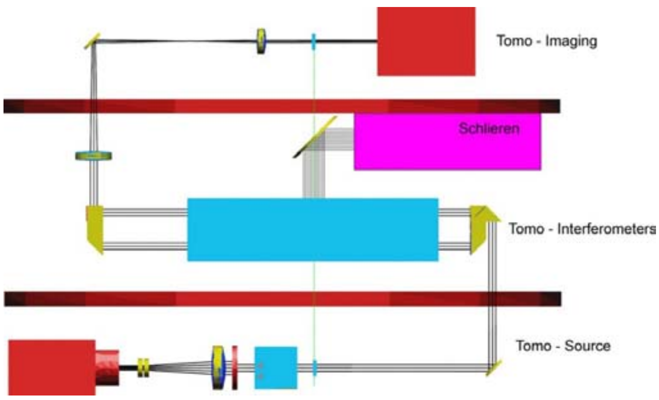

Fig. 7. Layout of optical systems (Lambda-X)

Beam generation

In the tomo-source level the single laser diode generates 6 beams with the help of a 50/50 beam splitter and two ±30° holographic gratings.

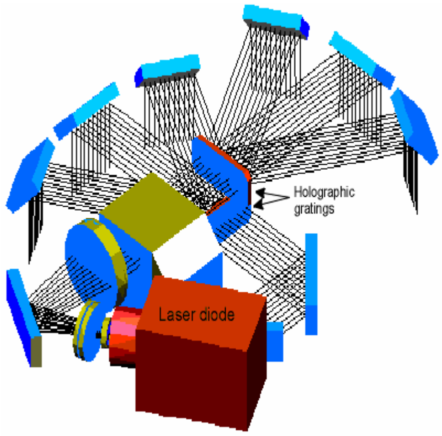

Fig. 9 Tomo-source level (Lambda-X)

Interferometers
The interferometers are of Mach-Zehnder type. This configuration is very robust since any small displacement or rotation of these prisms will not compromise the performance of the system (no additional fringes will be induced).

Experiment cell
An experimental cell with circular geometry has been selected. Thus to ensure that the laser beams are collimated in the liquid, cylindrical compensation lenses have been introduced. See Fig. 8.
Note that the compensation is only valid at the design temperature since the refractive index of the liquid is strongly dependant of the temperature. Since a reference cell filled with the same liquid of the same temperature is positioned in the reference paths of the interferometers, the system is operating correctly even if the ambient temperature differs from the design temperature up to ±5°.

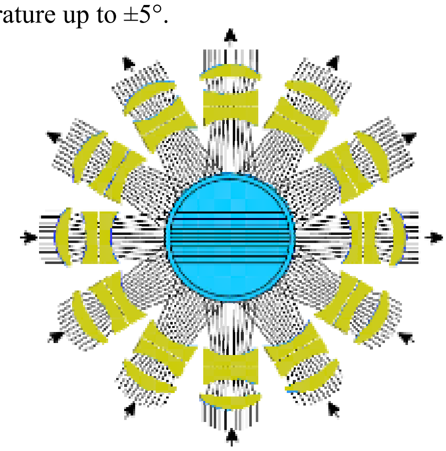

Fig. 8. Organisation of views.
The central part is the liquid. (Lambda-X)

Beam combination
The last level has two functions: the image of the cell is produced onto the CCD sensor, and three views are combined in each camera. See Fig. 11.

Phase shift
The tomographic reconstruction requires the measurement of the optical phase. Thus a phase shift system has been implemented. Its principle is to record a set of images of the same fluid state with a controlled modulation of the phase shift. The fringe phase is then calculated from these images.

3.6 Interface flatness control

One of the difficulties with an evaporating free surface is how to automatically detect and regulate the flatness to compensate for the evaporated liquid. The interface flatness control system in the ITEL module used the image from the Schlieren system and was verified during the MASER 9 flight.
A curved interface produces a non uniform image in the Schlieren system and it is easy to discriminate between an overfilled or underfilled liquid surface. This image from the Schlieren camera was fed to an onboard framegrabber card in the computer in order to make a real-time analysis in the onboard software. In the case that the image is not uniform, the injection unit will inject or retract liquid to achieve a flat surface.

3.7 Video system

The two cameras for the tomographic system as well as the camera for the Schlieren system were in progressive scan mode and were synchronised with the 25Hz phase-shift of the tomography laser source.
Each of the three cameras was connected to an earlier flight proven video recorder of MiniDV type.
During the flight on MASER 10 two video signals (interchangeable between three cameras) were transmitted to ground by digital TV-transmitters for real-time control of the experiment. A third, selectable, video signal was also transmitted via an analog transmitter as backup.

3.8 Electronic system and software

The experiment is controlled by an onboard computer stack of PC/104 format and electronics developed by SSC that incorporates a real-time operating system software. The system controls the experiment automatically during flight but the sequence can be overridden by tele-command. All data is saved onboard at 25 Hz during the active phase of the experiment. The data saving is synchronised with the video signal so that

all data is saved at the same time as each video frame is captured.
The main parts in the electronic system are:
- CPU including a CompactFlash card.
- I/O cards, analogue and digital input/output
- Motor cards, for injection unit and Schlieren aperture
- Video framegrabber, capturing Schlieren images
- TM/TC interface
- Housekeeping unit
- Power Switch unit
- Thermocouple amplifier
- I/F unit (with Sony LANC protocol) to control the MiniDV recorders
- Video switch unit
- Batteries and DC/DC converters

3.9 Ground Support Equipment

The module was operated and monitored during tests and flight by ground support equipment (GSE) including power control and module/experiment checkout computers.

4. MASER 10, CAMPAIGN AND FLIGHT

4.1 Preparation

The campaign took place at ESRANGE, Kiruna on April 18 – May 3, 2005. It included preparation on module level as well as tests on payload level both in the integration hall and in the launch tower. The main tasks are listed below:

- Preparation of Experiment module including optical alignment, Schlieren image check and aperture motor alignment
- Scientific flight simulation tests
- Bench test with MASER Service Module (MASM) and DVS
- Experiment module check on launcher
- Payload Assembly, and Payload Test, EMI test
- Induced vibration test
- Launcher and Blockhouse Preparations
- Payload Test, Payload in tower
- Test Countdown, and Launch Readiness Review

4.2 Hot Countdown

The final hot countdown started on May 2, 2005. The preparations for the flight started already before start of countdown by degassing the experiment liquid, ethanol, and filling the injection unit as well as starting the temperature control of the experiment module.
The injection unit was installed in the ITEL module about 4 hours before lift-off.
Two module checkouts were performed during the countdown.

4.3 Flight

The lift-off of MASER 10 took place on May 2, 2005 at 7:00 am.
Before flight the temperature control of the experiment cell and the injection unit had been successful and the temperature difference between the experiment cell and injection unit was nominal.
After motor burnout, the experiment was powered up and the initial filling of the experiment cell started after microgravity was achieved. The automatic filling of the experiment cell was smooth and without bubbles, and showed similarities to the experiment on MASER 9.
After the filling, the temperature was stable and the initial tomographic images were good. Thanks to the Schlieren system and the automatic surface regulation a flat interface was observed with an accuracy of about 20 microns after some oscillations. The flow/pressure sequence was started nominally, but was paused during the oscillations. After the gain had been lowered by tele-command, the sequence continued.

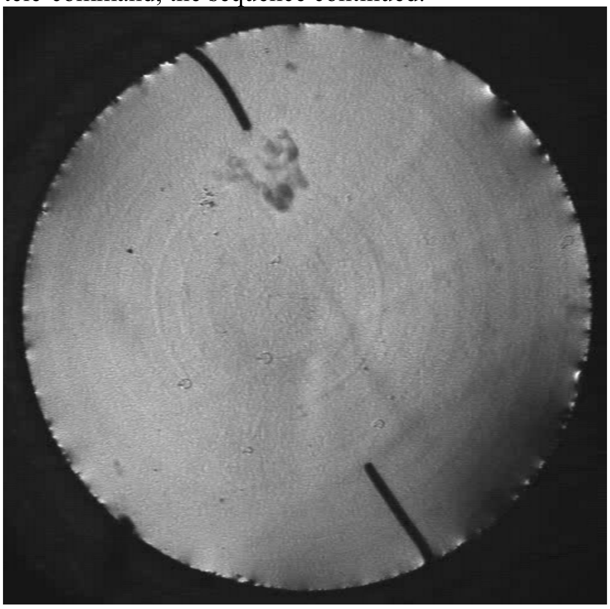

Fig. 10. Schlieren image from the flight showing the free surface from above and typical thermal ripples generated by evaporation.

The behaviour of the module during flight was normal except for the oscillating surface. After the gain was lowered, the surface regulation worked properly and ensured sufficient flatness for the tomographic views.
The quality of the transmitted images from the three cameras was good.

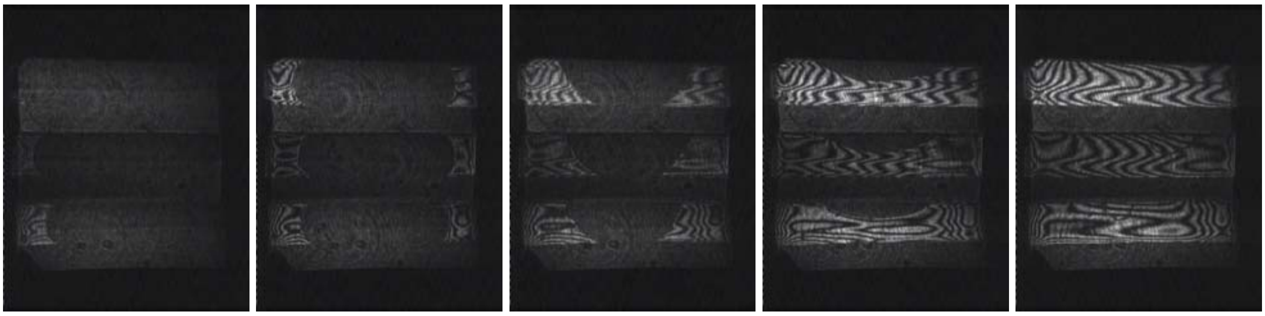

Fig. 11. Set of tomo images from one camera (three views on each camera) showing the filling sequence in microgravity. The free surface is upwards and the sequence starts from the left. In the first image there is liquid visible only on the left side but in next image the liquid has spread around the cylindrical glass and continues to fill the cell.

4.3 Result of the flight

The following results were observed directly after flight:

- Good thermal control of the cell during countdown and therefore at the moment of fluid injection. This is extremely important for tomography, as a good reference image is needed.
- No disturbances were noticed from pumps or centrifuges in the other modules.
- The initial injection of the fluid in the cell was perfect
- After the initial oscillations, a flat interface was observed during the flight due to the good quality of the Schlieren image and the automatic flatness control algorithm.
- The main scientific objective, to get quantitative measurements during different evaporation conditions was achieved. However, a full flight scenario could not be executed due to the initial oscillations.
- The interferometric tomography system worked perfectly.
- Images and data were recorded onboard.

5. CONCLUSION

All complex systems of the ITEL module such as liquid filling, surface regulation, interferometric tomography and Schlieren system worked successfully during the flight apart from the oscillations of the surface regulation. This problem could however be solved remotely by decreasing the gain of the regulation.
The automatic pressure control worked nominally. Tomographic reconstruction from the flight is underway at Lambda-X. The scientific evaluation is being performed by the PI.

6. ACKNOWLEDGEMENTS

The authors would like to take the opportunity to thank:

- ESA/ESTEC for their support, especially W. Herfs
- The mission scientific advisor: Prof. Dr G. Frohberg, University of Berlin.

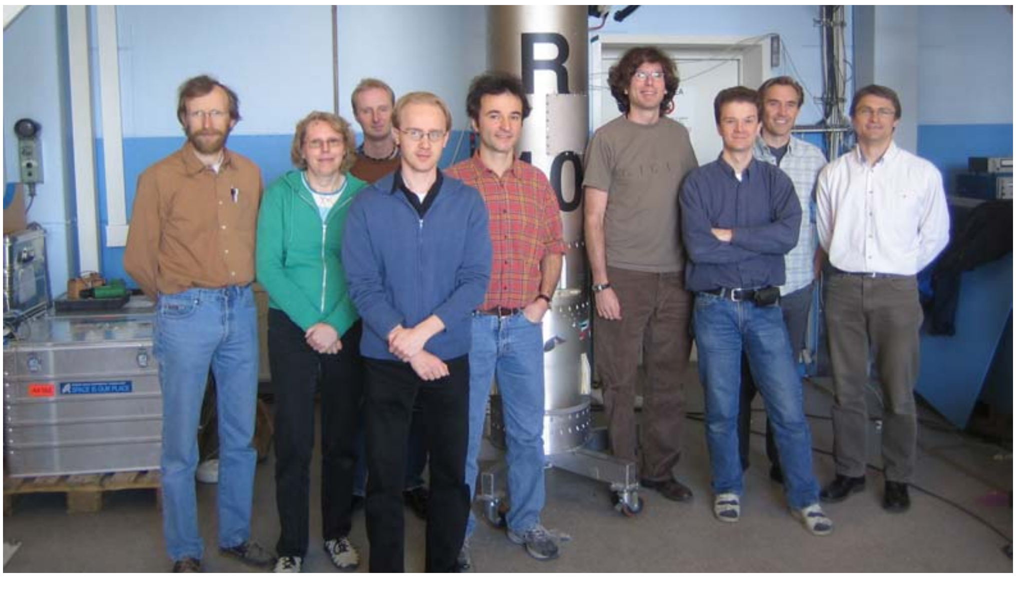

Fig. 12. ITEL team before launch