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# SLOSHSAT FLEVO MOTION SENSING SUBSYSTEM

by

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## Contents

ABSTRACT 5

1. INTRODUCTION 5

2. SLOSHSAT FLEVO EXPERIMENT 6
   2.1 Sloshsat FLEVO background: WSM 6
   2.2 Sloshsat FLEVO fluid dynamics 6

3. MOTION SENSING SUBSYSTEM DESIGN 8
   3.1 Motion simulation for sensor selection 9
   3.2 Detailed design of MSS 10
   3.3 MSS integration, verification, and calibrations 11
   3.3.1 MSS acceptance and assembly tests 11
   3.3.2 MSS S/C integration and verification 11
   3.3.3 MSS calibrations 11

4. FUTURE DEVELOPMENTS 12
   4.1 Building and flying MSS 12
   4.2 Post experiment data processing 12
   4.3 Future outlook 13

5. CONCLUSIONS 13

6. ACKNOWLEDGEMENT 13

7. REFERENCES 13

3 Figures

(14 pages in total)

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# SLOSHSAT FLEVO MOTION SENSING SUBSYSTEM

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## ABSTRACT

Within a small satellite project, Sloshsat FLEVO, a dedicated Motion Sensing Subsystem (MSS) is developed for a micro-gravity space experiment. Sloshsat FLEVO is a small free flying spacecraft designed for the investigation of forces exerted upon a partially filled tank by a liquid sloshing.

The MSS will monitor the motion of the spacecraft in flight. The MSS uses two types of specially selected sensors for micro-gravity measurements, the Allied Signal QA-3000-010 accelerometer, and a LITEF μ-FORS fibre optic gyroscope. These sensors respectively measure the linear acceleration and angular velocity in a certain point in the spacecraft, from which the motion of the whole experiment is determined. The Motion Sensing Subsystem will be manufactured within the project of the Sloshsat FLEVO satellite, scheduled to be launched with Space Shuttle in March 2000.

The MSS concept has extensively been tested and verified using dedicated motion sensing simulators. The MSS development will be tested and verified pre-flight, and will be submitted to an in-flight validation. The outcome of the sloshing experiments, including MSS measurements, is input for future AOCS design and development, when liquid to rigid mass ratios become larger and larger.

## 1. INTRODUCTION

If the motion of a space vehicle is to be controlled, this motion should be predictable. For a space vehicle with a rigid body, prediction of its motion is straightforward. However, if a part of the spacecraft, e.g. a fuel tank, is only partially filled with liquid, the motion dynamics become very difficult to predict.
In near future spacecraft will stay longer in orbit, and manned space programmes will be intensified. These developments imply larger amounts of fluids in fuel tanks, and water tanks in a micro-g environment. For spacecraft attitude control the effects and magnitude of disturbance by a sloshing liquid in parts of a spacecraft should be known. Therefore, the fluid dynamic models should be validated, and scientific research should bring more accurate and usable fluid dynamic models. Investigation of these models is foreseen with the 'liquid sloshing satellite' Sloshsat FLEVO (Facility for Liquid Experimentation and Verification in Orbit), developed at NLR in the Netherlands. Sloshsat FLEVO is mainly a tank, partially filled with liquid, and instrumentation for liquid diagnostic and spacecraft motion. The liquid height from the tank-wall is measured by capacitive sensors, and the spacecraft motion is measured by motion sensors. This paper deals with the Motion Sensing Subsystem (MSS) only.

The purpose of the Sloshsat FLEVO Motion Sensing Subsystem is twofold. Firstly, to measure and monitor the Sloshsat FLEVO satellite's motion, i.e. angular velocity and linear acceleration, for on-board motion control. Secondly, the Motion Sensing Subsystem measurements provide data from which angular velocity and linear acceleration can be determined for off-line experiment processing.

In section 2 Sloshsat Flevo experiment preparation activities are discussed, and the present state of the Sloshsat FLEVO satellite project is evaluated. The MSS sensors have been selected using motion simulating programs, and prototype post-processing programs, before MSS detailed design and analysis are performed (section 3). Section 4 discusses the MSS developments planned in preparation of the Sloshsat FLEVO in-flight experimentation. The post-flight evaluation of the experiment results should give more insight in micro-gravity fluid dynamics.

## 2. SLOSHSAT FLEVO EXPERIMENT

### 2.1 Sloshsat FLEVO background: WSM

In preparation of Sloshsat FLEVO earlier "micro-gravity" fluid dynamics experiments (parabolic flights, Spacelab 1, and D1) have been executed at NLR. Most significant was The Wet Satellite Model (WSM) experiment performed in 1992, developed at NLR, and launched from a MASER 5 rocket (Ref.1, 2). The WSM payload has a relatively simple configuration, being an annular cylindrical void half filled with liquid. The tank wall is wetted by the liquid, through an angular velocity vector along the cylinder symmetry axis giving it its initial motion. Consequently, the liquid deformation becomes a two-dimensional problem, in the axial and azimuthal direction of the reference coordinate frame. The symmetry axis is aligned with the axis of minimum inertia of the WSM satellite. Therefore, the initial motion becomes very rapidly unstable due to interaction between liquid and spacecraft after spin-up.
The resulting 'flat-spin' transition is relevant to spaceflight. Many spacecraft are spun about their axis of minimum inertia, especially during the coasting period between injection into orbit and insertion into transfer orbit in geostationary attitude.

The WSM experiment data consisted mainly of output from an arrangement of nine linear accelerometers. A large effort was devoted to solve the problem of reconstructing the three motion vectors, i.e. linear acceleration, angular velocity and angular acceleration, from this data (Ref 3). The 'flat-spin' transition was clearly retrieved from the data, and the whole experiment gave input for further liquid dynamics analyses, interpretation, and further development. As a result the Sloshsat FLEVO project is initiated, with support of an international investigation working group with scientists from the USA, Israel, and The Netherlands.

### 2.2 Sloshsat FLEVO fluid dynamics

Sloshsat FLEVO (Fig. 1) is, for the scientific part, the result from the need for a more advanced flight experiment, with a longer experiment duration, multiple experiment runs, a three dimensional tank, six directions of excitation, and liquid state instrumentation.

The ability to understand, predict, and accurately control the dynamics of space vehicles carrying large amounts of liquid, become more and more important. Pointing and stability requirements become more demanding for both scientific and telecommunication satellites, with growing liquid to mass ratios.

To contribute to the solution of this problem NLR has developed Sloshsat FLEVO. The objectives of this satellites are:

1. develop and complete the Sloshsat flight sloshing experiment

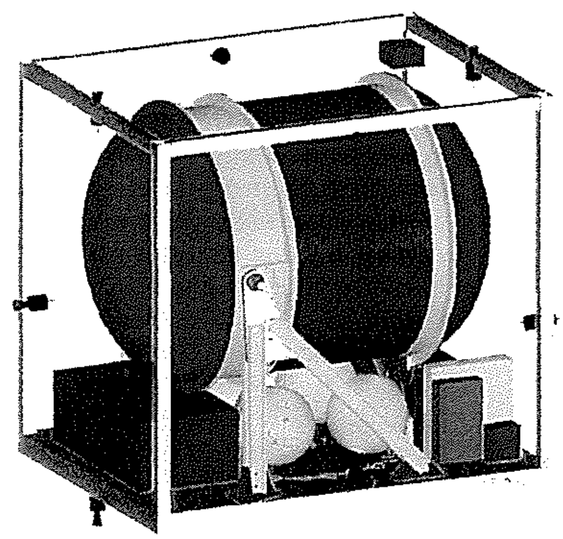

*Fig. 1 Sloshsat FLEVO satellite, schematic overview without solar panels*

2. develop and qualify a low-cost mini-spacecraft platform with manoeuvring capability,
3. obtain experiment data to verify and validate existing fluid dynamic models.

The free-flying activities include system calibration, calibration of tank sensors and motion sensors. Also pre-ejection check-out and calibrations, together with pre-ejection sloshing experiments are foreseen.

An international Investigators Working Group defines the experiments. Parties interested in participation in the IWG are expected to contribute to the realization of the project. The current defined experiments are categorized in three classes:
1. hydrostatics and stability experiments,
2. settling manoeuvres,
3. spacecraft dynamics.

The Sloshsat FLEVO payload consists of an experiment tank with elaborate instrumentation. The tank is a circular cylinder with two hemispherical ends. The volume of the tank is filled with approximately 34 litres of pure, demineralised water. The liquid height at the tank wall is measured at 270 locations in total. Additional sensors measure the liquid height with a better resolution, liquid velocity at the wall, and pressures and temperatures. The mass of the dry satellite is approximately 90 kg. The fluid rigid/mass ratio is therefore about 0.4.
The satellite will be launched from a HitchHiker-C in the Space Shuttle bay. The satellite will be in orbit near the Space Shuttle for almost two weeks, and a total of 24 hours of effective fluid dynamics experimentation is foreseen. The fluid-spacecraft interaction experiments are divided over several blocks during the duration of the Shuttle flight, allowing for ground-operational feedback in between experiment blocks (Ref. 4,5).

The objectives of the experiments are to obtain flight data to validate existing fluid dynamic models and software, characterise the dynamic interaction between liquid motions and spacecraft, provide understanding of the motions of liquid with a free surface in a "micro-gravity" environment. Further more, the experiment shall generate information on less well-organised flow patterns as a basis for further mathematical modelling, provide relevant information for the design of liquid management techniques in micro-gravity and obtain data on diagnostic instruments flight performances.

Presently the FLOW-3D computational fluid dynamics (CFD) programme of Flow Science Inc. is used for experiment predictions. An advanced non-linear spring-mass-dashpot simulation programme Sloshsat Motion Simulator (SMS) (Ref. 6,7,8) for complete manoeuvre predictions has been developed at NLR, using the experience gained from previous simulation program developments. The SMS models the liquid as a variable diameter sphere ('slug') with constant mass in a spherical enclosure of fixed size ('tank'). The interaction force and torque parameters between slug and tank can be chosen as desired, generally as a function of Sloshsat state variables.

The Sloshsat FLEVO satellite consists of a number of interfacing subsystems (Fig. 2):
- Payload subsystem (experiment tank)
- Motion sensing subsystem (motion sensors)
- Structure subsystem
- Thermal control subsystem
- Power subsystem
- Data handling subsystem
- Radio frequency subsystem
- Reaction control subsystem
- Ground support subsystem

The motion sensing subsystem is the subject of this article.

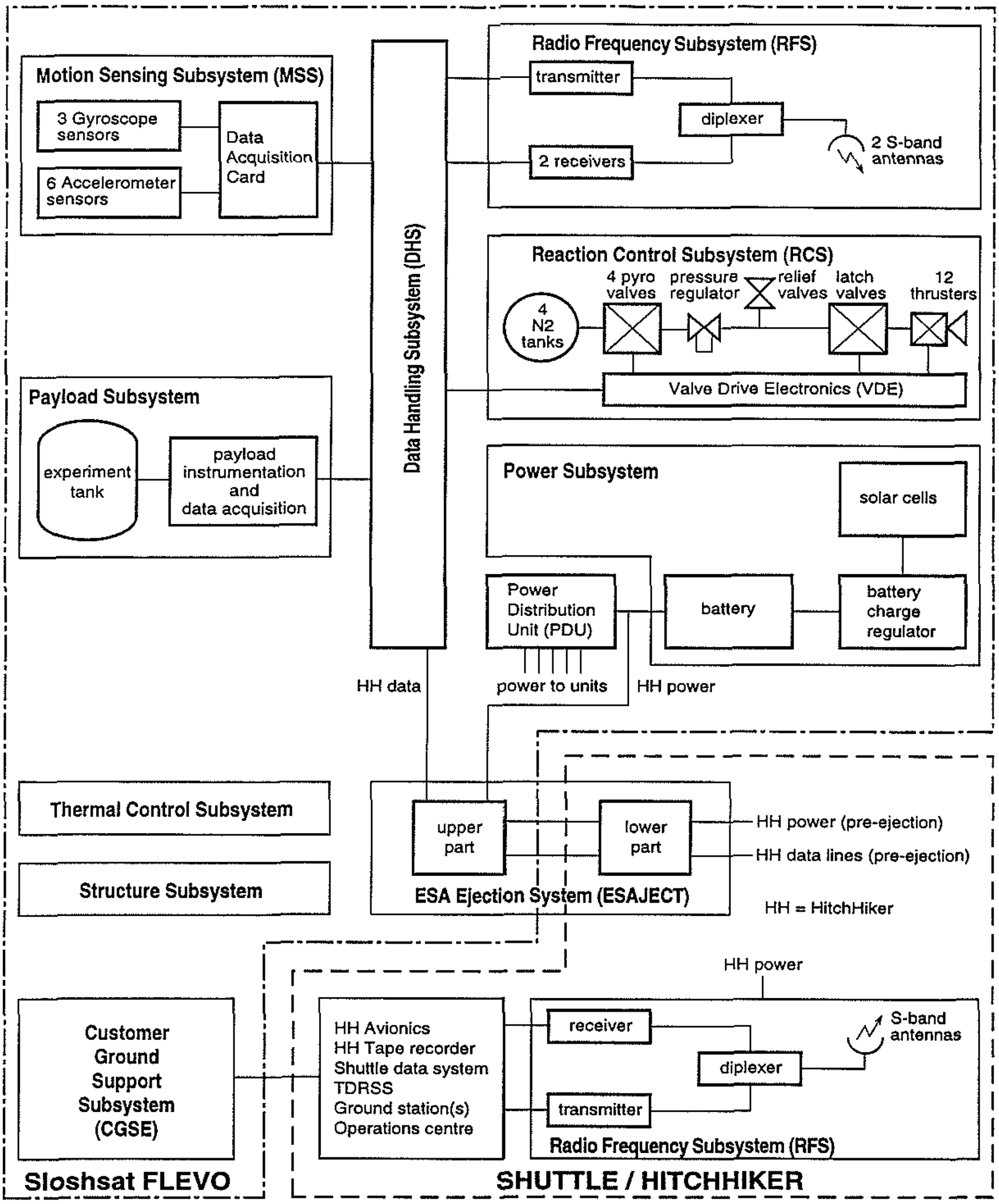


*Fig. 2 Block diagram of Sloshsat FLEVO*

## 3. MOTION SENSING SUBSYSTEM DESIGN

The Motion Sensing Subsystem has the following two main functions:

- to provide on-board measurements of linear accelerations and angular velocity for on-board motion control purposes,
- to provide measurement data from which angular velocity, angular and translational acceleration can be determined for off-line experiment processing purposes.

The MSS (Fig. 3) consists of the following units:
- three gyroscopes,
- three accelerometer units (each with 2 linear accelerometers),
- a MSS Box data acquisition unit,
- on-board software (data acquisition and measurement processing).

Special feature is that the motion sensors are being used for motion measurement, and motion control only. Sloshsat FLEVO does not require orbit or attitude control, but uses an internal reference coordinate frame in which the position and measurements of the motion sensors are accurately known.

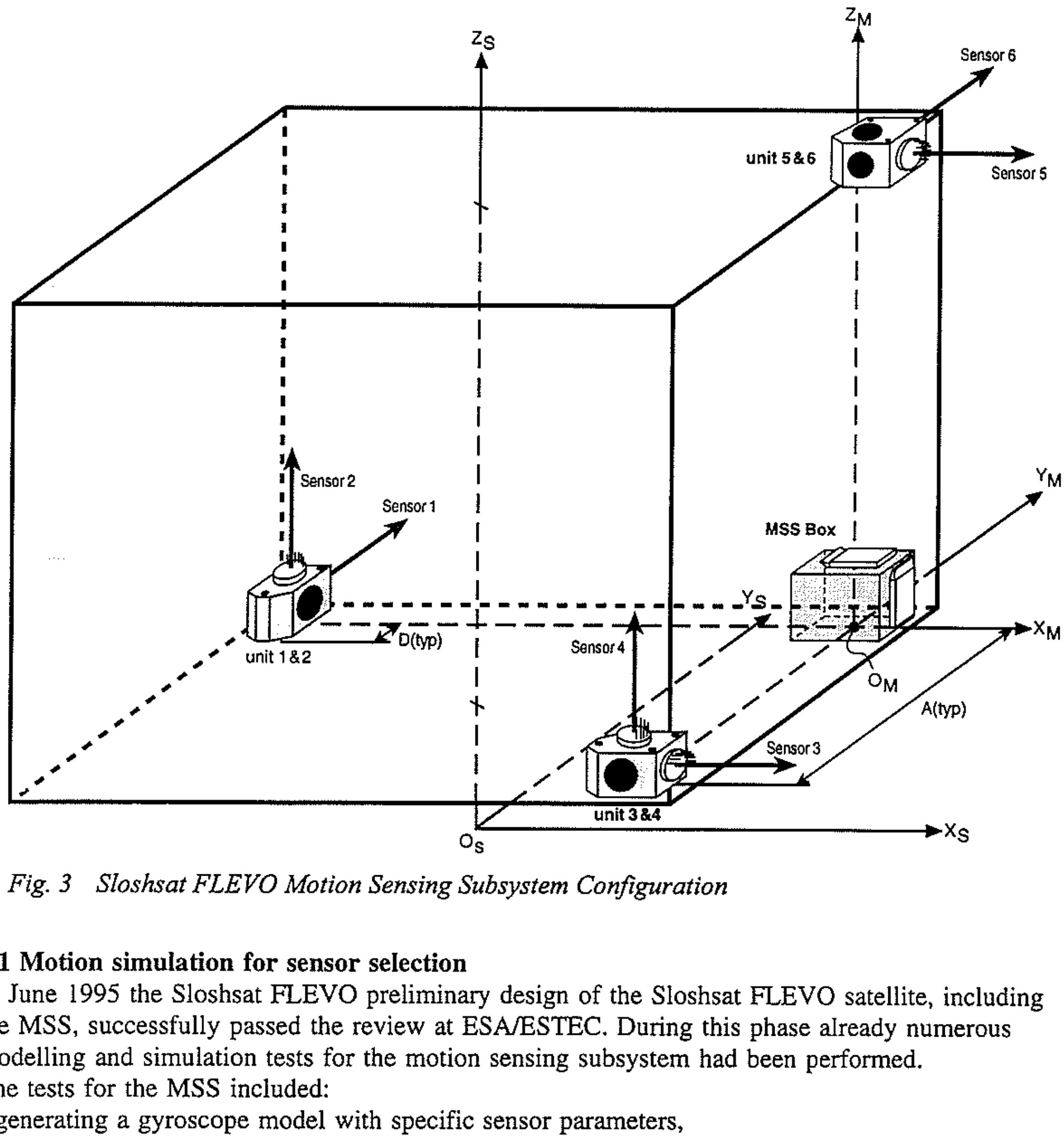


*Fig. 3 Sloshsat FLEVO Motion Sensing Subsystem Configuration*

**3.1 Motion simulation for sensor selection**

In June 1995 the Sloshsat FLEVO preliminary design of the Sloshsat FLEVO satellite, including the MSS, successfully passed the review at ESA/ESTEC. During this phase already numerous modelling and simulation tests for the motion sensing subsystem had been performed.
The tests for the MSS included:
- generating a gyroscope model with specific sensor parameters,
- generating an accelerometer model with specific sensor parameters,
- obtaining a configuration model of MSS,
- creating a motion model with typical spacecraft manoeuvres,
- upgrading and refinement of a sensor output simulation programme,
- upgrading and refinement of the post-processing programme,
- processing and presentation of obtained test data.

The motions models represented:

A. a low frequency (typical 0.1 Hz) sloshing fluid motion of Sloshsat FLEVO, with a large angular velocity about the Y-axis.

B. the same sloshing motion as motion A, however, angular acceleration impulses (simulating thruster impulses) are added.

C. a sloshing motion without the large angular velocity as in motion A, however, again with acceleration impulses.

The motions together with the MSS configuration and the sensor parameter models are used as input for the sensor output simulation program, developed at NLR, to obtain realistic sensor output with biases, alignment errors, noise, etc. The post-processing program uses these sensor outputs to retrieve the original motion. The difference between original motion input in the simulation program and the estimated motion output from the post-processing program indicates the errors to be expected using a particular sensor (gyroscope and/or accelerometer).
Using this test set-up a certain accelerometer and gyroscope have been selected for this phase.

At the beginning of the Critical Design phase a refinement of the sensor selection from the preliminary design was required (Ref. 9). The selection was limited to the 6 grades of sensors in the Allied Signal catalogue. The Allied Signal QA-2000-020 already complied with the MSS requirements, as shown by the simulations presented in the preliminary design.
With new tests it was verified that the requirements (Ref. 5) are more easily reached with model QA-3000-10. This accelerometer has a better scale factor, bias and axis misalignment sensitivity, over temperature range and over long period in time, than the QA-2000 series. The QA-3000-010 accelerometer will be able to measure the experiment liquid acceleration dynamics with a resolution better than 1 [μg].

The selected gyroscope in the preliminary design was taken into the final sensor selection together with two additional gyroscopes. Specifications of these three gyroscopes were obtained for the new trade-off (Ref. 9). This work was performed because of the attractive power and mass saving possibilities. The LITEF μFORS-36/6 gyroscope shows some advantages, in comparison to the TELDIX FOG MFK 4-2 gyroscope from preliminary design:
- lower white noise of 27 [°/hr/√Hz],
- lower mass of 150 [gram],
- lower power of 2 [Watt],
- smaller dimensions and mounting surface
- direct digital rate output, instead of rate-integrating output,
- standard interfaces (analog, digital RS-422 or RS-485),
- a software installation package, and interface modification program,
- the LITEF gyroscope is fully calibrated at delivery.

The specifications give, however, also some disadvantages, for the LITEF gyroscope:
- higher axis misalignment up to 10 [mrad],
- higher bias stability drift 1.7 $10^{-3}$ [°/s],
- higher scale factor error,
- smaller operating temperature range.

The LITEF gyroscope comes out of this trade-off as the best choice with respect to mass, size and power savings. Tests verified that the MSS requirements (Ref. 5) are also met with LITEF μFORS-36/6, and this gyroscope is selected for the motion sensing subsystem.

### 3.2 Detailed design of MSS

In the motion sensing subsystem design the following steps were taken in realisation of the Sloshsat FLEVO motion sensor configuration (Ref. 10.11):

- Research was performed to obtain the best applicable sensor output filtering of the analogue accelerometer on-board electronics, for filtering specifications were required before electronics design could start.
- The MSS electronics design has been detailed. A dedicated MSS Box, that also serves as mounting bracket for the three gyroscopes, houses the digital, analogue and filtering electronics on 4 Printed Circuit Boards together with a de-centralised micro-processor.
- The MSS embedded software was redefined and distributed over the MSS micro processor/controller and the on-board software in the Data Handling Subsystem. Both parts of the software perform their seperate tasks in the data retrieving process.
- Possible risks were identified, and measures were taken where necessary. Accelerometer leakage of the sensor housing in hard vacuum was found negligible in the short period of experimentation (2 weeks). Also the radiation risk for the MSS micro-processor and fibre optic gyroscope internal processors, although both C-MOS technology, was found negligible for such short time.
- The mechanical design of both the MSS Box, housing the data acquisition unit and serving as gyroscopes mounting bracket, and the three different accelerometer bracket configuration has been completed.

The motion sensing subsystem passed the critical design review at ESA/ESTEC successfully in May 1997.

## 3.3 MSS integration, verification, and calibrations

### 3.3.1 MSS acceptance and assembly tests
The MSS will be manufactured as soon as the 'go-ahead' for the complete Sloshsat FLEVO manufacturing is given. After manufacturing the prototype MSS will be assembled and tested in a subsystem integration test. The tests will take place using a ground software set-up:
- a complete prototype MSS will be tested with all sensors, structures, interfaces and on-board software, after manufacturing,
- MSS sensors will be read out with prototype electronics.

### 3.3.2 MSS S/C integration and verification
After final acceptance the complete assembled MSS will be delivered for integration in the Sloshsat FLEVO Spacecraft. Proper functioning of the MSS sensors, electronics and MSS on-board software will be verified using the Sloshsat FLEVO DHS.

The MSS Box and MSS accelerometer brackets have been designed such that they have very accurate mounting surfaces. The design is such that the inaccuracies remaine within the axis misalignments of the sensors themselves. After integration in the spacecraft the MSS Box and accelerometer brackets position needs to be measured in order to know the exact direction of the sensitive axes of all sensors and the location of the accelerometer seismic points.
The measurements of directions and locations will use special optical (mirroring) surfaces on the brackets. The surface positions are measured using an auto collimator. After processing of the measurement output the On-board Software tables will be up-loaded with accurate data of sensitive directions $\underline{s}$ and locations $\underline{r}$ of the MSS sensors in the payload coordinate frame.

The tests of the physical boundaries of the MSS with respect to EMC levels, temperatures, vacuum and vibration are performed on a system level of Sloshsat FLEVO tests. No separate tests of these aspects for MSS are foreseen, however, MSS will undergo the overall Sloshat FLEVO verification tests.

### 3.3.3 MSS calibrations
Because of the harsh vibration environment in Space Shuttle launch the accelerometer parameters

have to be calibrated in flight. The accelerometer bias and scalefactor may be effected by the vibration level. Therefore re-calibration of these parameters is required before Sloshsat FLEVO ejection. This section shortly describes the preliminary approach to the calibration of the Sloshsat Motion Sensing Subsystem. The extent of the calibration required, depends on the foreseen sensor errors relative to the motion sensing requirements.

- Prior to Shuttle flight the Motion Sensing Subsystem sensor parameters are known (ground calibration performed at sensor manufacturer).
- After Shuttle launch some critical parameters need to be re-determined (flight calibration).

Still, the sensor parameters are not known precisely after calibration, because parameters may be temperature dependent, power supply dependent. Calibration is not performed without errors, parameters change with time (usually called drift), and parameters change due to the environment accelerations and vibrations.

## 4. FUTURE DEVELOPMENTS

### 4.1 Building and flying MSS

As soon as the critical design for the complete Sloshsat FLEVO has been approved by ESA/ESTEC the preparations and realisation of the manufacturing phase of the motion sensing subsystem can be performed. Before the final acceptance review several steps in assembly, subsystem level tests, spacecraft integration and system level tests need to be taken, as discussed in section 3.3.

After successful integration of the MSS and all other subsystems, Sloshsat FLEVO will be shipped to NASA in the USA and the satellite will be stored and prepared for the Space Shuttle flight.

The sensors and sensor configuration are calibrated by the sensor manufacturer. The position of the sensor brackets will be measured at MSS integration in the Sloshsat FLEVO spacecraft. However, tests may have some influence on these parameters, possibly leading to bias shifts and/or re-positioning of sensors. These effects should be kept as small as possible although the design allows for some margin. Furthermore, long periods between integration and actual space flight experimentation may also lead to degredation e.g. bias shifts etc. (manufactures of the sensors only give a certain period of time for parameter stability). To circumvent the effects described here in advance, calibration of the most important sensor parameters is foreseen as discussed in section 3.3.3. The re-calibration can take place when the satellite is still on-board Space Shuttle, or in free-flight prior to, or in between experiment blocks.

### 4.2 Post experiment data processing

The motion of the Sloshsat FLEVO is reconstituted from six accelerometers and three gyroscopes. The three angular velocities are obtained almost instantly, except for misalignment correction and digital elaboration. The three gyroscope positive sensitive axes are purposely aligned with the three Sloshsat FLEVO reference coordinate frame axes, to avoid sign-misinterpretations.

The linear acceleration vector of Sloshsat FLEVO, from the force of the liquid on the tank wall, is not this straightforward. Except for the same axis-misalignment correction and digital elaboration as for the gyroscope, the accelerometer data is 'polluted' with centripetal acceleration effects. These need to be removed from the measurement data. For optimization the accelerometer configuration is redundant and consists of six linear accelerometers.

Immediately the data is used in the on-board software for the reaction control subsystem and thruster activation. Interpretation of experiment data on ground is performed with a dedicated post-processing programme. The MSS output data of the experiments is input for the fluid dynamic research and development, in order to verify and validate and/or refine present fluid dynamic models and software.

### 4.3 Future outlook

A candidate follow on experiment has been sumitted recently involving robotics technology (Ref. 12). An automation and Robotics (A&R) laboratory is being developed at NLR, intended to be test-bed for ESA/Dutch operations technology. A reference scenario involving liquid sloshing experiments based on an external robot arm, e.g. the European Robotic Arm, is analyzed to suggest next steps for further developments. Robotic arm supported experiments involving controlled rotations and accelerations are suggested, where an MSS may serve as a reference sensor system. A sloshing experiment on MIR using an external robotic arm would constitute a valuable complement to the two weeks Shuttle flight with Sloshsat FLEVO.

## 5. CONCLUSIONS

The following is concluded for the motion sensing subsystem:

- the Wet Satellite Model experiment initiated a method of obtaining unique data on the dynamics of spacecraft/liquid interaction. Although WSM encountered some intrinsic difficulties with interpreting the data, the Sloshsat FLEVO Payload and MSS sensors circumvent these problems with a more straightforward measurement approach,
- the preliminary design as well as the detailed design of the motion sensing subsystem both have been successfully concluded. MSS consists of three gyroscopes and six accelerometers together with a data acquisition unit and accurate mounting brackets. The straightforward design philosophy could easily be re-used in future spacecraft,
- the motion sensing subsystem in Sloshsat FLEVO will support in the development of the fluid dynamics models and software programmes, and possibly lead to better spacecraft control algorithms,
- a future sloshing application is suggested using an external robotic arm, e.g. on MIR, for long term "micro-gravity" experimentations and development, possibly with the use of a reference motion sensing subsystem.

## 6. ACKNOWLEDGEMENT

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Main contractor is the National Aerospace Laboratory NLR (The Netherlands) with participation of Fokker Space (The Netherlands), Verheart (Belgium), Newtec (Belgium), Rafael (Israel) and NASA (USA).

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