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"Experiment Classes and Future Facilities for Fluid Science Experimentation"

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EXPERIMENT CLASSES AND FUTURE FACILITIES FOR FLUID SCIENCE EXPERIMENTATION

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Lectures Notes for the ICTP Workshop on Space Physics:
Materials in Microgravity

1. INTRODUCTION

In what follows an attempt is made to categorize the Fluid science experimentation areas and to consider a number of aspects that appear of interest in deriving guidelines for the design and operation of multiuser facilities. In particular requirements of FS experimentation and of the Columbus scenario will be discussed for the operational conditions that affect the microgravity experimentation in Fluid Sciences; criteria for the conception of new multiuser facilities are given that are able to cope with the requirements of the user community and with the constraints of the APM.

The requirements from the user community and the (evolving) APM environment and features suggest Telescience as the best operation mode for reaching the goals of Fluid Science activities in a near future. It is therefore appropriate to consider the implications of the FS Facilities design and operation on Telescience and on the Space and Ground segments of the Columbus project.

2. FLUID SCIENCE EXPERIMENTS

All the Microgravity Sciences experimentation is related to the behaviour of fluid in a microgravity environment; however, conventionally, one may refer to Fluid Science experiments as those that utilize the typical instrumentation and diagnostic equipment in use in classical Fluidynamics and Physics of Fluids for the study of the thermofluidynamic fields that are established inside fluid specimens (generated by external or internal stimuli). This implies that often in Fluid Science (FS) transparent fluids are employed together with illumination, visualization and non invasive measurement techniques.

The main feature that characterizes most of the FS experiments is that no specimen retrieval is necessary at the end of the run, since all the measurements are performed during the course of the experiments.

A first classification of the possible areas of research can be made in terms of Basic and Applied researches (See Fig. 1, Ref. 2); these last have a special meaning in a microgravity context and indicate experimentation performed in support of the applicative Microgravity Sciences (i.e. Material, Life and Engineering Science) simulating the processes that take place in fluid systems.

Basic FS researches themes need not to be discussed in this context.

Support research themes for MS, LS and ES are typically suggested by the need of understanding the complex processes that cannot be monitored and or visualized during the experiment itself but can only be assessed on the basis of an end product (e. g. metallographic examination of a solid specimen, separation during an electrophoresis process, heat transfer coefficient of a heat pipe).

Typically the end product is the result of many, time integrated, heat and mass transfer processes in multiphase media; FS simulation experiments try to separate effects, to understand cause-effect relationships by looking inside the specimen, and to follow the processes on-line with the aim of optimizing the process itself (e. g. crystal growth, cell culture, heat transfer processes).

Past experience tends to show that the success of MS and LS processing in microgravity is achieved through a number of steps:

1. Exploratory experiment, that qualitatively assesses the microgravity relevance and benefits
2. Computer modelling and simulation experiments for mastering the relevant phenomena and processes
3. Prototype experiment for Space processing

For most of the application areas we are still at the first step; it is expected that many other simulation FS experiments will be suggested when Space activities in Material and Life Sciences will be resumed.

Many times support experiments try to fill the gap between initial exploratory experimentation and Space processing with the aim of separating different effects for a better comprehension of the phenomena, of understanding the processes, measuring parameters, mastering and controlling the phenomena and, eventually, optimizing the conditions for Space processing.

Geometry, aspect ratios, dimensions, Prandtl and Schmidt numbers are the typical parameters that are of interest for devicing simulation experiments; however, support experiments suffer sometimes by the lack of "equivalent", transparent, low temperature, chemically inert fluids that can simulate the behaviour of the fluid of interest.

According to the above mentioned types of experimentation, another categorization of the FS experiments could be made in terms of the experiments objective and of the degree of sophistication: quick-look exploratory or quantitative data collecting experiments.

This second classification may have a greater impact on the Facility requirements (duration of experiments, Facility type and operations) that will eventually dictate the design criteria for the Flight and Ground equipment.

Short duration experiments, of exploratory type, that require a large percentage of crew involvement (setting, manipulation, termination) will be accepted with difficulty in a Columbus context, unless an ad hoc multiuser facility is being conceived that is very flexible and that plays the same role of a general purpose wind tunnel in aerodynamics.

For the quantitative experiments the type of the diagnostics, the telescience operations, the long duration of the experimentation, the degree of complexity of long lasting multiuser facilities suggest that there is no reason why the shirt-sleeve way of operating the Facility should prevail and the experiments be conducted as in Ground Laboratories. The unique environment and the implications of Space operations (large costs and long times for preparation) makes the microgravity experimentation completely different from that carried out on ground, where learning by mistakes is a current practice. Previous experience with FS facilities for Spacelab for which the shirt-sleeve ground Laboratory approach was familiar to the users, to the Facility designers and Manufacturers and to the Payload Specialists is not applicable to the design of Columbus FS Facilities.

In fact, it would not be suitable to repeat, in a Columbus context, the Spacelab (SL-1 and D-1 missions) operations that have shown how difficult it is to operate a multiuser FS facility on tight time schedules. High level expertise and long PS training avoided major troubles from the very strict sequence of operations, the unexpected events and the impossibility of keeping neither the absolute timing of the experimnet (i.e. the MET of the experiment start) nor the relative time (i.e. the scheduled experiment duration).

A final consideration may be of interest for future Fluid Science experiments to be carried out in the Columbus segments.

A large number of Material and Life Science experiments in microgravity look for the diffusion controlled processes, not jeopardized by the buoyancy induced convective motions. The difficulty is that, even though no convective motion is induced in orbit, the processes are not easily controlled: controlling purely diffusion processes in microgravity might prove as difficult as controlling ground "natural" convection (due to the one g-level). In fact speaking of zero-g, diffusion controlled processing does not imply that one can control the diffusion; in most of the practical cases (unsteady conditions, three dimensional fields) the diffusion processes could be evaluated but not controlled (e.g. the concentration gradients evolution over a growing crystal surface). In some cases, instead, an amount of controllable convection could be beneficial for the problem under consideration.

The above remarks lead to three preliminary considerations about the experiments of interest for Columbus elements, that represent the input to FS Facilities design criteria:

1) Special, general purpose microgravity Facilities have to be conceived to carry sequences of short duration exploratory experiments
2) Long duration, quantitative FS experiments will be run in a mode that may be entirely different from that in use in ground Laboratories; e.g.controlled directly by the PI from ground
3) Experiments that would benefit from the control of convective transports should be accomodated in special Facilities with provisions for inducing a controlled amount of convections in the test specimens.

3. CONSIDERATIONS ON FS FACILITIES DESIGN

Designing a facilitiy for Columbus elements today, is a difficult task because of the possible assumptions about the configurations of in orbit and of ground segments. The risk is that the design will be nothing but an exercise that will generate a number of requests to ESA or to NASA. An additional difficulty exists: the S/S scenario will be necessarily evolving in time so that a Facility designed for one configuration (say the Initial Orbit Configuration, IOC) will not be optimized for a subsequent, more favourable scenario (and viceversa). To obtain a sufficient degree of efficiency, all during the entire Facility life-time one must design the Facility as a modular system that evolves in time together with the Space and the Ground segments.

Let us try to make a number of feasible assumptions in the scenario that would represent the requirements for a convenient exploitation of the microgravity environment and that will lead to the specifications of the operational scenario in which FS facilities should operate.

The assumptions refer to the following points:

1. Type of skill and amount of crew time available on board
2. Life time of the Facility
3. Manned and /or man-tended periods during the Space Station life
4. EDRS characteristics
5. Ground segment and support Centres

Ideally the user would select the above 5 factors to optimize the scientific return of the Space operations and then design the Facilities accordingly; in practice many of the above factors are imposed by considerations other than users requirements.

In what follow we try to identify what are the parameters that affect the Facility design and to derive applicable guidelines for conceiving new Facilities to be operated, ten years from now, in Columbus elements.

Man will be available in Space and help running experiments. In the final S/S and Columbus Scenario it appears logical and safe to assume that crew members (or PS) will:

a) perform all the needed manipulations on board the APM (installation, removal and storage of samples, facility setting, etc.) together with any minor equipment repair, refurbishment and Facility upgrading.

b) perform the major Facility settings during the man-tended phase on the MTFF, together with the loading and removing of the samples canisters (or similar) and with equipment repairing, refurbishment and upgrading.

The above requests are in line with the probable lack of specific scientific expertise on board during the entire operation time of the Space equipment. In the above scenario the PI himself should conduct his experiment and interact with it in a telescience mode by receiving data on-line and by sending appropriate commands from an equipped user Support and Operation Centre.
When specifically required and in very special cases the PI himself can fly and perform his experiments on board (as it was done in SL-3 with the USA Drop Dynamic Module).

There are different times that are related to the Facility operation and that strongly affect its design: Platform life time, Facility life-time, number of hours of operation of the Facility, obsolescence of the technologies utilized in the equipment, projection in time of the users interests. All these time factors must be taken into account in conceiving a Columbus Facility. Synchronization and matching of these time factors are necessary to mantain acceptable values of the benefit: cost ratio during all the operational life of the Facility. However the contraddicting requirements and the difficulty of predicting these time factors call for great flexibility and modularity of the Facility and its subsystems.

Platform construction schedule will influence the Facilities design criteria. Furthermore the decisions related to the presence of the man on board of the Columbus elements will also have a direct impact on the microgravity experimentation. A good example is the debated problem of the Assured Crew Return Capabilities (ACRC) that could be solved by an orbiting Safe Haven, by a Crew Emergency Return Vehicle (CERV) or by an expendable vehicle to be sent from ground; the selected solution will strongly influence the meaning and the time extension of the Early Man Tended Capability (EMTC). If this period is substantially extended in time, or if emergencies (or other reasons) occur that suggest the Crew to be evacuated for long periods of time, then one could be forced to operate experiment Facilities in a man-tended mode (even in the APM). Facilities that will exhibit the greatest utilization will be those that can be operated both in a manned and in a man tended mode and that are designed accordingly.

Telelink through DRS system, is also an essential factor in the Facility design. The main features of specific interest are: coverage, time delay in data transmission and number of Mips available; limitations in any of these factors reduces the Telescience operability of the FS Facility.
FS facilities and experiments are those in greater demand of telelinks for Telepresence, Telemonitoring, Telecontrol and for on-line quantitative data acquisition (typical two-dimensional and three-dimensional diagnostic data request a high rate data acquisition system). Partial coverage, as that resulting from two (instead of three) orbiting European Data Relay Satellites may be detrimental for Telescience implementation and may suggest the implementation of special devices (e.g. expert system and/or Artificial Intelligence) in the Facility to guarantee its operability during the Loss of Signal (LOS) periods. Time delays in the downlink and uplink transmission also limit the interactive operations of the PI during the experimentation; for instance it would be very difficult to manage experiments whose characteristic times are much shorter that the delay times than occur between the control data (being sent to Space) and the video images, corresponding to the control data acquisition (being received on ground).
Typically diagnostic equipment for Fluid Science experimentation generate a very large amount of data (video images, thermography, interferometry, holography, etc) that easily

saturate the DRS channels, if no provision is taken (e.g. data compression, on board pre-elaboration, on board decision making, etc) that also affect the design of the subsystems of the Facility.

Ground segment and Support Centres where preflight, during flight and post flight activities take place, are essential elements in the design and operation of FS multiuser Columbus Facilities. Specific FS discipline oriented requirements on Ground Segment come from: 1) the area of investigations (indicated in the previous Section), 2) the typical parameters to be measured and controlled, 3) the fact that Fluid Science experiments are often more demanding in terms of on-line crew attendance and, finally, 4) the fact that very often real time and/or off-line results could be made available much faster, since the PI is not supposed to wait until the sample is returned back to him for examination.
These considerations explain why an FS experimentation could be less dependant on crew schedule (PS return to ground for APM, refurbishment schedule for MTFF) and suggest that recording and storage of experiment parameters on-board support systems, like tapes, films, holographic plates, etc., that need to be brought to ground for data retrieval, should be avoided, whenever possible, in FS experimentation.
Telescience operational philosophy for Fluid Science is, therefore, really needed and possible at the same time; it allows the user (Principal Investigator) to be directly involved in the run of his experiment and, consequently, guarantees, with respect to the traditional way of performing scientific tests, a number of relevant advantages. The Telescience mode of operations is aimed at obtaing the following goals:
1) a more rational conduct of the experiment because of the control and involvement of the PI that, on the basis of his expertise, can modify the experimental conditions in order to best utilize the available time; 2) on-line quick analyses and experiment assessment that will contribute to greater scientific returns; 3) utilization of the support of ground facilities (that do not suffer by the typical Space contraints of volume, mass, power, etc.). This philosophy will prove to be a powerful driving force and will lead to the implementation in Space of new technologies such as Automation and Robotics, Expert Systems, Artificial Intelligence, etc.

Telescience operational mode is obviously an efficient way to drastically reduce crew tasks and activities allowing a less stringent need on training astronauts about unfamiliar scientific operations and to focus their attention in systems management.

4. GUIDELINES FOR A FLUID SCIENCE LABORATORY FSL DESIGN

In an APM context the Fluid Science Laboratory (FSL) is intended as a multirack (say 4 racks), multifacility apparatus in which FS experimentation takes place.

It is obvious, from the above considerations, that from the microgravity users point of view the best solution would obviously be to dispose of a high skill on board, of a long life-time Facility that could be operated, at any time, also from ground by the PI sitting in his Home Base with the support of all the possible expertise (man, machines, Expert systems, etc). This is a wishful thinking that is closer to a dream than to reality . Strong compromises will have to be found in recognition that the microgravity users are not the only people utilizing the Space Station and that the decisions on the Space Segments are taken mainly on the basis of other considerations.

To avoid stronger and stronger conditioning of the Columbus environments, must try reduce the Payload in the Space platform by locating on board the essential minimum in terms of Hardware and Software and by removing and bring to ground whatever possible (man, H/W, S/W, Expert Systems, Electronics) where they can operate, grow, be upgraded and substituted without major problems and without interfering with Space systems.

FS diagnostics should, for instance, make extensive use of all the devices for transmitting data to ground (e.g. digitation, TV cameras, on-board preelaboration) and should take advantage of on-ground elaboration facilities (to be regarded as an essential complement of the on-board diagnostic systems). Each on-board Facility must have, as ground counterpart, equipment and structure that allows support activities to be carried out: designing a FS facility for Columbus imply also the design of ground Facilities (Fig.2).

For instance it is necessary to set up dedicated laboratories on ground endowed with the typical research tools in use in the field of microgravitational fluidynamic, (e.g. optical laboratories with thermocameras, Schlieren devices, interferometry, illumination systems, etc.). It appears essential also to dispose on ground of Functional Models of the Facility, i.e. functional replicas of the on-board device. The Functional Model will be a working tool on ground that can be used for ground experimentation, for diagnostics development, for refurbishement simulation and for allowing a continuous upgrading of the Facility to include new technologies. Other requirements are dictated by the PIs and are related to the Support Equipment that FS experiments may require during the microgravity investigations. For instance the possibility of experiment simulations, physical and numerical, run in parallel with the microgavity experimentation (like the control experiments in use in Life Science) should be offered to the user community.

Test Beds activities are also essential when interactive operations are foreseen. It is important to point out that the Telescience operations deeply affect the training of the PS and of the PI and demand the availability of Facilities at the USOC. The training for the experiment on a specific Facility should involve all the people that partecipate in the experiment execution. There are two types of trainings: 1) a traditional one, that strictly follows the schedule of on-board and on-ground operations and 2) a specific training for the interactions between PI and PS in Telescience investigations.

In both cases the most important training tool is the Engineering Model (EM) of the Facility. Parallel updating of EM and FM is also essential. In fact not only the present but also the following crews, that were not involved in the development of the multiuser Facility, have to be trained and it would be dangerous for a PS to be trained on a version of the Facility and to find, on board, a different one.

In conclusion the best way of conceiving the Fluid Science Laboratory is as an integrated apparatus composed by a Space and a Ground part.

The Space part is basically composed by stimuli actuators and diagnostics sensors. Modularity and flexibility call for different diagnostic modules (typically non invasive) that are assembled around a test section containing the fluid under study. The assembling of there modules appears very difficult if one thinks in terms of large diagnostic equipment but could be solved (even by telemanipulation) if extensive use is made of optical fibers (active and/or passive) that connect the different modules (e.g. illumination sources, interferometry, TV cameras, thermographic cameras, etc) with the test section. In this way complex displacements of large equipment will be avoided and volume utilization (diagnostic modules will stay in a dedicated rack and the fiber optics tip will be moved around) will be optimized. This modular solution will:

1) favour the FS facilities, that compose the FSL, to be identified for their containment modes (fully contained, partially contained, containerless, convection controlled),
2) avoid problems of duplication of diagnostic equipment
3) make it possible the substitution of obsolete diagnostics (that are developing rather fast)

The Ground Equipment, that should be available at the USOC to support Fluid Science Telescience experiments, may be defined by considering the diagnostic systems needed by the PI for the conduct of his experiment. Two categories of diagnostics exist:

A) On-line:

1) for monitoring, for quick look analysis and/or for experiment control,
2) for quantitative measurements.

B) Off-line:

1) for experiment assessment and decision makings (rerunning and rescheduling)
2) for final experiment evaluation.

Fluid Science experiments performed so far have made mainly use of off-line diagnostics of type 2).

Future Telescience activities call for efforts in the development of all kind of on-line diagnostics and of off-line type 1) systems.

On-line quantitative control and measurements require strong computing supports, especially when parameters at many field points are to be computed.

An appealing concept is the non intrusive computerized diagnostics, aimed at helping on-line Telescience experiment controls. In many instances, in fact, one would like to control the experiment by parameters that are not directly measurable or that would require intrusive probing. Often these quantities can be computed, through numerical models and by fast computers, by utilizing experimental parameters measured at different locations, (e.g. at the test cell boudaries). The ground part of the Facility in this case will be able to "measure" (by digital computation) and display temperatures and velocities at inaccessible internal points of the fluid sample and to control the experiment (e.g. by setting boundary conditions at subsequent time steps) with the most appropriate logics (Fig.3).

References

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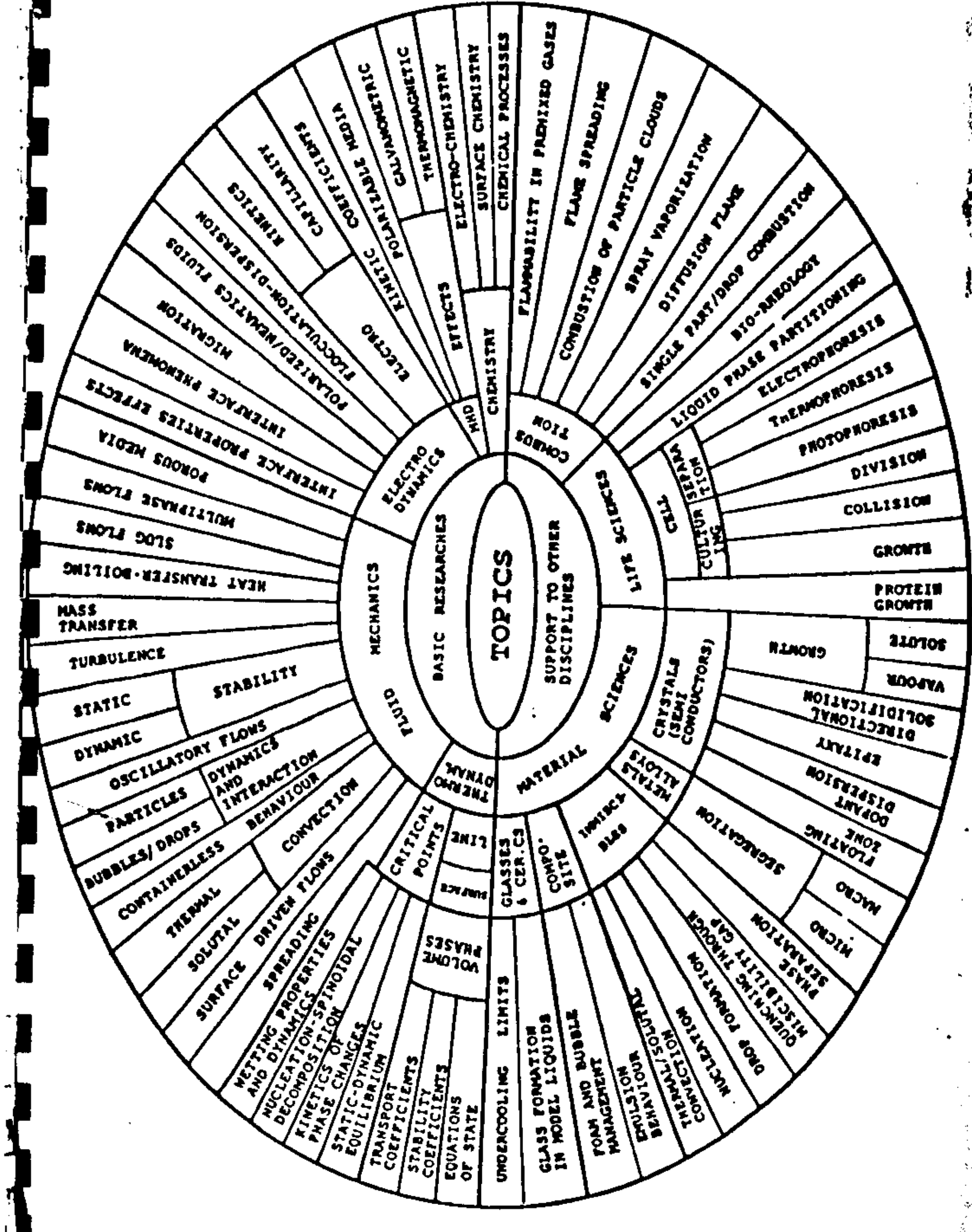

Fig.1 - ENVELOPE OF THE AREAS OF INTEREST FOR THE FLUID SCIENCE

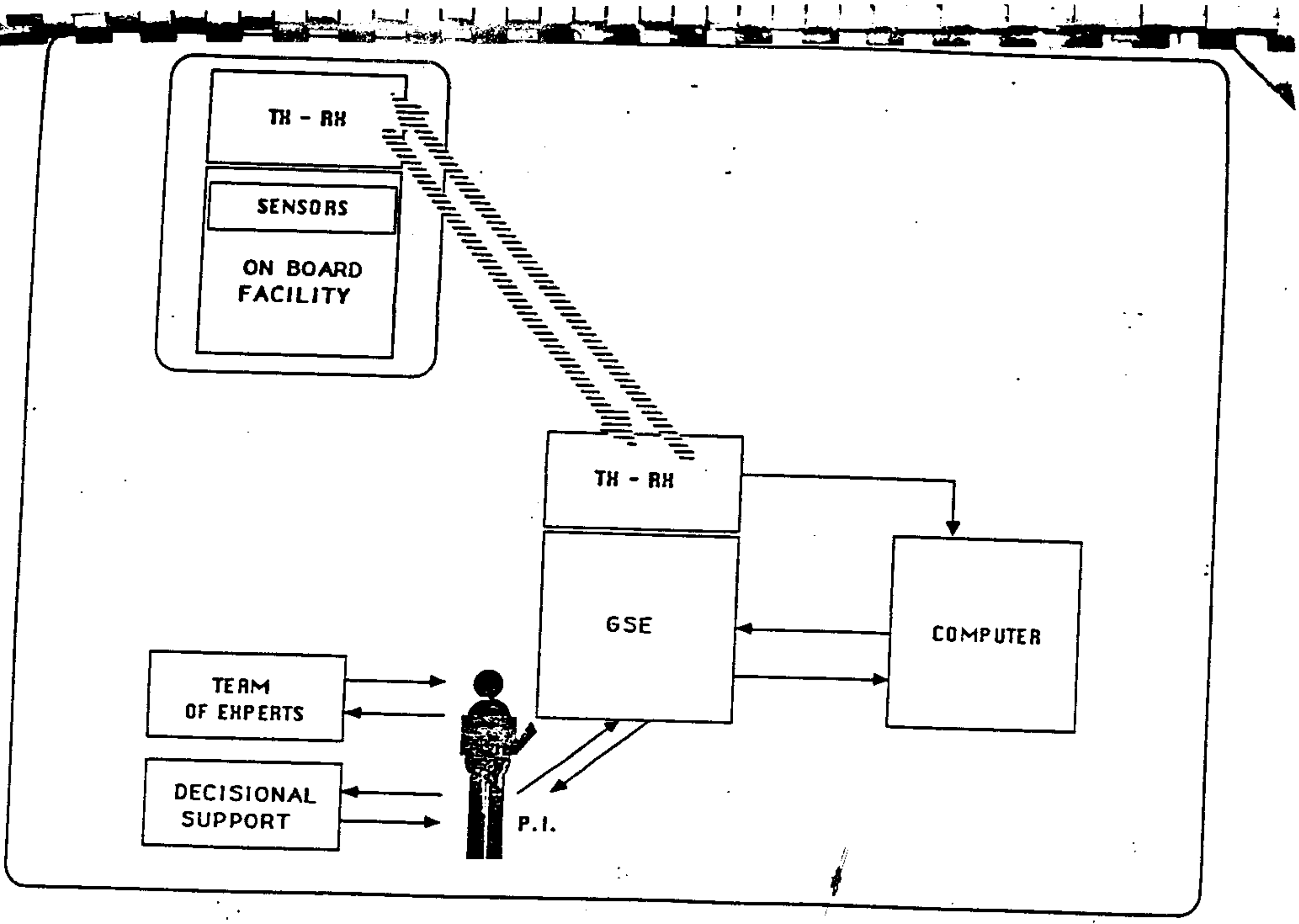

Fig.2 - TELESCIENCE FOR OPTIMAL FSL OPERATIONS