

Computer Simulation of Fluid- Physics-Module Operations on the First Spacelab Flight

Abstract The advantages of computer simulation in the utilisation of a Spacelab multiuser facility, namely the Fluid Physics Module, are discussed. Details are presented with particular reference to an experiment to study floating liquid zones under microgravity conditions (Expt. 1-ES-331), scheduled for flight as part of the First Spacelab Payload in September 1983.

Résumé On examine les avantages de la simulation par ordinateur dans l'utilisation de l'installation Spacelab à utilisateurs multiples, notamment le Module de Physique des Fluides. On présente les détails d'une expérience en particulier (1ES-331) destinée à l'étude des zones liquides flottantes en condition de faible pesanteur à bord de la Première Charge utile Spacelab.

Introduction

Experiment 1-ES-331¹ is one of seven experiments to be conducted in the Fluid-Physics Module (FPM) on the first Spacelab flight in September 1983. It is designed to study the mechanical stability of floating liquid zones which, aside from the purely scientific interest in the physico-chemical aspects of the interfaces, are of widespread application in the production of highly prized semiconductor materials for the electronics industry.

When the Spacelab project began in the mid 1970's, simpler use of space as an environment for research was envisaged: the investigator would submit the timing for his experiment and provide instructions for the Spacelab crew on how to operate it (for Expt. 1-ES-331, a preliminary proposal was sent to ESA in 1974). Meanwhile, technical specifications were laid down, after the grouping of several related experiments, for the development of a suitable multiuser facility, in the form of the FPM. The output to be returned to the investigator was to be a tape recording of housekeeping data and several reels of photographic film, in addition to the experiment hardware itself.

It now transpires that a much greater return than originally anticipated can be gained from the Spacelab FSLP experiments. Firstly, having realised how important human intervention is in fluid-mechanics research, much more effort is now being devoted to crew training, not only in the use of the facilities themselves but also in the aims and goals of the research project in the broad sense. The Payload Specialist's role then becomes more that of a research-assistant, rather than a mere 'operator'.

The recent decision to re-fly the Fluid-Physics Module on German Spacelab mission D1, thereby enlarging the user community, means that there is a growing need to supply not only the necessary hardware, but also the appropriate means to get the best out of it.

As noted in a recent review of experimental facilities², easy access is of paramount importance to the experimental investigator. However, it is not feasible for each to have his own engineering model, and a flood of paper work and sporadic visits to a remote workshop seem a poor substitute. This paper is an attempt to highlight some of the advantages of computer simulation of all, or at least of the more crucial, elements involved in the utilisation of a multiuser facility. The FPM itself, the real-time data downlink, fluid behaviour, and even the Payload-Specialist's actions can be simulated both for training purposes and for research in the development phase, where continuous interaction is required to arrive at an optimised standard sequence to be followed during the flight and to prepare contingency procedures.

Other related uses of computer simulation, such as in the design of the sophisticated and costly facilities themselves, where it can help to foster good contact between scientists and engineers, or the more usual application for automatic experiment control, are not dealt with here.

What to simulate

The flow of information begins with the investigator when he thinks out the scheduling, and passes to the crewman who enters the commands at the FPM control panel; the information from the FPM itself is then recorded and delivered back to the investigator. Ideally, the investigator would like to have access to all the links in the chain — operator, FPM and data-acquisition system — at his place of work. As this is not realistic, his best alternative is to model their behaviour, and the cheapest method would appear to be computer simulation. Freed from the housekeeping work-package that sharing a multiuser facility in a multiuser laboratory imposes, the investigator can then concentrate on the essential aspects of his own experiment and research.

The FPM is a 50 kg device³ to be mounted in the Spacelab Materials-Science Double Rack (MSDR), which 'manages' the data acquisition (apart from the films inside the FPM). Present planning for the First Spacelab Payload (FSLP) foresees that real-time access to the data downlink and direct voice contact with the

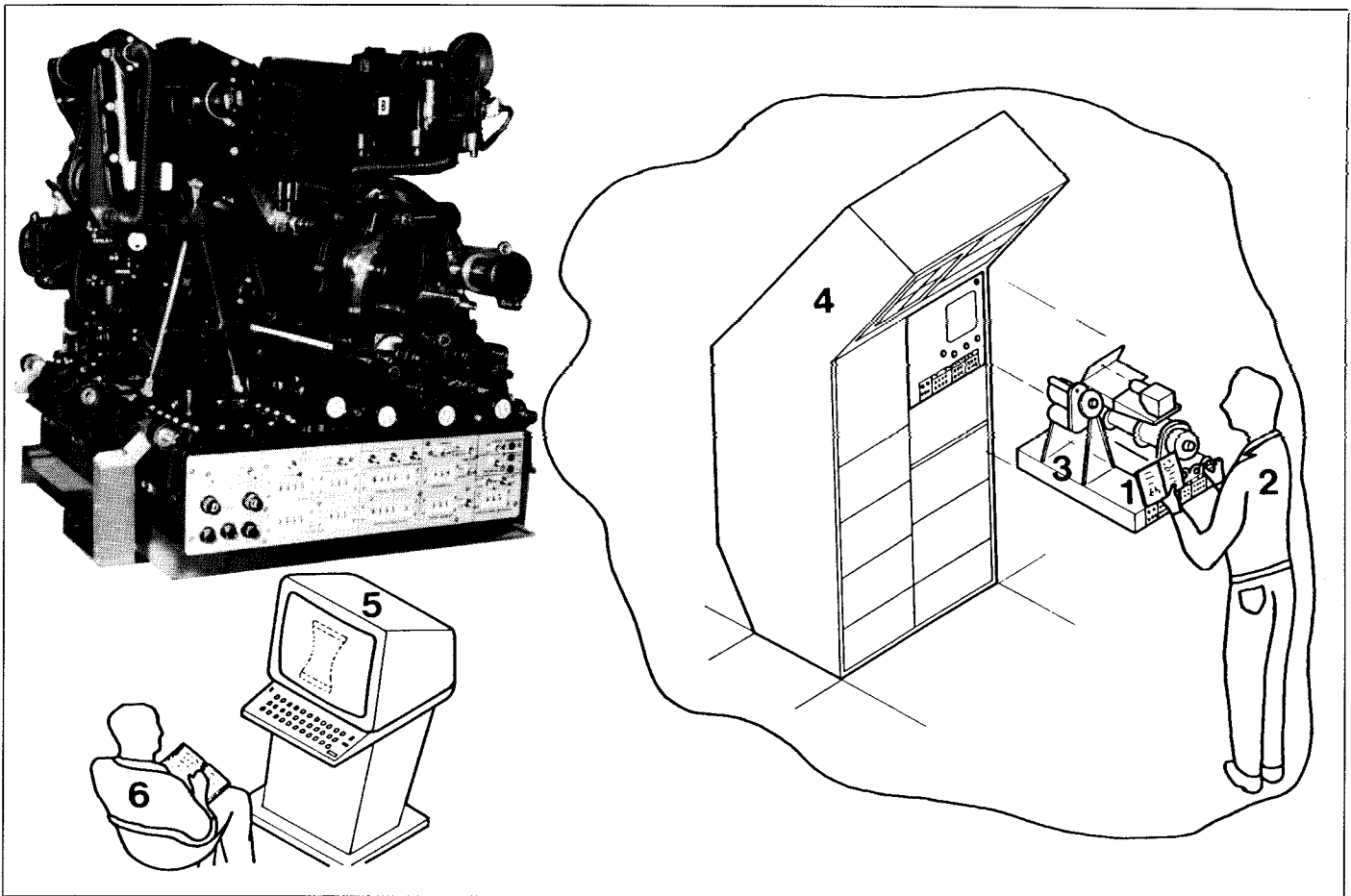


Figure 1. Information-processing elements in in-orbit experimentation: 1. Handbook of Experiment Procedures; 2. Payload Specialist; 3. Fluid-Physics Module; 4. Data-Acquisition System; 5. Data Downlink; 6. Investigator

Payload Specialist in charge of the experiment, will be provided to the fluid-physics investigators (Fig. 1). This will allow real-time monitoring of events and, if the need arises, on-the-spot correction of the experiment sequence or at least discussion with the Payload Specialist in order to achieve the best return. Most FPM experiments are split into two runs, in our case lasting 30 min each, with 9 h between runs; lack of proper feedback from the investigator in this intervening period would waste much of the effort that has been invested.

Although some computer procedures for fluid-behaviour simulation will be mentioned here because of their special interest for crew training, it must be borne in mind that knowledge of actual fluid behaviour is what is sought, and the fluid-mechanics computational problem is a separate research entity. Another computer application not dealt with here is computerised data reduction from photographic film, to which a great deal of effort needs to be devoted.

For simulation purposes, the Payload Specialist can be considered as a robot, closely following the steps laid down in the Handbook of Experiment Procedures (HEP) and not reacting to any feedback from the FPM. He introduces the appropriate parameter values and waits, according to what the procedures say, until the next input is due for entry. The aim of the simulation is to arrive at a rough idea of times and step-sequence compatibility. It is possible to go further to some kind of low-level interaction, but it must always be borne in mind that human-interface simulation can only be achieved if the delicate mechanisms of intelligent human responses are disregarded.

Table 1 shows a portion of the instruction set belonging to Run 1 of Experiment 1-ES-331. Preparation of these procedures (just the nominal sequence has more than 300 steps) was a time-consuming task, several meetings being necessary with the crew and many hours of familiarisation with the facility, all of which implies too much travelling. Computer simulation could alleviate this expenditure of time (and money).

Operator simulation

Table 1. Detail of actions in the Handbook of Experiment Procedures for Exp. 1-ES-331, Run 1

Step	Description	Value
..
..
..
.4	Set camera: camera mode exposure interval frames	B CINE .25 1 400
.5	Start camera	
.6	Start translation CAUTION: a perfect cylindrical zone with well attached edges must be obtained. If not, inject more liquid and help with rotation or vibration. Do not forget to get back to current position.	
.7	Set translation: FP position (mm) FP speed (mm/s) RES position (mm) RES speed (mm/s) Comment: from point B to point C (Fig.1). Cylindrical evolution.	108.8 .999 091.0 .835
.8	Set camera: camera mode exposure interval frames	B BRIEF .25 1 100
.9	Start camera	
.10	Start translation CAUTION: be sure the zone does not break until phase 7. From now on, there is a high risk of breakage. Avoid any unwanted perturbation.	
2.	AXIAL OSCILLATION Comment: the aim is to excite the first natural frequency of the zone (Fig.2). If that is achieved large amphora-like oscillations must appear.	
.1	Set oscillation: frequency (Hz) ramp amplitude (mm)	0.10 FAST .5
.2	Comment: select display mode 0 if possible. Set camera: camera mode exposure interval frames	B BRIEF .25 1 100
.3	Start camera	
.4	Start oscillation	
.5	Set oscillation: frequency (Hz)	0.00
..
..
..

With the need for continuous updating, the experiment step description for 1-ES-331 has been kept in a computerised data file which, for simplicity, we call the HEP file. The payload operator's actions can be simulated (in as far as stated above) by means of a computer procedure (called 'OPE') which, when interrogated every time cycle (every second, for instance) by the main procedure, simulates the actual state of the FPM Control Panel. A simplified flow diagram is presented in Figure 2.

Clock pulses cause the OPE procedure to be run once every cycle; the cycle time must be longer than the maximum time needed for OPE execution if a 'busy' signal is to be avoided. The OPE procedure has point access to the HEP data file, loads output buffer with status signals T , C , ..., and variables F_p , F_s , N_f , ... (Fig. 2), and maintains two internal variables for housekeeping: P , the operator's finger position on the HEP, and W , the current waiting time (for example, if 'shot 100 frames at 1 s interval' is read, and there is to be no feedback, the operator has to bear in mind that he must wait 100s before a new shooting sequence can be initiated, though he can preadjust some other settings in the meantime).

FPM control-panel simulation

Once the FPM control-panel's status is known from the output of OPE, a new computer procedure can be developed to provide a realistic simulation of the settings (dials, lights, etc.) as seen by the operator; let us call this display procedure 'SET'. This procedure will require a high-definition graphics screen and a permanent mask with viewing slots to which the variables can be fed at a given refreshing rate (slower than the OPE cycle from which the values would be drawn). Its role in the overall simulation project is shown in Figure 3.

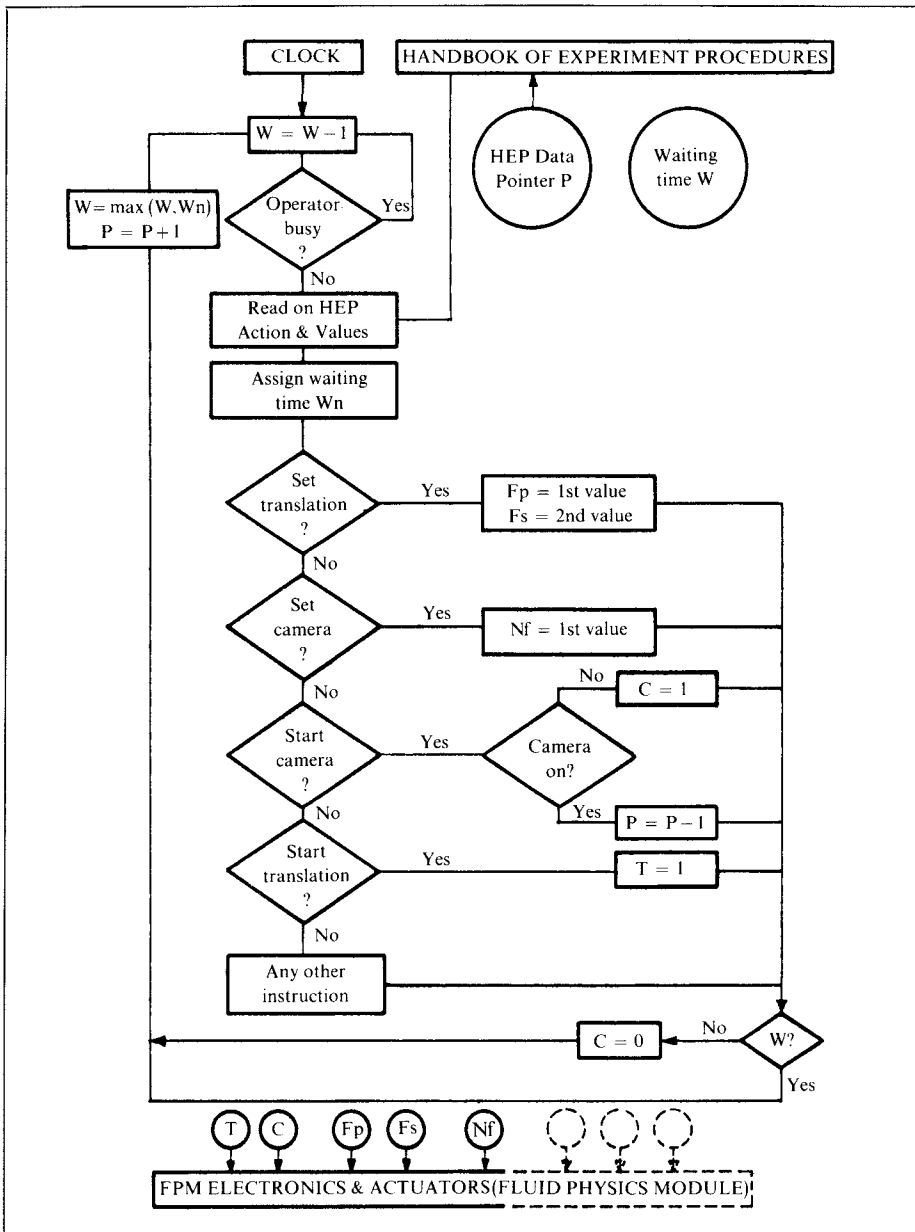
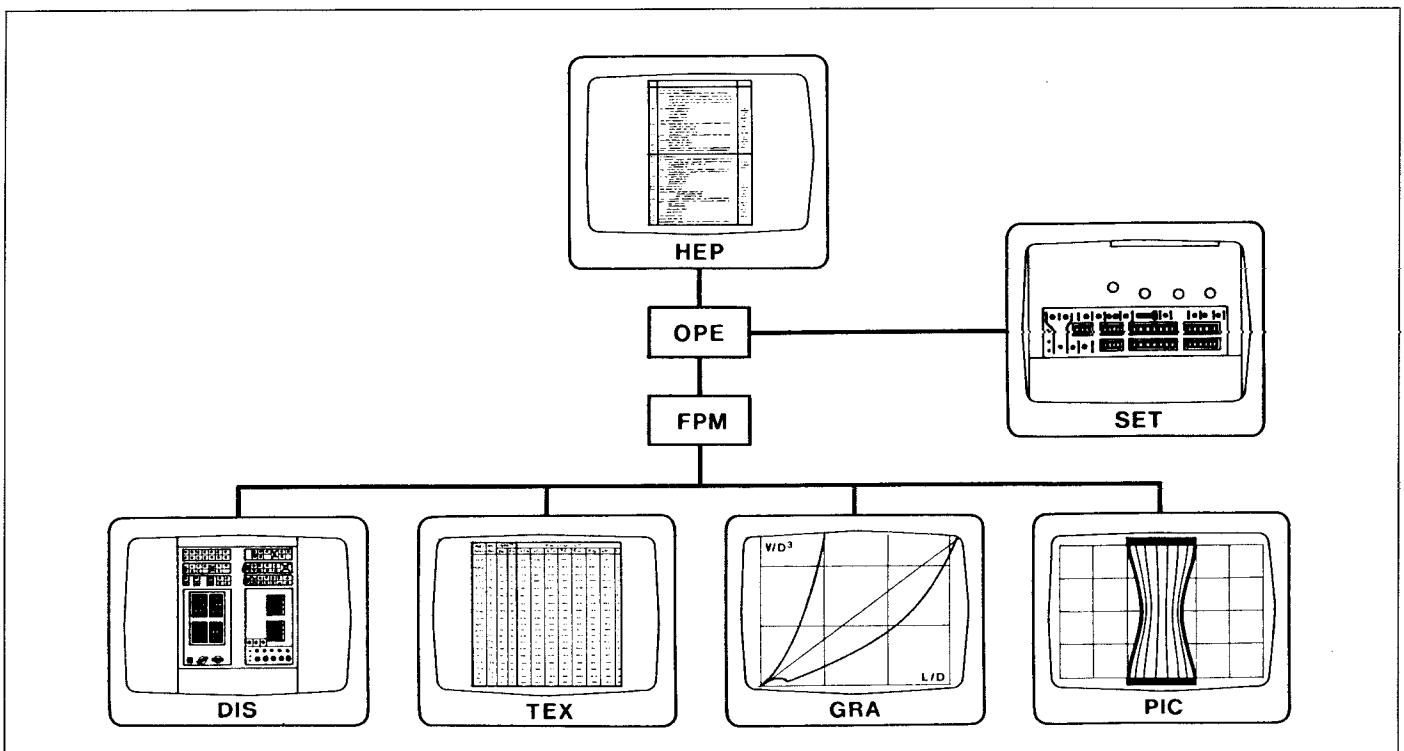


Figure 2. Flow diagram for OPE, the operator simulation procedure. Input: instructions written in the Handbook of Experiment Procedures. Output: status signals T, C, ... (T = translation on, C = camera on) and variables Fp, Fs, Nf, ... (Fp = Front Plate Final Position, Fs = Front Plate Axial Speed, Nf = Number of Frames). Two housekeeping variables are needed: P = current pointer position in HEP file, and W = current waiting time (operator busy or shooting taking place)

Figure 3. General diagram for the overall simulation of Fluid-Physics Module experiments. Information inputs from the Handbook of Experiment Procedures (HEP) are processed by the Operator (OPE) and the Fluid-Physics Module (FPM) procedures, and output in various formats: SET shows the settings on a plotted control panel; DIS shows the displays of the MSDR Central Console; TEX shows the data downlink in text form; GRA shows the liquid column status in graphic form; and PIC shows a computer-generated image of the floating zone



For present FPM utilisation, this readout simulation might be something of a luxury, but for future FPM improvements and for a foreseeable new era of computer-assisted FPMs, for which a microprocessor will take over the housekeeping burden, it could be a very valuable tool.

FPM simulation

At this stage a working mathematical model of the FPM is required, the aim being to transform the input parameters from OPE to the time-dependent output used in the presentation modes shown in Figure 3.

On the first flight, the Payload Specialist will have access to the real equivalents of the SET, DIS and PIC format outputs, i.e. he will be able to glance at the FPM control panel and see the settings (simulated by SET); he will be able to examine the displays in the MSDR Central Console (simulated by DIS) and watch the liquid through the small window in the FPM front cover (simulated by PIC). The Payload Specialist has no time in flight to note down every detail of what he actually does (his actions are, however, recorded in TEX) and the graphics format (GRA) would demand some unscheduled computations on his part. On the other hand, the investigator on the ground receiving the downlinked data stream only has access to the TEX output and the voice link, but cannot see the actual liquid's behaviour (PIC). In mid-term planning, the possibility of having a Spacelab-to-ground video link for fluid-physics experiments might be considered.

For a working simulation, the FPM can be assumed to behave ideally because it has been designed as a precision apparatus to allow the application of well-controlled disturbances, with little internal 'noise'. This is the main difference between the pioneering demonstrations on Skylab-IV and the accurate experiments to be conducted on Spacelab. Therefore, only direct linear outputs will be assumed, without transients, ripples, cross-couplings, etc. The actual FPM front-plate position, for instance, can be derived from

$$Fp = Fp_{old} + Fs_{new}(T - T_{start})$$

from $T > T_{start}$ until $(Fp_{new} - Fp)(Fp_{new} - F_{old}) > 0$

where Fp is the front-plate axial position, Fs is the front-plate axial speed, and T is time.

A further refinement in FPM simulation can be achieved by using the computer's standard loudspeaker to generate sounds resembling those of real FPM operation, such as the clicking of the camera at every shot (normal modes are 1 fps and 8 fps).

Ground-link simulation

It has already been mentioned that Experiment 1-ES-331 involves two runs of 30 min each, 9 h apart. In total, the FPM sends 20 words of 16 bits each (4 for identification and 12 for data) every second, which for 1-ES-331 reduces to 8 binary status signals plus 9 variables. With a carefully thought out format, a well-trained investigator will be capable of grasping all the information as it comes down, and the benefits of occasional feedback to the Payload Specialist must not be overlooked.

TEX support at least should be provided in real time to the investigator, both on screen and in hard copy, taking into account that only one line of text every second is involved. The GRAPHIC presentation should be of great value because of its easy to grasp nature and it demands only a plot routine, either on CRT or paper.

In any case, a requirement must be set for converting the coupled motion of the reservoir to liquid volume units, because of the handicap the present FPM has in this respect; namely

$$V = (Fp - Rp) A$$

where V represents the liquid volume in the floating zone, Fp the front-plate axial position, Rp the reservoir axial position and A the effective reservoir area, which is a constant of the apparatus.

Table 2 is a printout of the TEX procedure (see also Fig. 3).

The nominal configuration for Exp. 1-ES-331 is a long cylindrical liquid bridge held between two equal end discs by surface-tension forces. The liquid column is subjected to very well controlled mechanical disturbances: liquid-volume variations, disc separations, disc vibrations, independent or combined disc rotations and lateral disalignments. Aside from these disturbances, other singular events take place during the experiment because of the choice of column formation procedure: initially the zone is empty and liquid is fed through a centred hole in one of the discs (the liquid emergence is a very complex phenomenon); the liquid boundary then advances over the disc surface (the spreading theory is also an unresolved problem) until it reaches the disc's edge and gets anchored to it; the spherical cap thus formed is filled with additional liquid until it grows large enough to make contact with the opposite disc, where fast spreading takes place (this aspect is the subject of Exp. 1-ES-327). Moreover, controlled breakage of the liquid column and a recovery procedure involving coalescence of the two spherical gaps formed are planned. The final liquid removal from the zone (sucking from the syringe-like reservoir) is so complex that a manual cleaning procedure will be followed by the operator.

The investigator derives the information he needs by monitoring the shape of the free surface – nearly always axisymmetric – and the internal fluid motion which is tracked via small solid tracers premixed with the working fluid.

Simulation of liquid behaviour

TIME min:sec	STEP TIME	STATUS		V A L U E S										
		TRFR	OHEC	L/D	V/D ³	FTP	REP	FRS	RRS	OR	OF	LAT	TMP	g/s
0: 0	0			0.00	0.00	0.0	0.0	+0	+0	.0	0.00	0.0	1.0	3.5
0: 1	1			0.00	0.00	0.0	0.0	+0	+0	.0	0.00	0.0	1.0	3.5
0: 2	2			0.00	0.00	0.0	0.0	+0	+0	.0	0.00	0.0	1.0	3.5
0: 3	3			0.00	0.00	0.0	0.0	+0	+0	.0	0.00	0.0	1.0	3.5
0: 4	4			0.00	0.00	0.0	0.0	+0	+0	.0	0.00	0.0	1.0	3.5
0: 5	0	**		0.00	0.00	0.0	0.0	+0	+0	.0	0.00	0.0	1.0	3.5
0: 6	1	**		.00	0.00	.1	.1	+0	+0	.0	0.00	0.0	1.0	3.5
0: 7	2	**		.01	0.00	.2	.2	+0	+0	.0	0.00	0.0	1.0	3.1
0: 8	3	**		.01	0.00	.3	.3	+0	+0	.0	0.00	0.0	1.0	3.1
0: 9	4	**		.01	0.00	.4	.4	+0	+0	.0	0.00	0.0	1.0	3.1
0:10	5	**		.01	0.00	.5	.5	+0	+0	.0	0.00	0.0	1.0	3.1
0:11	6	**		.02	0.00	.6	.6	+0	+0	.0	0.00	0.0	1.0	3.1
0:12	7	**		.02	0.00	.7	.7	+0	+0	.0	0.00	0.0	1.0	3.1
0:13	8	**		.02	0.00	.8	.8	+0	+0	.0	0.00	0.0	1.0	3.1
0:14	9	**		.02	0.00	.9	.9	+0	+0	.0	0.00	0.0	1.0	3.1
0:15	10	**		.03	0.00	1.0	1.0	+0	+0	.0	0.00	0.0	1.0	3.1
0:16	11	**		.03	0.00	1.1	1.1	+0	+0	.0	0.00	0.0	1.0	3.1
0:17	12	**		.03	0.00	1.2	1.2	+0	+0	.0	0.00	0.0	1.0	3.1
0:18	13	**		.03	0.00	1.3	1.3	+0	+0	.0	0.00	0.0	1.0	3.1
0:19	14	**		.04	0.00	1.4	1.4	+0	+0	.0	0.00	0.0	1.0	3.1
0:20	15	**		.04	0.00	1.5	1.5	+0	+0	.0	0.00	0.0	1.0	3.1
0:21	16	**		.04	0.00	1.6	1.6	+0	+0	.0	0.00	0.0	1.0	3.1
0:22	17	**		.04	0.00	1.7	1.7	+0	+0	.0	0.00	0.0	1.0	3.1
0:23	18	**		.05	0.00	1.8	1.8	+0	+0	.0	0.00	0.0	1.0	3.1
0:24	19	**		.05	0.00	1.9	1.9	+0	+0	.0	0.00	0.0	1.0	3.1
0:25	20	**		.05	0.00	2.0	2.0	+0	+0	.0	0.00	0.0	1.0	3.1
0:26	21	**		.05	0.00	2.1	2.1	+0	+0	.0	0.00	0.0	1.0	3.1
0:27	22	**		.06	0.00	2.2	2.2	+0	+0	.0	0.00	0.0	1.0	3.1
0:28	23	**		.06	0.00	2.3	2.3	+0	+0	.0	0.00	0.0	1.0	3.1
0:29	24	**		.06	0.00	2.4	2.4	+0	+0	.0	0.00	0.0	1.0	3.1
0:30	25	**		.06	0.00	2.5	2.5	+0	+0	.0	0.00	0.0	1.0	3.1
0:31	26	**		.07	0.00	2.6	2.6	+0	+0	.0	0.00	0.0	1.0	3.1
0:32	27	**		.07	0.00	2.7	2.7	+0	+0	.0	0.00	0.0	1.0	3.1
0:33	28	**		.07	0.00	2.8	2.8	+0	+0	.0	0.00	0.0	1.0	3.1
0:34	29	**		.07	0.00	2.9	2.9	+0	+0	.0	0.00	0.0	1.0	3.1
0:35	30	**		.08	0.00	3.0	3.0	+0	+0	.0	0.00	0.0	1.0	3.1
0:36	31	**		.08	0.00	3.1	3.1	+0	+0	.0	0.00	0.0	1.0	3.1
0:37	32	**		.08	0.00	3.2	3.2	+0	+0	.0	0.00	0.0	1.0	3.1
0:38	0	*		.08	0.00	3.3	3.3	+0	+0	.0	0.00	0.0	1.0	3.1
0:39	1	*		.09	0.00	3.4	3.4	+0	+0	.0	0.00	0.0	1.0	3.1
.....
.....

Table 2. Suggested format for real-time presentation of the downlinked data stream for Exp. 1-ES-331

In parallel with theoretical and experimental studies (using plateau tanks), we have also been working on computer simulation of fluid behaviour. A computer procedure has been developed that predicts the outer shape of a quiescent zone based on FPM input data, the stability limits being implemented for volume variation, disc separation, disc-vibration frequency and solid-body rotation. Another computer procedure gives the dynamics of breakage (shapes and motion). Computer procedures have yet to be developed for the rest of the processes mentioned above.

Unfortunately, with the available facilities, the computation takes too long for real-time simulation: tens of seconds for equilibrium-shape generation (inverting an algebraic implicit expression) and some hours for breakage evolution (following a finite-difference scheme).

There appear to be two possible approaches to overcoming this slowness problem: to prepare a large store, load the most representative data and interpolate in a real-time search, or to develop faster empirical algorithms that would give an approximate solution sufficiently quickly at the expense of absolute accuracy.

Having reached the point where operator, FPM, working liquid, data acquisition and even data analysis seem amenable to some type of computer-simulation procedure, one might well ask what then is the point of going into space to experiment? In our view, to simulate is to reproduce part of a system behaviour by modelling in order to ease the study of the remainder; and that is exactly the point of the space-based experiments, to study the unknown element.

Conclusion

An investigator using unfamiliar equipment in a new environment is bound either to spend too much time mastering the new facilities, or to make only partial use of the capabilities being provided.

It has been realised that much better support to investigators using multiuser facilities could be provided by computer simulation of all or part of the external elements entering the information loop, from the input of ideas to the output of experimental data (always from the investigator's point of view).

The provision of computer models would greatly benefit new and more experienced scientists alike, by reducing travel time and releasing effort that could be better devoted to the research aims and not to the means. Its benefits for crew training are obvious, and the relevance for overall improvement of the FPM (not just the hardware, but also its utilisation) is beyond question.

Bearing in mind the above advantages and ESA's involvement in fluid physics under the Microgravity Research Programme, it would seem advisable to consider pursuing these types of computer-simulation activities as a parallel line of support to the already envisaged neutral-buoyancy-experiment facilities to be provided to the Spacelab materials-science user community.

References

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