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National Aerospace Laboratory NLR

NLR-TP-2000-630

SLOSHSAT FLEVO
Facility for liquid experimentation and verification in orbit
Description of the mini satellite

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SLOSHSAT FLEVO
FACILITY FOR LIQUID EXPERIMENTATION AND VERIFICATION IN ORBIT

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ABSTRACT

Sloshsat FLEVO[1] is a mini satellite for the study of liquid dynamics and liquid management problems in space (Figure 1). The behavior of water in an instrumented tank in the satellite will be monitored to help understand how sloshing affects the attitude and orbit control of space vehicles. The micro-gravity disturbance by liquid in a tank is determined as well. Of the total mass of 129 kg of Sloshsat FLEVO, 33.5 kg is liquid water in a smooth 87-liter tank. Sloshsat FLEVO is to be launched from the Space Shuttle, and operated for two weeks from the ground via the Space Shuttle communication channels. The satellite is currently being completed.
This paper describes mission objectives, project, all spacecraft subsystems, testing, operations, safety aspects, and status.

INTRODUCTION

The ability to understand, predict, and accurately control the dynamics of spacecraft with large amounts of liquid on-board becomes increasingly important[2, 3]. Missions, such as landings on celestial bodies, or International Space Station servicing, are carried out with maneuvering vehicles that carry a large fraction of their mass in liquid form. However, the effect of sloshing on spacecraft control has proven difficult to predict. To address this problem, NLR has conducted several fluid/spacecraft dynamics interaction experiments in "micro-gravity", such as aircraft parabolic flight experiments, Spacelab-1 and D1 experiments and the sounding rocket experiment Wet Satellite Model WSM. The need for a more advanced flight experiment resulted in the development of Sloshsat FLEVO (Facility for Liquid Experimentation and Verification in Orbit).

MISSION OBJECTIVES

The objectives of the Sloshsat FLEVO mission are to design, develop and perform the flight experiment, to obtain data to verify/validate existing Computational Fluid Dynamics (CFD) models, and to develop and qualify a maneuverable mini satellite complying Shuttle requirements.
NASA has the particular goal to demonstrate that propellant can be settled at low thrust levels (Bo<12), either applied continuously or by on/off modulation[3].
An objective of NLR is to validate its Sloshsat Motion Simulator (SMS) for use in AOCS simulators and for control algorithms on-board spacecraft[2].

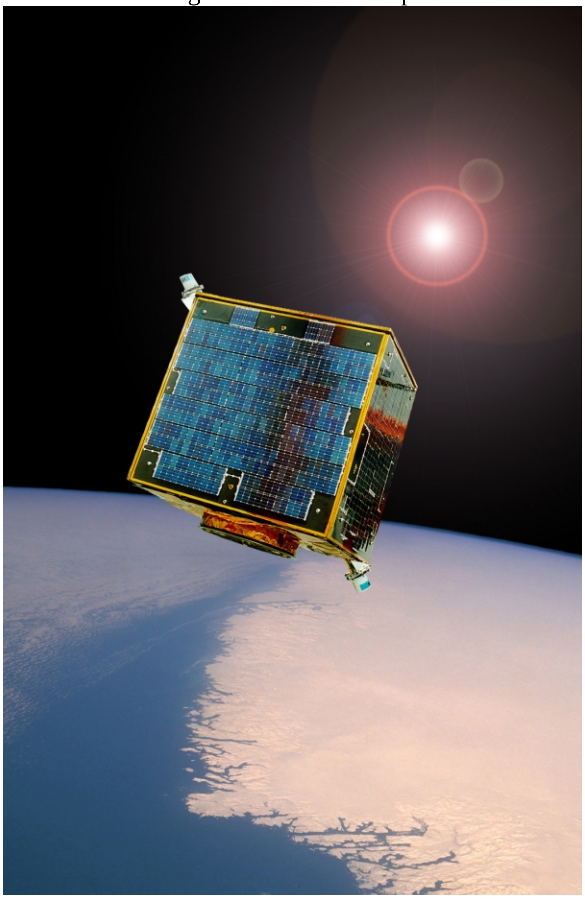

Figure 1 Artist impression of Sloshsat FLEVO after ejection

STOF PROJECT DESCRIPTION

Some time after Shuttle launch, Sloshsat FLEVO will be ejected by the ESA Ejection System ESAJECT. Sloshsat FLEVO communicates with the Orbiter via the Hitchhiker Communication System HHCS. The three systems: Sloshsat FLEVO, ESAJECT, and HHCS together, form the so-called Slosh Test Orbital Facility STOF (Figure 2).
An additional fourth system, the Advanced Crew Terminal ACT, is located on the Orbiter aft deck.
An overall block diagram of the above, with emphasis on Sloshsat FLEVO, is shown in Figure 5.

ESA Ejection System, ESAJECT[4]

ESAJECT is an ejection system developed for the ejection or jettison of small payloads (50 - 150 kg) from the Hitchhiker Bridge, compliant with the Shuttle safety requirements. The system is developed under ESA's Technology Demonstration Program and will make its first flight for the ejection of Sloshsat FLEVO.
ESAJECT consist of a main structure bolted to the Hitchhiker double bay pallet, and a payload interface ring bolted to the payload (see Figure 3). Both parts are clamped together by a Marman clamp-band system and two pyrotechnic separation bolts. The system is equipped with a "jamming free" contact-less power and data transfer system (for payload operation prior to ejection). Firing the separation bolts will eject the payload by means of eight spring-loaded push rods.
Verhaert Design and Development (Belgium) developed ESAJECT (www.verhaert.com).

Hitchhiker Communication System, HHCS

The HHCS, also mounted on the Hitchhiker double bay pallet, provides full duplex S-band communication between Sloshsat FLEVO and the Orbiter. Together with the Radio Frequency Subsystem of Sloshsat FLEVO this system operates over a range of virtually zero up to 80 nautical miles (bit error rate $<10^{-6}$). The HHCS high gain antenna needs to be pointed by the Orbiter to the satellite with an accuracy of 10 degrees (half cone). HHCS routes the continuous 16 kbps downlink datastream to ACT (see below) and Ku-band downlink and splits-off the low rate data stream to be down-linked via S-band. The S-band uplink is transmitted to the satellite.
Newtec (Belgium) has developed both the HHCS and the RFS (www.newtec.be).

Advanced Crew Terminal, ACT[5]

To support the mission, the astronauts operate an IBM ThinkPad with ACT software installed. The main task is to store all telemetry data on harddisk. Upon request, these data can be dumped via Ku-band. ACT also provides the astronauts with ground operator compatible data screens.
NLR and Origin have developed ACT under ESA contract (www.origin.nl, and www.nlr.nl).

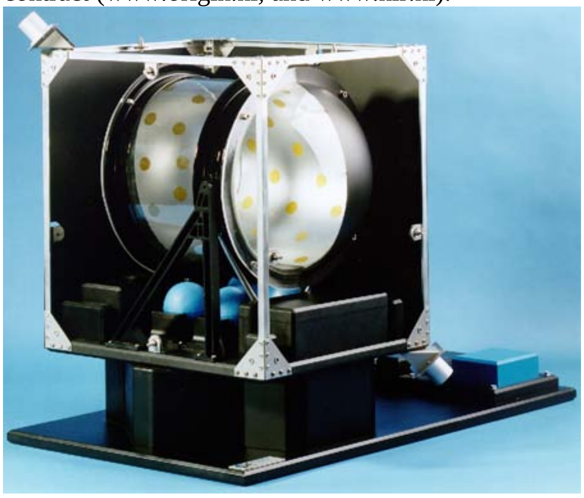

Figure 2 Model of STOF with the Sloshsat FLEVO spacecraft on top of the ESA ejection system ESAJECT, mounted together with the Hitchhiker communication system HHCS (on the right) on a Hitchhiker double pallet

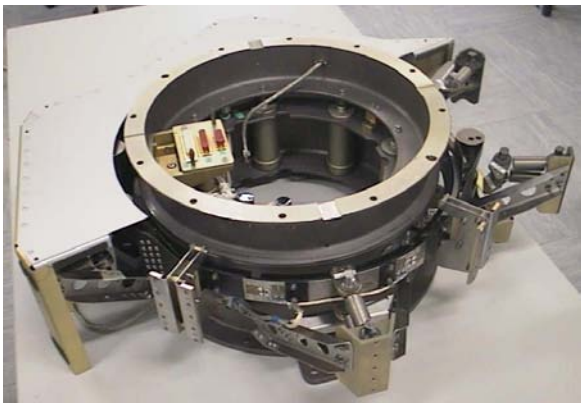

Figure 3 ESA Ejection System ESAJECT (flight system) shown without electronics and half of the MLI mounting box.

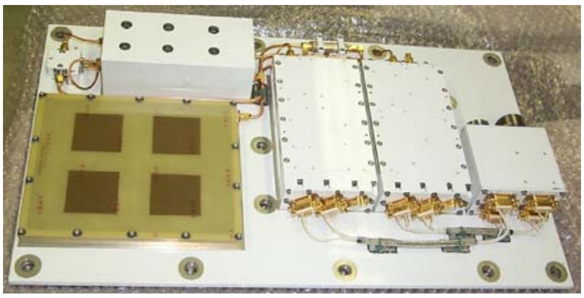

Figure 4 Hitchhiker Communication System HHCS (flight system), with directional antenna on the left, diplexer on the top left, transmitter and receiver on the right and the Hitchhiker connection box on the far right.

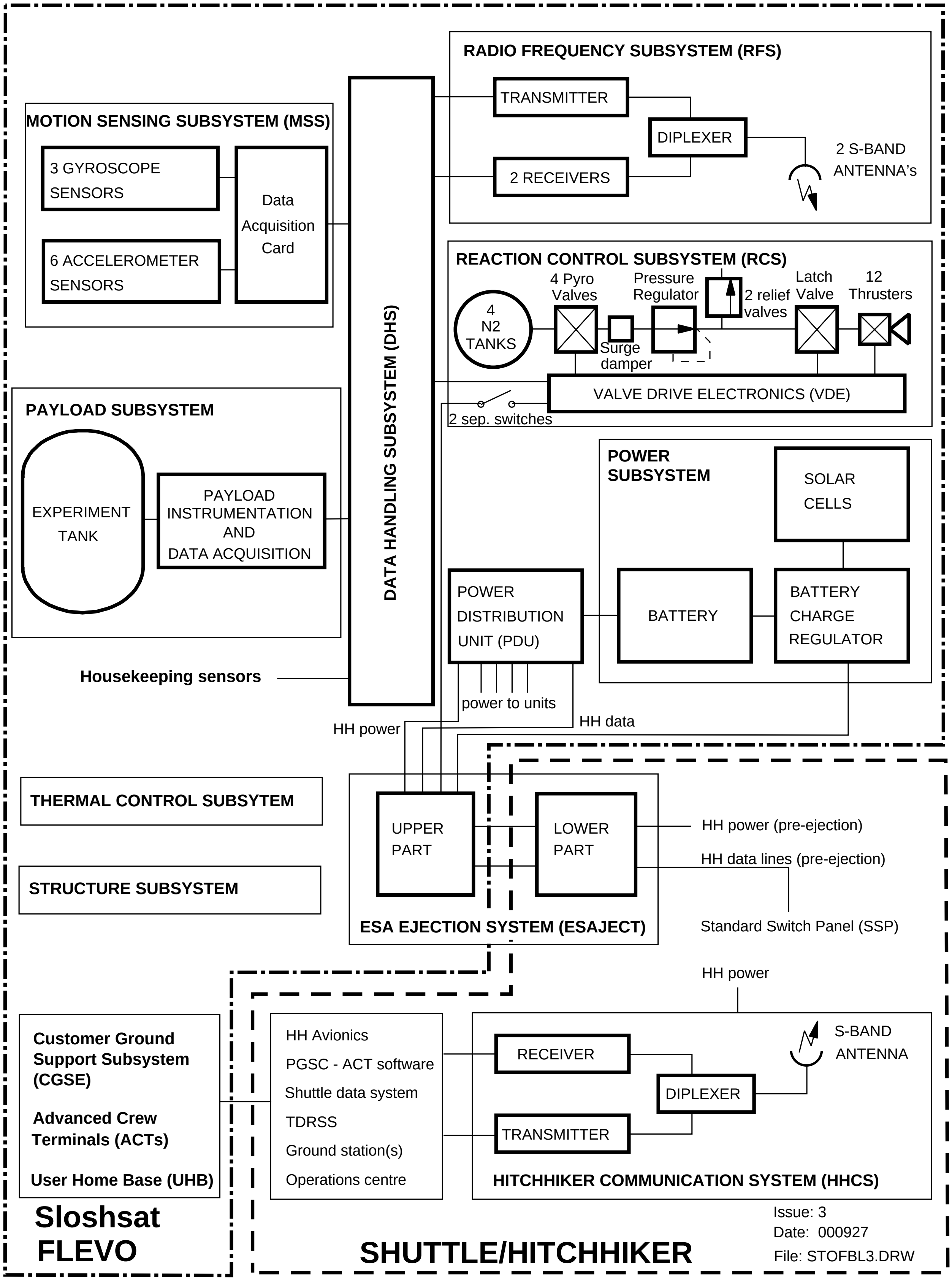

Figure 5 STOF overall block diagram

SPACECRAFT DESCRIPTION

In this section the more special characteristics of the various Sloshsat FLEVO subsystems are described. After the subsystem name, the header shows the acronym and subsystem responsible company.

Payload subsystem PLS (NLR)

The payload consists of an instrumented experiment tank with a cylindrical part (length and radius of 0.228 m) and hemispherical ends (Figure 6 and Figure 7). This 86.9 liter tank is filled with 33.5 liters of de-ionized water and nitrogen gas (@ 1 bar). Due to the main capacitance sensing principle, the tank structure is manufactured from non-metal materials (aramid fiber reinforced epoxy). In order to maintain the required high water quality a polyethylene liner was selected. The tank production progressed inside out, started with an aluminum mold of the tank void (Figure 6), applying the successive layers and embedded sensor parts, and finally dissolving the aluminum core.
Equally spaced along the tank inner wall, the capacitance is measured between 137 platinum wire rings embedded in the wall (Figure 6). This information is used to determine the local water height at 270 locations to a maximum depth of 3 cm with a frequency of 3 Hz.
The cool-down characteristics of 10 current pulsed NTCs provide 3 liquid velocity measurements every 2 seconds at 10 locations.

Figure 6 Mounting of a platinum ring on the tank mold

The tank-mounted electronics (Figure 7) accept raw power from the power bus and collect and format all sensor data. Data are sent to the on-board computer via an RS-422 bus. Therefore, the PLS can be easily operated stand-alone from a PC, which highly facilitates the development and test activities.

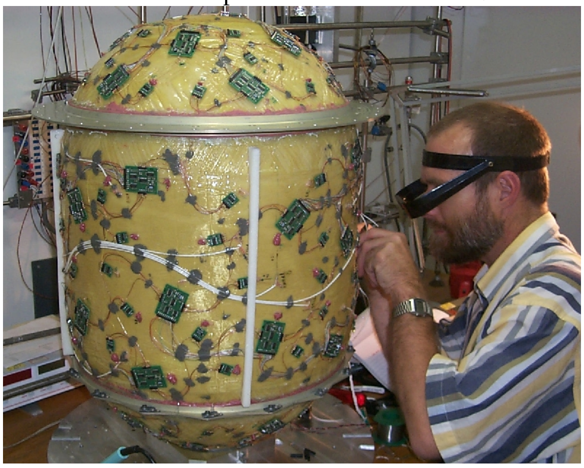

Figure 7 Mounting sensor electronics on the experiment tank

Structure subsystem STS (Fokker Space)

The spacecraft is box-shaped as shown in Figure 8. Originally the size of a single Hitchhiker pallet dictated the overall dimensions: 0.92 x 0.75 x 0.97 m. Later-on a double-size pallet became available.

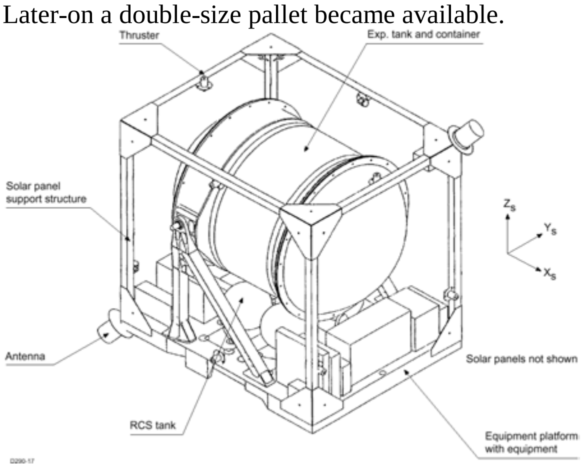

Figure 8 Sloshsat FLEVO primary structure

A Hitchhiker driven design challenge was to keep the lowest structural eigen-frequency sufficiently above 35 Hz. On the other hand the experiment requires keeping the S/C mass low in order to maximize the liquid-rigid mass ratio. This led to the design of a stiff but light sandwich platform, with aluminum honeycomb and face sheets on which most equipment is mounted (see Figure 9).
The structure of the solar array panels is a 10.5 mm thick composite with aluminum honeycomb and carbon fiber face sheets. Sliding bolt-down points solved the problem of the significant difference in

thermal expansion between these solar panels and the aluminum support structure.
For safety and handling reasons the experiment tank is mounted in an aluminum container filled with N_2 gas at 1 bar.

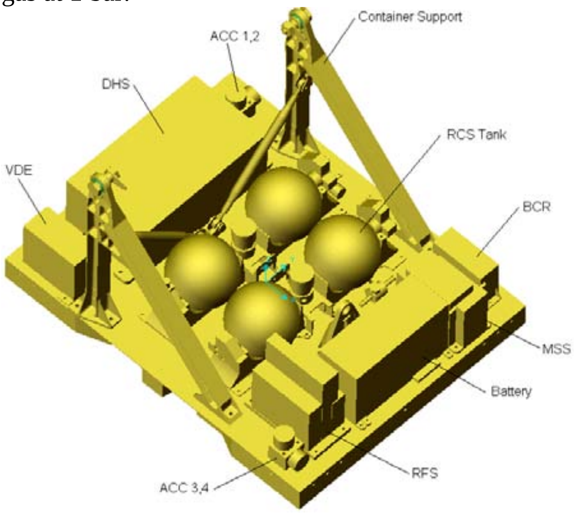

Figure 9 Equipment platform layout showing: the 3 container supports, 4 out of 6 accelerometers ACC, the data handling subsystem DHS, the valve drive electronics VDE of the reaction control subsystem RCS, the radio frequency subsystem RFS, the NiCd battery, the motion sensing subsystem MSS electronics with attached gyroscopes, the battery charge regulator BCR and the RCS gas supply equipment in the center

Thermal control subsystem TCS (Fokker Space)
The thermal control is passive. Multi-layer insulation is applied over the experiment container and the complete bottom side of the spacecraft (Figure 10).

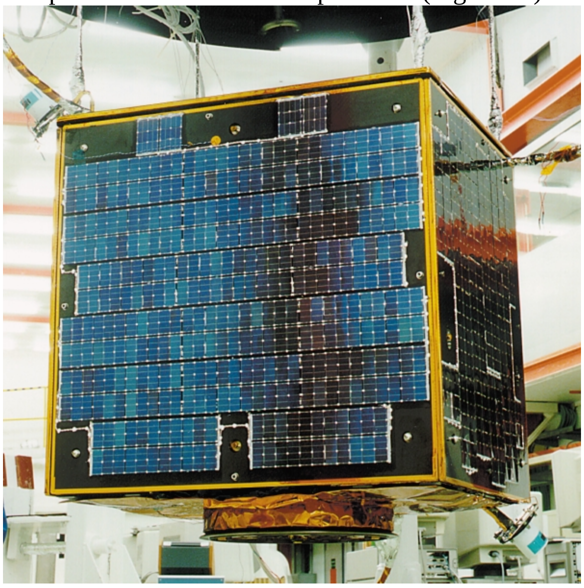

Figure 10 Sloshsat FLEVO as prepared for thermal-vacuum test

The inside temperature level is trimmed by applying specific coatings and giving the inner sides of the five solar panels an appropriate emissivity (calculated partial coverage by low emissivity-tape).
Ten thermostat-controlled heater systems prevent the tank, battery and 8 thrusters from getting too cold.
The most demanding thermal mission phases are those derived for safety while still attached to the Orbiter.
The spacecraft thermal-vacuum test passed successfully (Figure 10), validating the thermal design.

Power subsystem PWS (Fokker Space)
Sloshsat FLEVO has to be able to operate 14 days in a Shuttle orbit (orbit period 90 min, sunlit 60 min). In Operational Mode the satellite subsystems use 35W of electrical power, excluding heater power which consumes up to 24W @ 28V. When the battery is low, the S/C switches automatically to Hibernation Mode (3.4W, excluding heaters) to enable recharge.
Body mounted solar panels are located on five sides of the S/C (see Figure 10). Panel size dependent each provides between 52 and 66 W (@ 36.5V @ 65^{o}C @ 1360W/m^2). Fokker Space manufactured the panels, Kvant (Russia) the silicon solar cell part, with 17 solar cell strings in total.
The battery contains 22 Sanyo KR4400D NiCd cells. The nominal voltage is 28 V with a measured capacity of 5.1 Ah (143 Wh). The battery, designed by Surrey Satellite Technology Limited, meets the Shuttle safety requirements.
The battery charge regulator BCR uses the relatively new temperature derivative detection (Tdt) method for end of charge detection (originally developed at ESTEC). When the battery is fully charged, the excess solar array power is dumped via 4 foil heaters that are embedded in the MLI covering the bottom of the S/C. The power bus is unregulated, ranging from 24V (battery low) to 36.5V (sunlit, battery full). Prior to ejection the satellite receives Orbiter power (up to 28V, 3A), routed via the ESAJECT.
The internal power supply is equipped with four inhibit relays, which are necessary to meet the Shuttle safety requirements (two fault tolerant against mishaps). Prior to ejection an astronaut will close the latch relays from the Orbiter's standard switch panel SSP, to make the internal power supply operational.

Data handling subsystem DHS (NLR)
The data handling subsystem DHS consists of the system processor unit SPU-IV board, the sensors and actuators control S&A board, and the hibernation control board HCB. Electronics parts with industrial temperature range have been used. For safety circuits

MIL-STD-883B class B parts have been used. The housing, with 5 VME slots, accommodating the above 3 double size Euro-format boards (2 spare slots) and separately the power distribution unit PDU.
***The SPU-IV processor board* design** is based on the design for the TPX experiment (flown on STS-61). The functions include execution and storage of the on-board software OBS, control of the PLS and MSS outputs via RS-422, control of the two other VME boards, asynchronous telecommand and synchronous telemetry interface with the RFS and asynchronous communication with the EGSE. Some detail: 68020 microprocessor, 68882 coprocessor, 16 MHz clock, 256 kB UV-EPROM (OBS), 256 kB SRAM, and 128 kB EEPROM (parameters, variables, experiment control tables), and a watchdog circuit.
The sensors and actuators S&A board performs all analogue sensor conditioning, sampling and AD conversion (12-bit), except for the stand-alone PLS and MSS subsystems. Digital inputs are formatted. This board controls all RCS actuators, 12 thruster valves, latch valve, pyro selection and fire, which are commanded to the RCS-VDE drivers.
The hibernation control board HCB is the only board in the DHS that is never switched off during flight. The main function is to control the hibernation power relay HPR in the PDU, which switches Sloshsat FLEVO between operational mode and hibernation mode. During hibernation, most equipment is switched off, in order to reduce power consumption (see Table 2) to allow for battery charging.
The board has the circuitry to switch autonomously to hibernation mode when the battery low status persists for > 4 minutes, OR, a valid HHCS signal is not received for longer than 4 minutes, OR, upon a processor board watchdog time-out. The board switches to operational mode when the HHCS carrier is detected for > 20 s constantly AND the battery charge status is high for > 20 s continuously.
Other functions are to generate the 3 and 30 Hz system clock and VME bus interrupts, the 16128 Hz telemetry clock, and to keep the Sloshsat elapsed time SET (3 Hz time since power-on), all from the same clock crystal.
The always-on electronics are optically isolated.
The thruster timer board is a recently required safety addition to the system. It is part of a two-fault redundant protection scheme against the re-contact hazard (Sloshsat FLEVO flies back and hits the Orbiter within the ground radar detection period). Two redundant circuits determine the total impulse of any thruster combination that can produce translational acceleration. When a preset safety limit is surpassed, the satellite is forced to the hibernation mode. This board operates completely independent from the on-board software, and is mounted piggyback on the S&A control board.
The power distribution unit PDU provides power switching and DC/DC conversion functions. The main power relay MPR and the hibernation power relay HPR are located in this unit. The functionality of the HPR is discussed above with the HCB. The MPR is nothing more or less than a satellite on/off switch. This latch relay can only be externally controlled (via ESAJECT or test connector), therefore, this relay shall be “on” before ejection.
In hibernation mode only the HCB, the receivers and the heater circuits receive power (see also Table 2).

On-board software OBS (NLR)

The OBS consists of the software executed on the processor of the Data Handling System (DHS). This software controls all the on-board data acquisition and control functions. The DHS also communicates with the PLS and MSS intelligent subsystems and collects their measurement data.
The angular rate of Sloshsat FLEVO is commanded and controlled by 3 single-axis rate-feedback loops. Attitude control is not required. Linear and angular accelerations can be commanded via a force and torque vector, or by direct commanding of thrusters.
The OBS design is based on control by two tables, the most recent parameter base MRPB and the experiment action control table EACT. These two tables allow for late configuration and adaptation of the system operations.
The MRPB contains all state information within the OBS and makes this information accessible in a uniform way. Part of this state information is the most recent control and measurement data. Also defined in the MRPB are the source of all measurement data and the destination of the control data. Modifications to the MRPB (even during flight) allow for late changes in the configuration or modification of the behaviour of Sloshsat FLEVO. Modification can be made either to a single field or by up-loading a complete redefined MRPB.
The EACT controls the steps and sequences of steps within pre-defined experiment scenarios. The EACT consists of 42 slots that each can contain experiment scenarios of up to 355 code lines. During flight new scenarios can be up-loaded.
The OBS software performs all its actions within a 1/3 second time frame and all data in the MRPB is based on this 1/3 second time frame. For certain data a ten time higher temporal resolution is required, for this data multiple entries are defined in the MRPB.

The state diagram of the DHS-OBS combination is shown in Figure 11. In operational mode, opening the RCS latch valve enables the experiments.

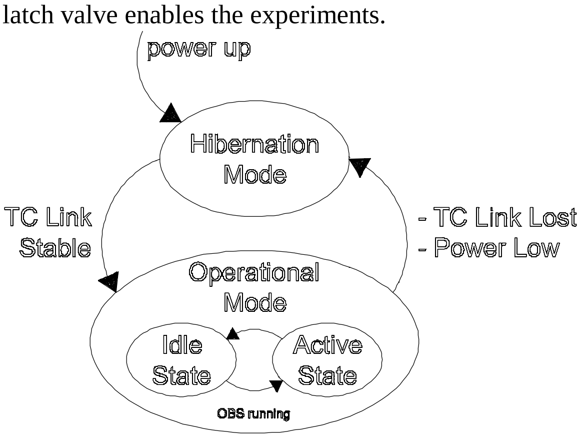

Figure 11 Data handling subsystem and On-board software state diagram

The OBS is developed on a UNIX development system on incremental basis. Most tests are performed on the target hardware, as they require some form of real-time performance or specific real-time operation system (pSOS) functionality.

Radio frequency subsystem RFS (Newtec)

The RFS subsystem provides full duplex, S-band, FM (FSK) modulated, continuous radio link with the HHCS on Hitchhiker/Orbiter. The RFS components are a transmitter (1W RF), dual receiver, three diplexer filters, a circulator/switch, and 2 hemi omni antennas. Important characteristics include low power consumption (Table 2), uninterrupted communication for any attitude of Sloshsat FLEVO, fully functional inside the cargo bay (< 1m) and up to 80 nautical miles with a bit error rate less than 10^{-6}.
Both identical receivers are active continuously, each with their own antenna. The transmitter signal is routed to the antenna of which the receiver detects the strongest HHCS uplink signal. This unique feature provides omni-directional coverage with the two antennas (-5dB at 90^o) mounted back to back on the spacecraft (Figure 1 and Figure 8).
The RFS-HHCS combination employs 'internal' error correction (Hamming code with up to 2 consecutive corrupted bits due to antenna switching), and scrambling/de-scrambling of both up- and downlink. The net telemetry of 16.128 bps (20 kbps gross) is transmitted at 2.205 GHz. The 1.2 kbps net uplink at 2.075 GHz (20 kbps gross).

Reaction control subsystem RCS (Rafael)

The cold gas reaction control system provides the spacecraft with full translation and rotation control.
A subsystem overview is given in Figure 12.
Four spherical carbon/epoxy-wound stainless steel tanks, store 1.6 kg of nitrogen gas (473 bar @ 20°C). The high pressure enables economic utilization of the limited space available. The tanks are of a "leak before burst" design, developed and tested in accordance with MIL-STD-1522A. The burst pressure is >1700 bar. The tanks are pre-pressurized and mechanically sealed at manufacturing. Each tank is equipped with an attached accessories assembly, that includes a pyro valve PV, and a filter F (Figure 12). The pyro valve includes an RAFAEL-developed initiator, which complies with MIL-STD-1576. One of the tank-assemblies also includes a high-pressure transducer, and the test port valve.
The four interconnected tanks are opened and depleted in sequence during flight. A surge damper decreases the shock wave pressure that develops when a tank is opened, and which otherwise would drive the qualification pressures.
The tank supply pressure is reduced in a two-stage pressure regulator to the working pressure of 16 bar (static = no flow). The lockup pressure (pressure after more than 8 hr with no flow) of the regulators is 17.4 bar. In case both regulators would fail open (safety design case), the downstream pressure would be equal to the high pressure, forcing an almost impossible qualification pressure. Therefore, two pressure relief valves are mounted downstream of the regulators. Each can handle the total flow with a minimum pressure rise, which defined the 35 bar maximum design pressure of the low-pressure part. When a relief valve opens, a nullifier prevents force and torque exertion.
A latch valve can close off the low-pressure pipework and thrusters from the above gas feed system. In flight this valve is only opened when slosh experiments are performed. The sensitivity of the regulated pressure to the pulse modulation of the thrusters was examined. Due to the difference between the static pressure (16 – 17.4 bar) and the pressure level with flow (14.5, 14.25, 13.6 and 13.1 bar for 1 up to 4 thrusters simultaneously) the average pressure was found to depend on the pulse duty cycle. A model that predicts the pressure level versus mass flow rate and pulse modulation was established. The average thruster force is 0.785N at 14 bar gas supply. A low-pressure transducer provides the actual working pressure. This measurement will be used for accurate post-flight thrust calculations.

The on-board software in the DHS controls the RCS functions. The drivers for the valves (thrusters, latch valve and pyro valves) are located in a separate unit, the valve drive electronics VDE. This unit also houses the safety functions that are required to disable pyro valve operation when still attached to the Orbiter or in the neighborhood of the Orbiter (separation switches, timers, and power relays). The VDE has been developed by ESTEC.

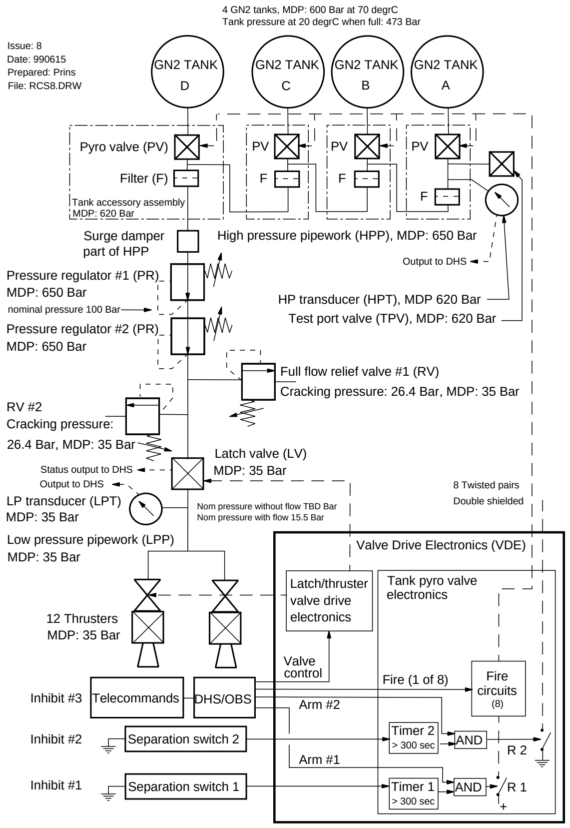

Figure 12 Reaction control subsystem RCS block diagram

Motion sensing subsystem MSS[6] (NLR)

The MSS task is to measure the complete spacecraft acceleration field for slosh experiment purposes and the rotation rates for angular rate control. To this end 6 linear accelerometers and 3 gyroscopes are implemented.

AlliedSignal QA-3000-10 accelerometers are selected as best compromise between performance and cost. For the fine range output of ±30 mg, their current outputs are converted to voltage, pre-amplified and passed through a 4-pole, 4 Hz low-pass Bessel filter and then digitized (16 bit) with 30 Hz in the MSS electronics. The anti-aliasing filter is expected to reduce the sensor noise to below 1 μg (1σ, 0.1–3 Hz). The unfiltered ±1.5 g range output is digitized with 3Hz. The sensor manufacturer supplies 4-th order temperature compensation models for bias, scale-factor, output axis and pendulous axis misalignments. Accurate in-flight bias calibration procedures are foreseen.

The acceleration data are used for the post-flight determination of the liquid force and torque exerted on the spacecraft[7]. The accelerometer outputs are not used on-board. The accelerometer configuration is chosen such that 3-D linear and angular acceleration can be calculated with high accuracy. A similar ‘ballistometer’ scheme with nine accelerometers, developed at NLR, has been used for the WSM sounding rocket experiment in 1993.

For real-time angular rate control, three Litton-Litef μFORS-36/6 optical fiber gyroscopes are installed. These sensors produce a direct digital output. The gyros are configured for a range of ±98 degree/s. Some typical specifications: bias stability ≤ 6 °/hr (1σ), random walk noise ≤ 0.45 °/√hr (1σ), scale factor error ≤ 0.15 % (1σ), and misalignment ≤ 2 mrad. The actual sensors perform considerably better.

The MSS electronics accept raw power from the power bus and collect and format all sensor data. Data are sent to the on-board computer via an RS-422 bus with 3 Hz intervals. Therefore, the MSS can be easily operated stand-alone from a PC, which highly facilitates the development and test activities.

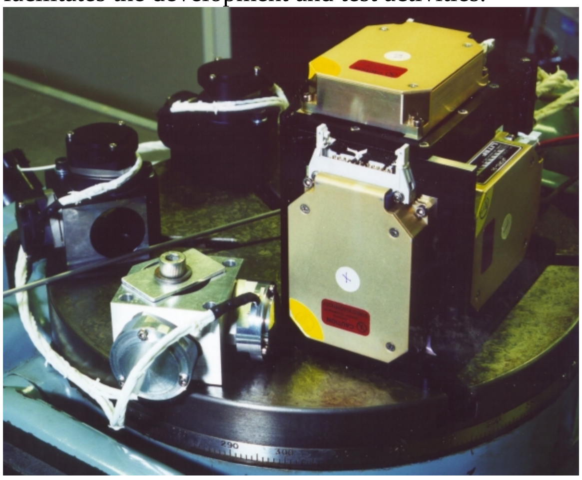

Figure 13 Motion sensing subsystem components under test; three accelerometer brackets with 2 accelerometers each on the left, and the MSS electronics box with the three orthogonal mounted gyroscopes on the right

Ground support equipment GSE (NLR)

The complete Sloshsat FLEVO software system consists of the on-board software OBS and the test support and ground operation TSGO software components. The TSGO software both supports the test and flight operations phases. In the operational phase this software is executed on two standard PC's, one that performs the real-time monitoring and control of the spacecraft (Figure 14) and another that performs the data receiving, storage and pre-processing functions. During operations these two parts are connected via telecommand and telemetry TM/TC links.

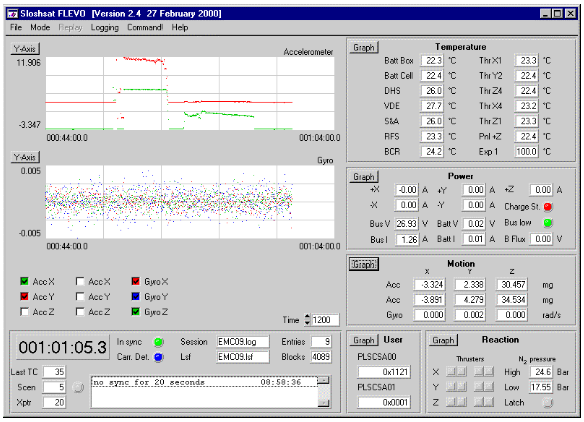

Figure 14 Typical EGSE operator screen, graph features, telecommand history, housekeeping data, etc.

SYSTEM SCHEMATIC AND BUDGETS

The mass and power budgets are shown in Table 1 and Table 2, respectively. The Sloshsat FLEVO electrical interfaces are summarized in Figure 17.

Table 1 Dry mass distribution (kg)

Subsystem	Mass	%
Dry mass:		
PLS	10.3	10.8
STS	37.8	39.5
ESAJECT upper part	6.2	6.5
TCS	0.9	0.9
PWS	7.0	7.4
DHS	6.5	6.7
Cable harness	2.8	3.0
RFS	5.4	5.7
RCS (incl. 1.6 kg GN2)	15.4	16.1
MSS	3.4	3.5
Total dry mass	**95.7**	
Experiment water	33.5	
Total mass at launch	**129.2**	

Table 2 Power consumption from raw power bus (Watt @ 28V)

Mode -->	Operational	Hibernation
Subsystem (inc. internal DC/DC converter loss):		
PLS	3.5	0
DHS	4.3	0.3
PDU (DC/DC losses)	2.4	0.3
Cable harness losses	1.0	0.2
RFS	11.0	2.6
RCS	2.1	0
MSS	10.8	0
Total (exc. heaters)	**35.1**	**3.4**

Mode -->	Operational	Hibernation
Heaters (resistive load @ 28V):		
PLS heaters (4)	6.5	6.5
Thruster heaters (8)	12.0	12.0
Battery heater (1)	5.4	5.4
Total (maximum)	23.9	23.9
Nom. orbit average	**0**	**5**

TESTING

Testing followed the normal path of any satellite, including thermal-vacuum, metrology, end-to-end functional, EMC (Figure 15), and vibration testing. The determination of the center of mass and moment of inertia required special attention because of the stringent experiment accuracy requirements. A torsion wire test set-up was developed (Figure 16), already proven successful during WSM development.

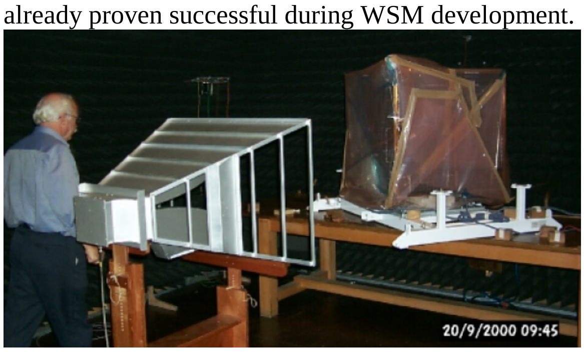

Figure 15 One of the EMC test set ups

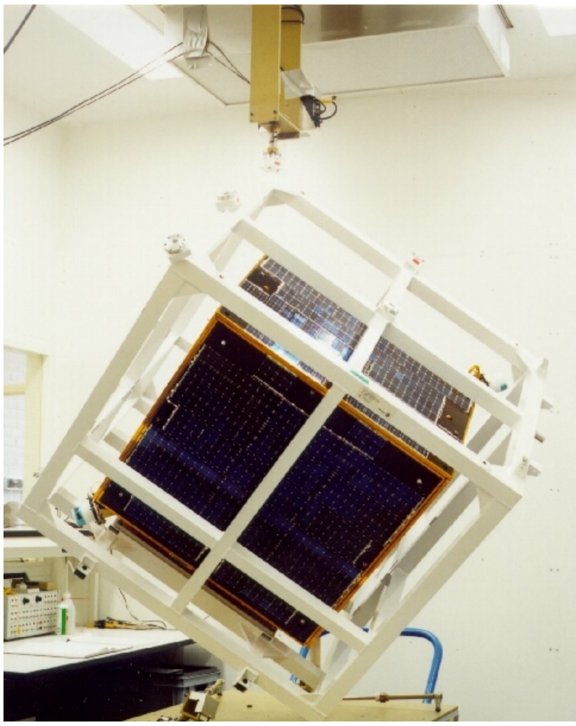

Figure 16 Moment of inertia measurement set up

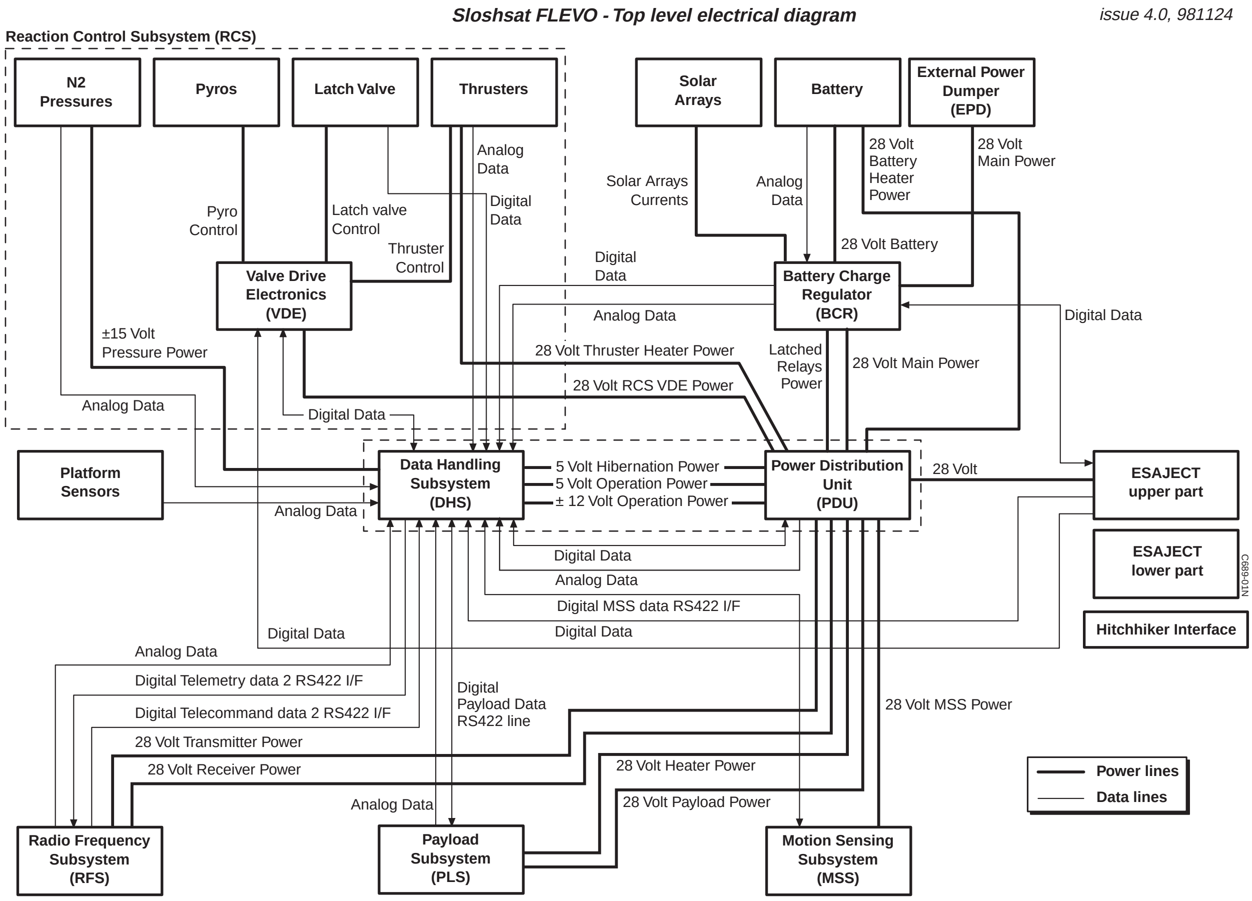

Figure 17 Sloshsat FLEVO top level electrical diagram

OPERATIONS

Sloshsat FLEVO will be operated in real time from the Operation Control Center OCC at Goddard Space Flight Center GSFC, Washington DC. The data transmission fully depends on Shuttle-ground data relay by the Orbiter (Figure 18), limiting the operational life to the duration of the Shuttle flight. The almost continuously available S-band link is used for control and quick view of the experiments. The full experiment data stream of 16 kbps is transmitted in real time whenever the Ku-band link is available. After the completion of each experiment run, the complete recorded data set (PGSC/ACT) is dumped to the OCC via Ku-band. The real-time and post-run-dumped data are routed to experimenters at their User Home Base UHB, via Internet. With ACT software they will be able follow the experiment in real time (low speed S-band telemetry), equal to the astronaut view (PGSC/ACT).

The total experiment time will be at least 24 hours, divided over approximately 20 experiment runs, spread over the Shuttle's mission duration. Quiescent

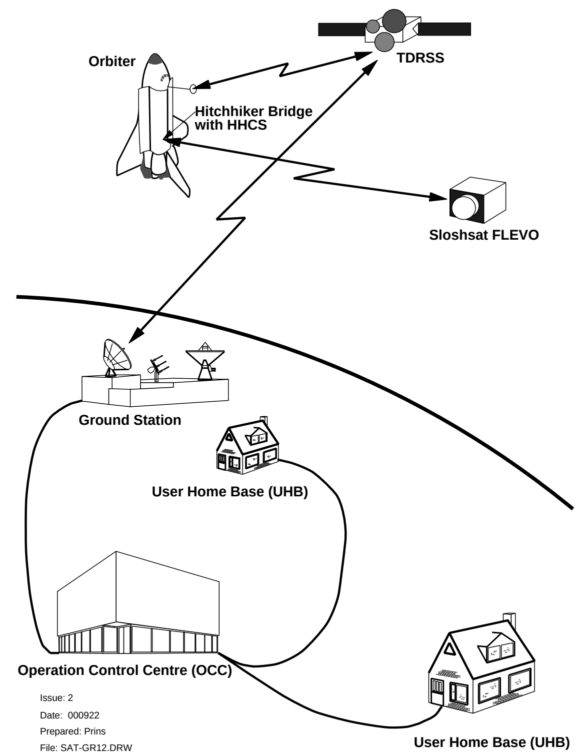

Figure 18 STOF operational communication routing

periods in hibernation mode between experiment runs will allow the water to settle and the battery to be charged. Before ejection, nominally on day 2, in-orbit checkout and calibration will be performed. A few sloshing experiments will be executed using Orbiter induced motion. This allows forced tank motion almost without fluid/spacecraft interaction (very small liquid/rigid ratio).
After ejection the Orbiter flies to an operational distance of ≥50 nautical miles, in the Sloshsat FLEVO orbit. The distance and the relative delta-V are regularly checked by a NASA ground-based radar system. Whenever this tends to grow out of safety limits (e.g. <50 nm) or out of the 80 nm operational range of HHCS-RFS, the Orbiter has to adjust its orbit again to that of Sloshsat FLEVO.
At operational distance, a free-flying checkout and some calibrations will be performed. Next, Sloshsat FLEVO will execute its free-flying experiment program, which includes e.g. fluid transfers from one tank end to the other, transfers to flat spin, and spinning translations. At the end of the mission, with all RCS gas depleted and safety conditions permitting, the Orbiter will rendezvous with the spacecraft for calibration purposes. The Orbiter will not retrieve Sloshsat FLEVO. A natural orbit decay will de-orbit the satellite after approximately 0.5 year.

SAFETY

Sloshsat FLEVO, being Shuttle launched, is subject to the stringent safety rules defined for manned space flight. The strong implications, although expected from the start, proved more severe than anticipated. In particular, the RCS and PWS designs have been safety driven. When the satellite was integrated already, the re-contact hazard was identified, forcing hardware additions and operational constraints.
Note: A complicated payload such as Sloshsat FLEVO requires intensive and costly interaction with the NASA safety staff. The information flow path is very long as well (subcontractor, prime contractor NLR, ESA, NASA GSFC, and NASA JSC and visa versa), which complicated matters further.

STATUS

Sloshsat FLEVO testing is completed, except for the combined vibration test with ESAJECT. After this final test STOF will be ready for integration on the Shuttle Hitchhiker Bridge, 7-8 months before launch. Earlier this year the STOF planned launch with ST-107 was changed to the research mission R2, and later to a possible launch opportunity with R3.

SUMMARY

The paper summarizes the design and development of the Sloshsat FLEVO small-satellite. The mission objectives were shortly stated, followed by a description of the larger STOF project.
The more special characteristics of the various subsystems are highlighted. Safety aspects and operations are shortly touched.

NOTE BY THE AUTHOR

The Sloshsat FLEVO small satellite development has been challenging. Considering the necessary research, the problems encountered and the small size of the development team, it has been rewarding to all involved. Being part of a small-sat team gives the opportunity for personal professional growth. The core team members are active in several different disciplines, otherwise shared by a much larger team.

The fluid dynamics scientists are impatiently waiting for the flight data. Industry has shown considerable interest already. Expectantly, results will lead to a better understanding of the increasingly important fluid dynamics interaction of spacecraft. Spin-off to earth-bound applications already takes shape.

ACRONYMS

ACC	ACCelerometer
ACT	Advanced Crew Terminal
BCR	Battery Charge Regulator
CFD	Computational Fluid Dynamics
DHS	Data Handling Subsystem
EACT	Experiment Action Control Table
EGSE	Electrical Ground Support Equipment
ESAJECT	ESA eJECTtion system
FLEVO	Facility for Liquid Experimentation and Verification in Orbit
HCB	Hibernation Control Board
HHCS	Hitchhiker Communication System
HPR	Hibernation Power Relay
MLI	Multi Layer Insulation
MPR	Main Power Relay
MSS	Motion Sensing Subsystem
OBS	On-Board Software
PDU	Power Distribution Unit
PFM	Prototype-Flight Model
PGSC	Payload and General Support Computer
PLS	PayLoad Subsystem
PWS	PoWer Subsystem
RCS	Reactions Control Subsystem
RFS	Radio Frequency Subsystem
S&A	Sensor & Actuators
S/C	SpaceCraft
SMS	Sloshsat Motion Simulator
SSP	Standard Switch Panel
STOF	Slosh Test Orbital Facility
STS	STructure Subsystem
TCS	Thermal Control Subsystem
TM/TC	TeleMetry/TeleCommand
TPX	Two-Phase flow eXperiment
VDE	Valve Drive Electronics
WSM	Wet Satellite Model

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5 E. van Oijen, M. Wolff, P. Dujardin. "The Advanced Crew Terminal, an Integrated, Common, Low Cost and Configurable Toolset for Operations Activities". Presented at IAF Amsterdam, October 4-8, 1999. NLR-TP-099438
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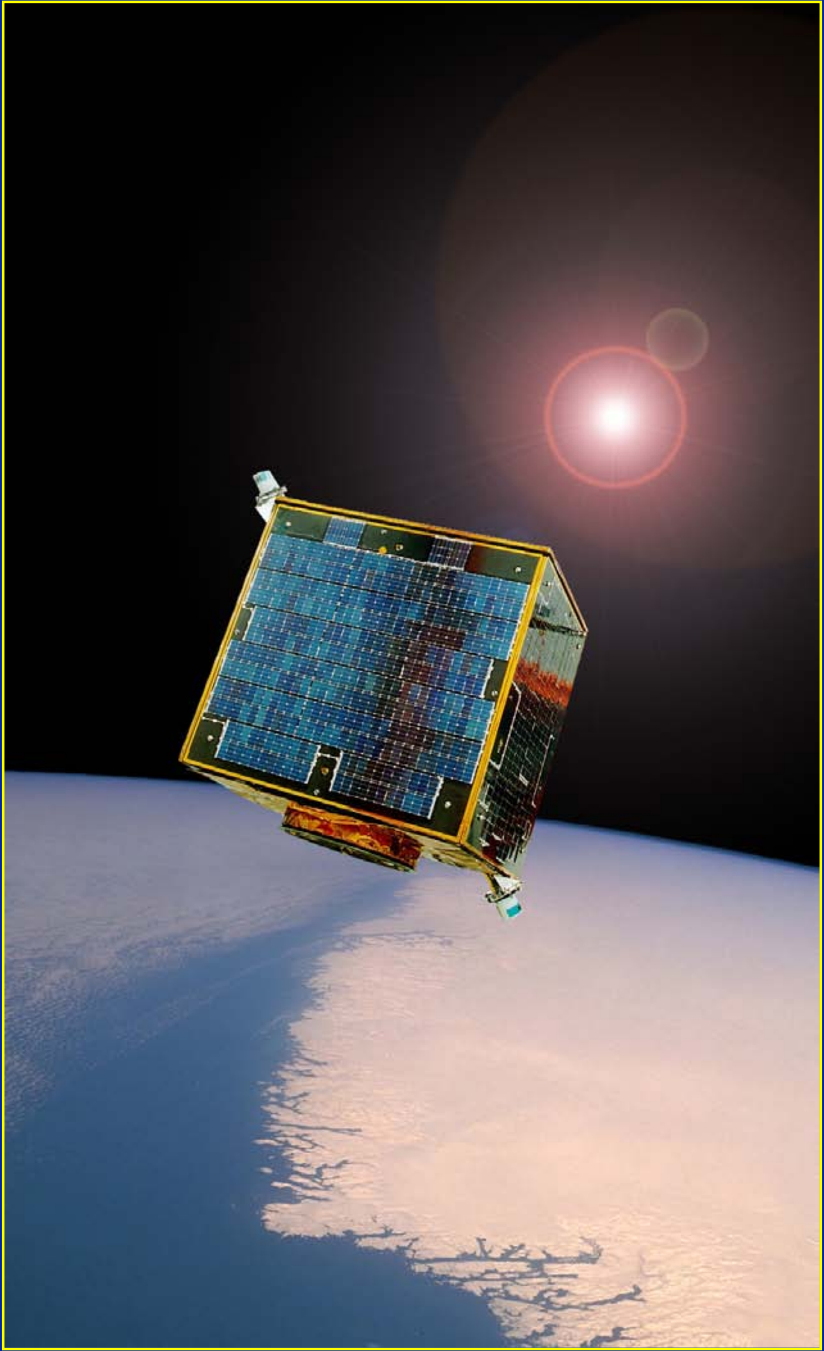
ACKNOWLEDGEMENT

The author is project manager and chief designer of Sloshsat FLEVO. He wishes to express his gratitude for the dedication of his fellow engineers at NLR, Fokker Space, Rafael, Newtec, and Verhaert, who were and still are involved in the project.
The co-operation with NIVR, ESA and NASA professionals has been both challenging and rewarding.
A special acknowledgement goes to dr Jan Vreeburg of NLR who initiated and still leads the science of the project, and dr Hans Roefs of NLR for his never failing support, in particular on the fundraising side.

Sloshsat FLEVO is a harmonized programme between the European Space Agency ESA and the Netherlands Agency for Aerospace Programmes NIVR. Main contractor is the National Aerospace Laboratory NLR with participation of Fokker Space (The Netherlands), Verhaert (Belgium), Newtec (Belgium), Rafael (Israel) and NASA (USA).
The Sloshsat FLEVO development is performed in the framework of the ESA Technology Demonstration Programme TDP Phase 2, the NIVR Research and Technology NRT programme, and NLR's own research and development programme.

Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR



Sloshsat FLEVO

Facility for Liquid Experimentation and Verification in Orbit

J.J.M. Prins
(presented by H.F.A. Roefs)
National Aerospace Laboratory NLR
The Netherlands

51st International Astronautical Congress
2-6 October 2000 Rio de Janeiro, Brazil

Sloshsat FLEVO

Contents

- **Objectives**
- **Project**
- **Description**
- **Status**

Sloshsat FLEVO Objectives

- **Develop and qualify a low-cost small satellite**
- **Develop and perform the flight experiments**
- **Obtain experiment data to verify/validate fluid dynamics models and simulators**

Sloshsat FLEVO Project

- **Spacecraft development team (Netherlands, Belgium, Israel)**
  - Prime contractor: NLR
  - Sub-contractors: Fokker Space, Verhaert, Newtec, Rafael
  - Co-operation: ESA, NASA
- **Science team (IWG)**
  - Univ. of Groningen and Delft (The Netherlands)
  - NLR
  - Technion (Israel)
  - ESA, NASA
- **Contract**
  - European Space Agency ESA
  - The Netherlands Agency for Aerospace Programmes NIVR

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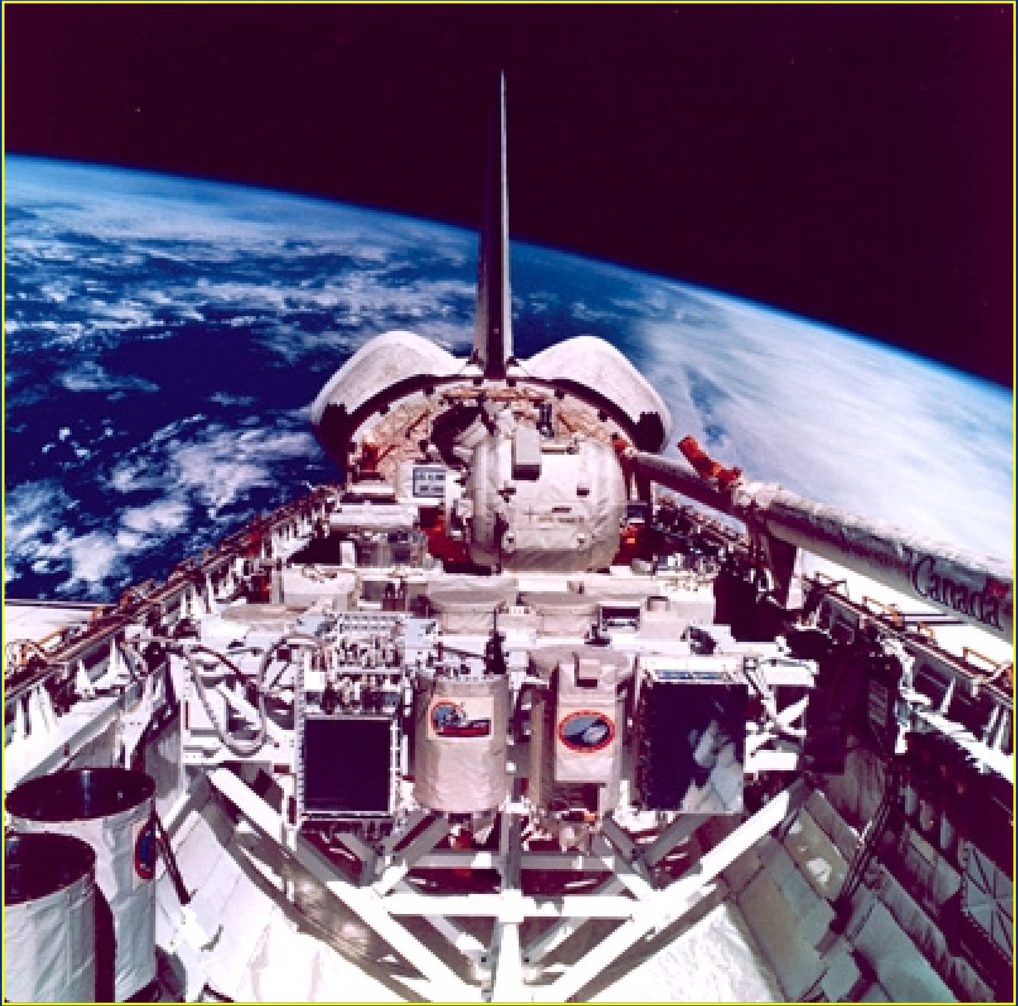
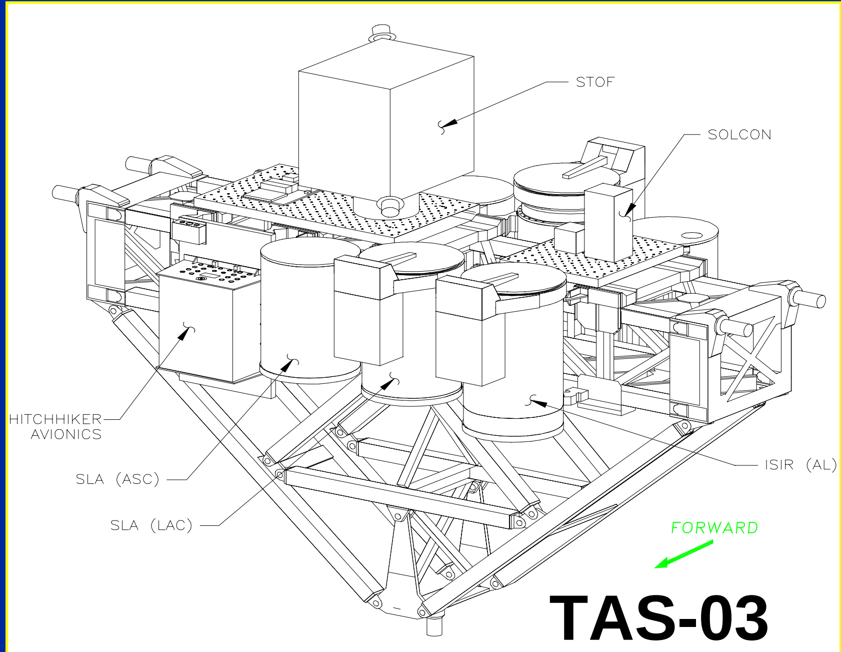
Sloshsat FLEVO
Shuttle Hitchhiker payload





Internet site: http://sspp.gsfc.nasa.gov

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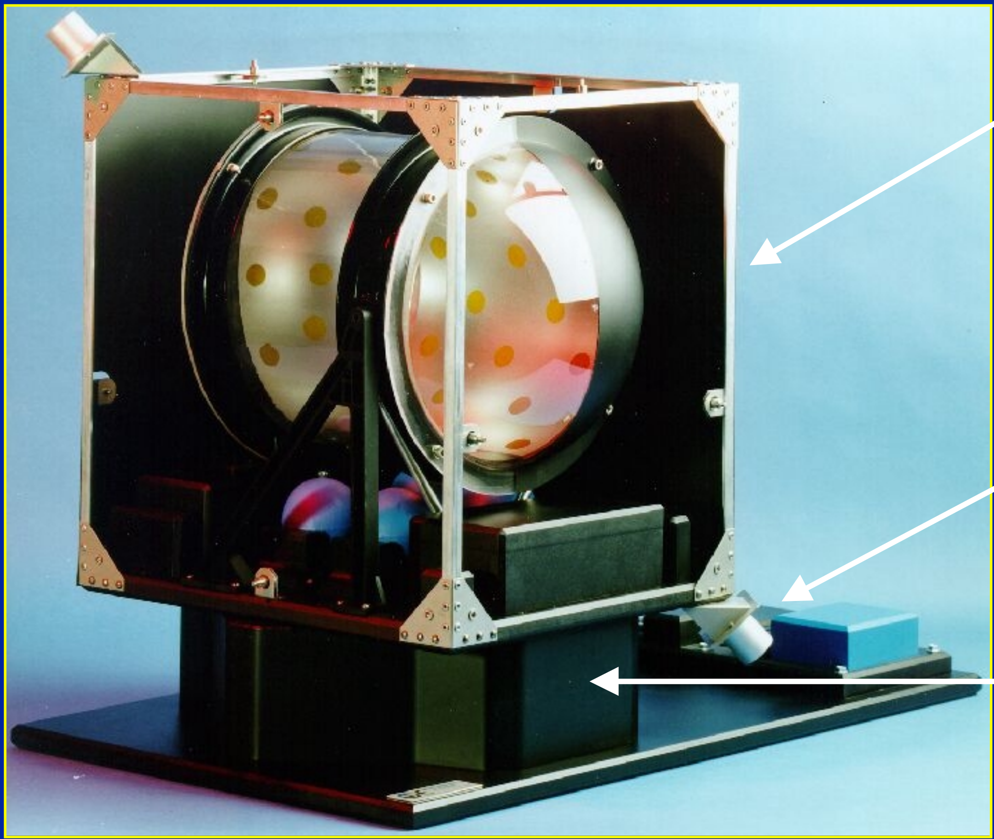
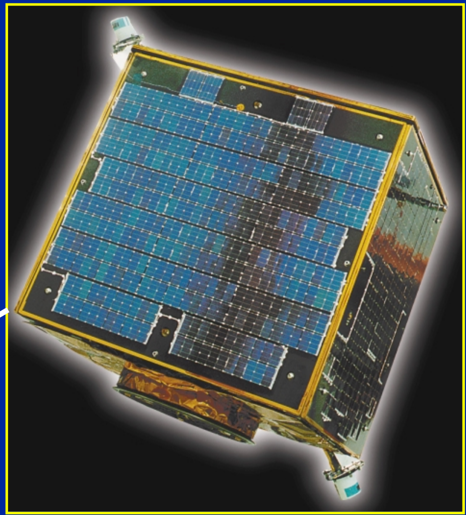
National Aerospace Laboratory NLR

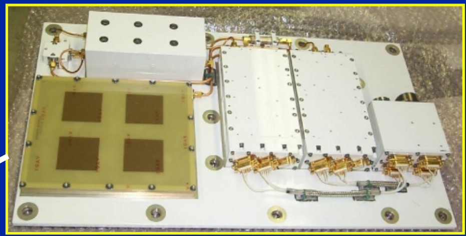
Sloshsat FLEVO STOF overview

Slosh Test Orbital Facility STOF

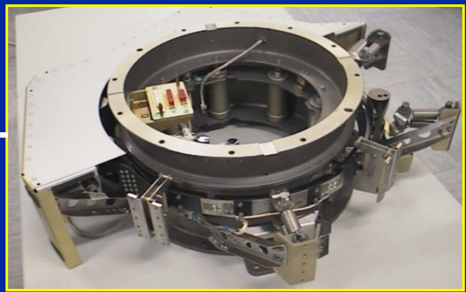




Sloshsat FLEVO
NLR (Netherlands)



HHCS
HitchHiker
Communication System
Newtec (Belgium)



ESAJECT
ESA Ejection System
Verhaert (Belgium)

Sloshsat FLEVO
Design overview

- **Mini-satellite launched/ejected from Shuttle Hitchhiker**
- **Orbit: trailing Shuttle at 50 - 70 nautical miles**
- **Operational life time: Shuttle flight duration**
- **Communication: Ground / TDRSS / Shuttle / HH / HHCS**
- **Spacecraft dry mass: 96 kg**
- **Experiment liquid mass: 33.5 kg (liquid/rigid ratio: 0.35)**

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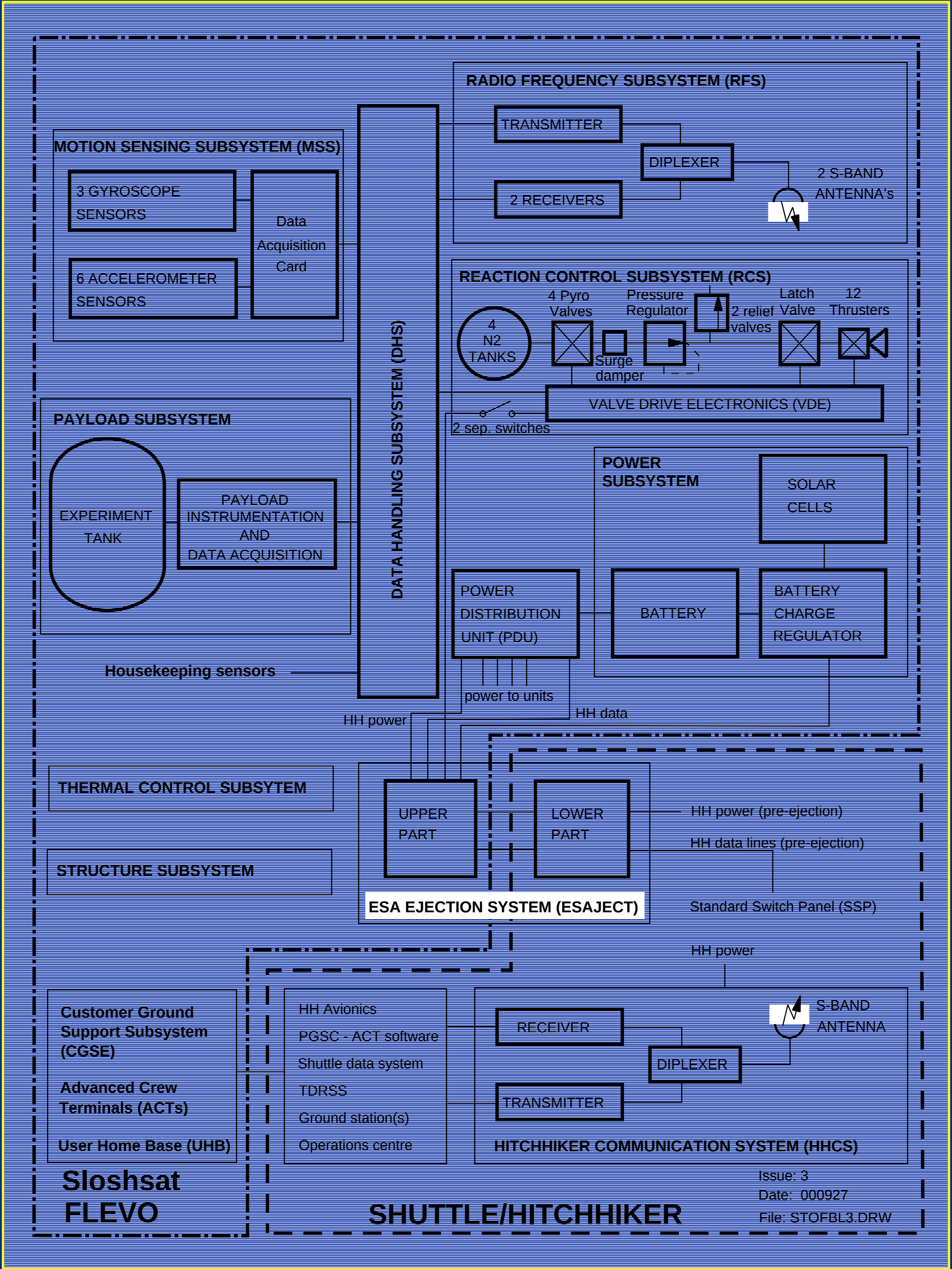
Sloshsat FLEVO STOF block diagram



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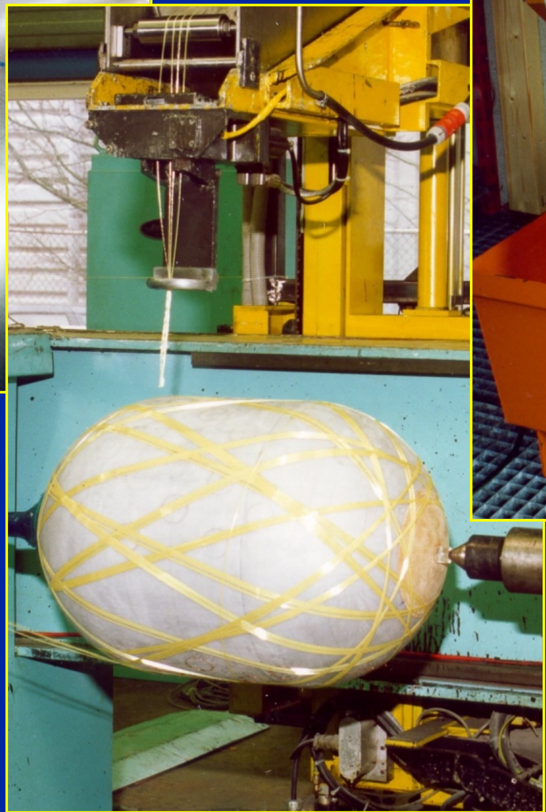
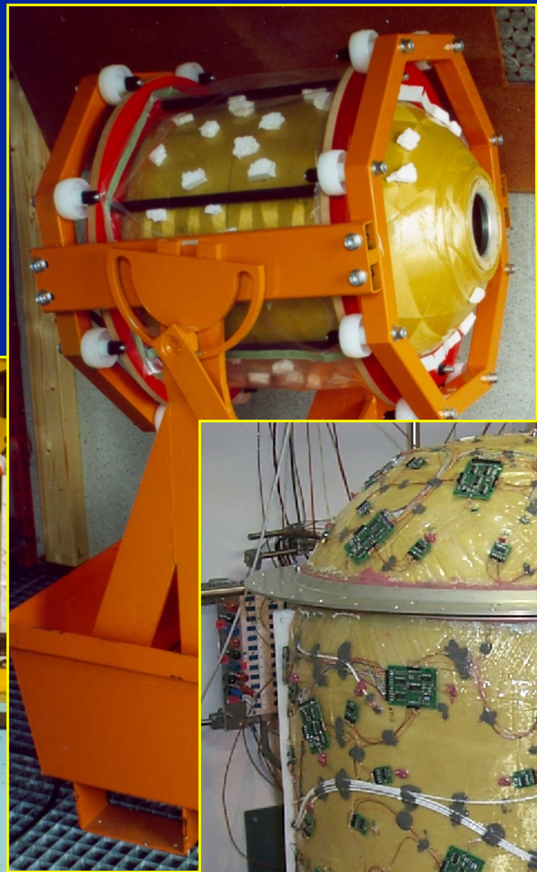
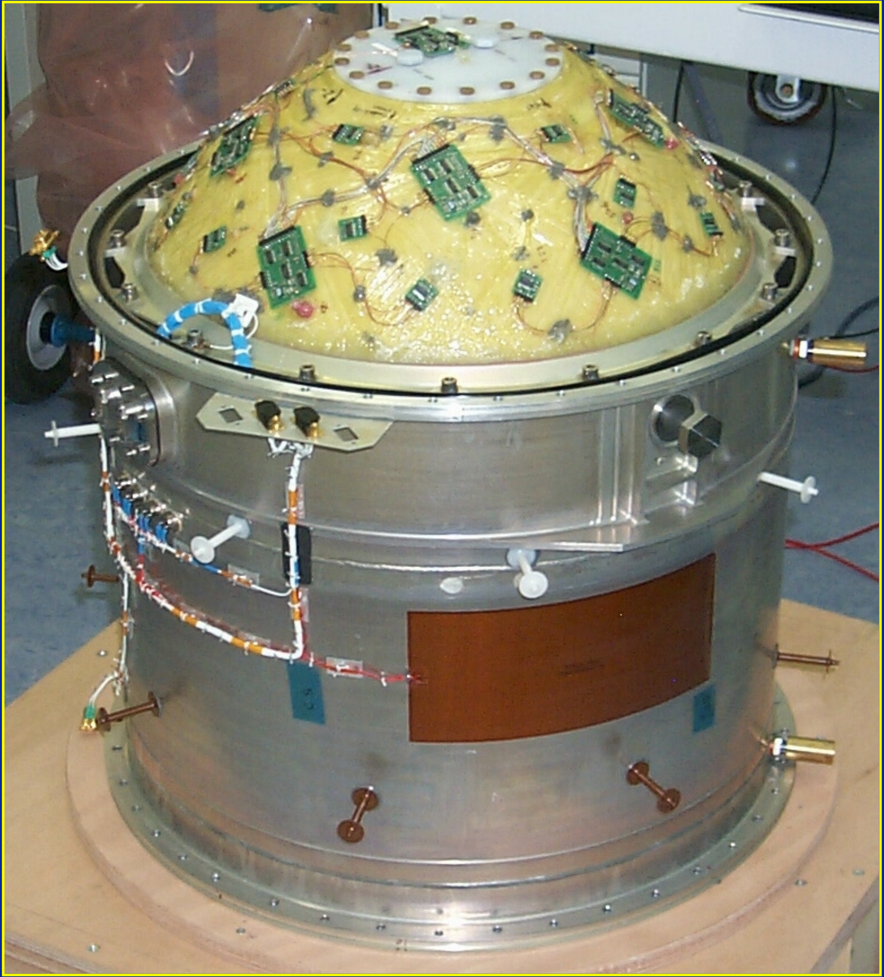
Sloshsat FLEVO Tank development





Sloshsat FLEVO
Experiment tank characteristics



Cylinder, hemispherical ends

Radius/length: 0.228 m

Volume: 86.9 liter

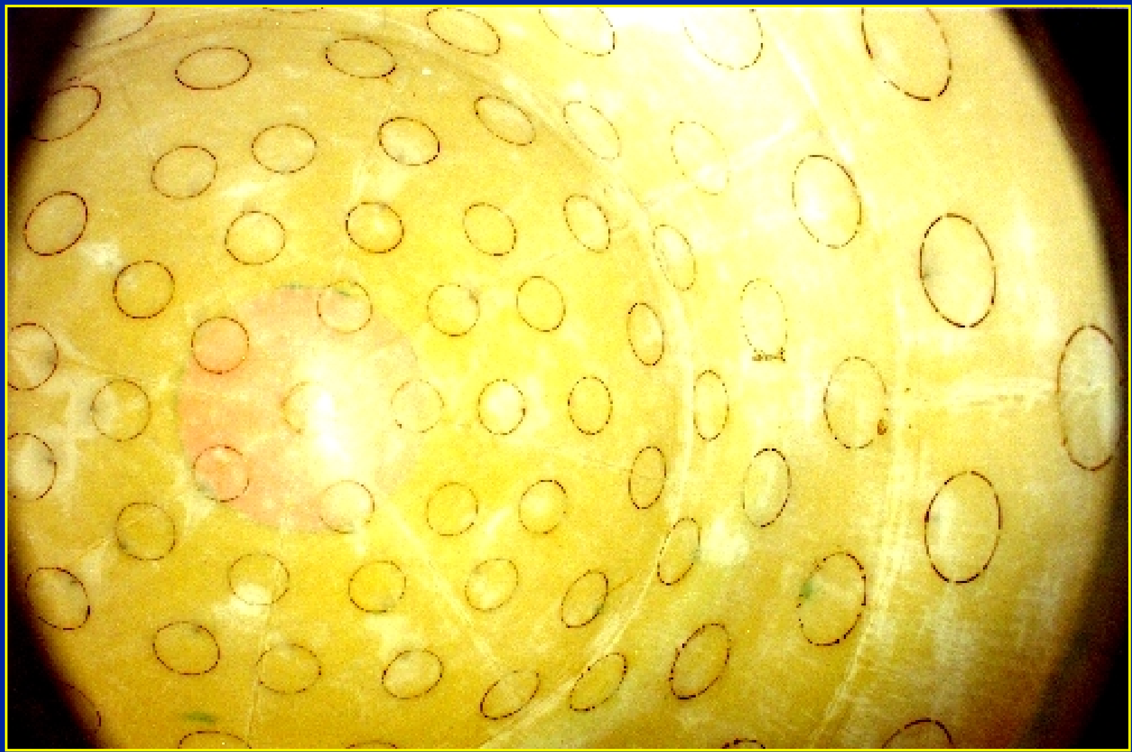
Liquid (water): 33.5 kg

Void: N2 gas at 1 bar

Aramid reinforced epoxy, polyethylene liner

Mounted in container

Sloshsat FLEVO
Liquid state measurement



- Contact line location, coarse height (270)
- Velocity (10)
- Fine height (3)
- Conductivity (1)
- Temperature (1)

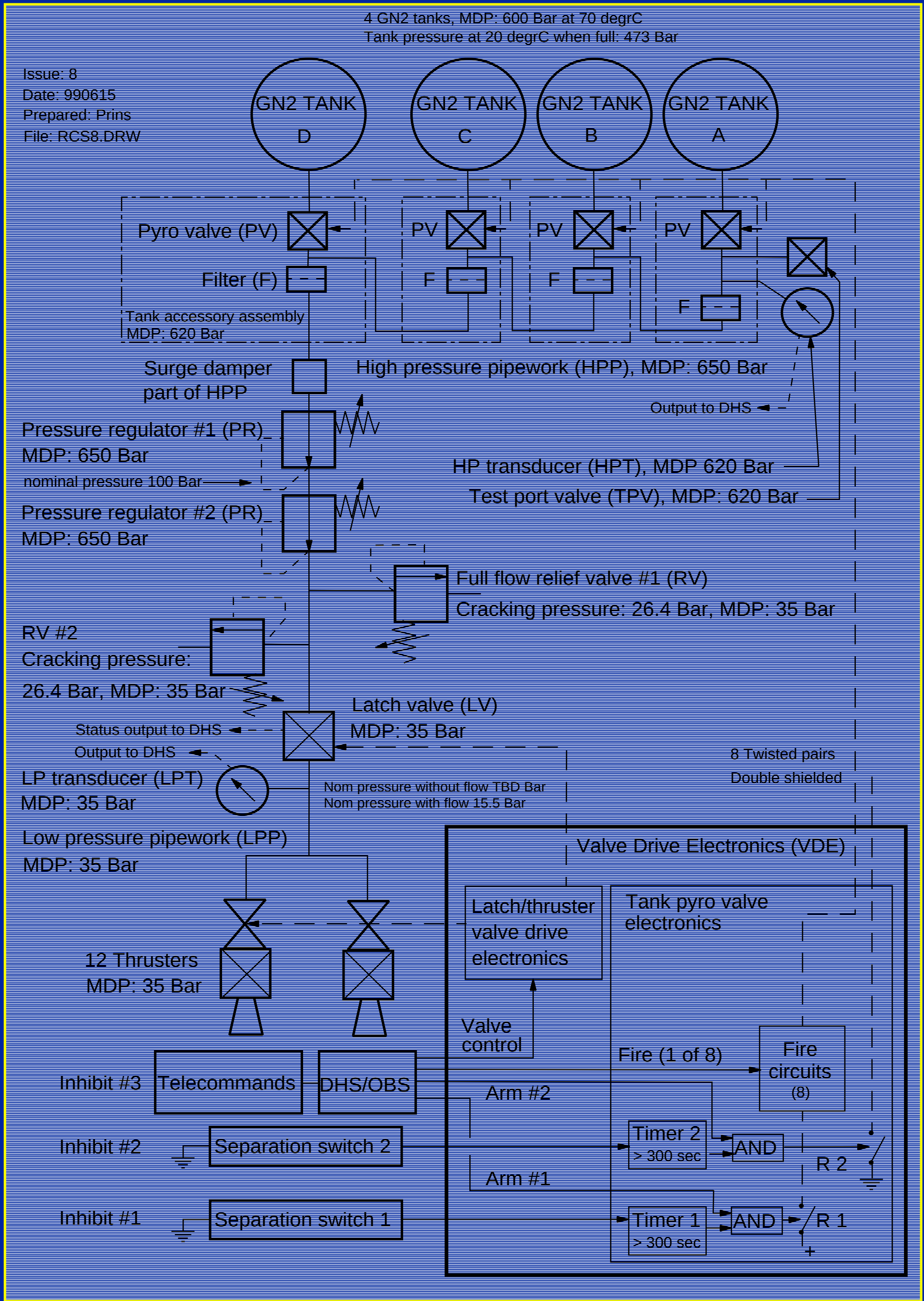
Sloshsat FLEVO
Satellite state measurement

Electronics

Gyroscopes (3)

Accelerometers (6)

Flight units in test setup



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Sloshsat FLEVO Reaction Control Subsystem RCS

Cold gas (nitrogen, 1.6 kg)

4 Tanks 600 bar @ 70^{o}C

Pyro valves

12 Thrusters 0.8 N

Manufacturer: Rafael, Israel

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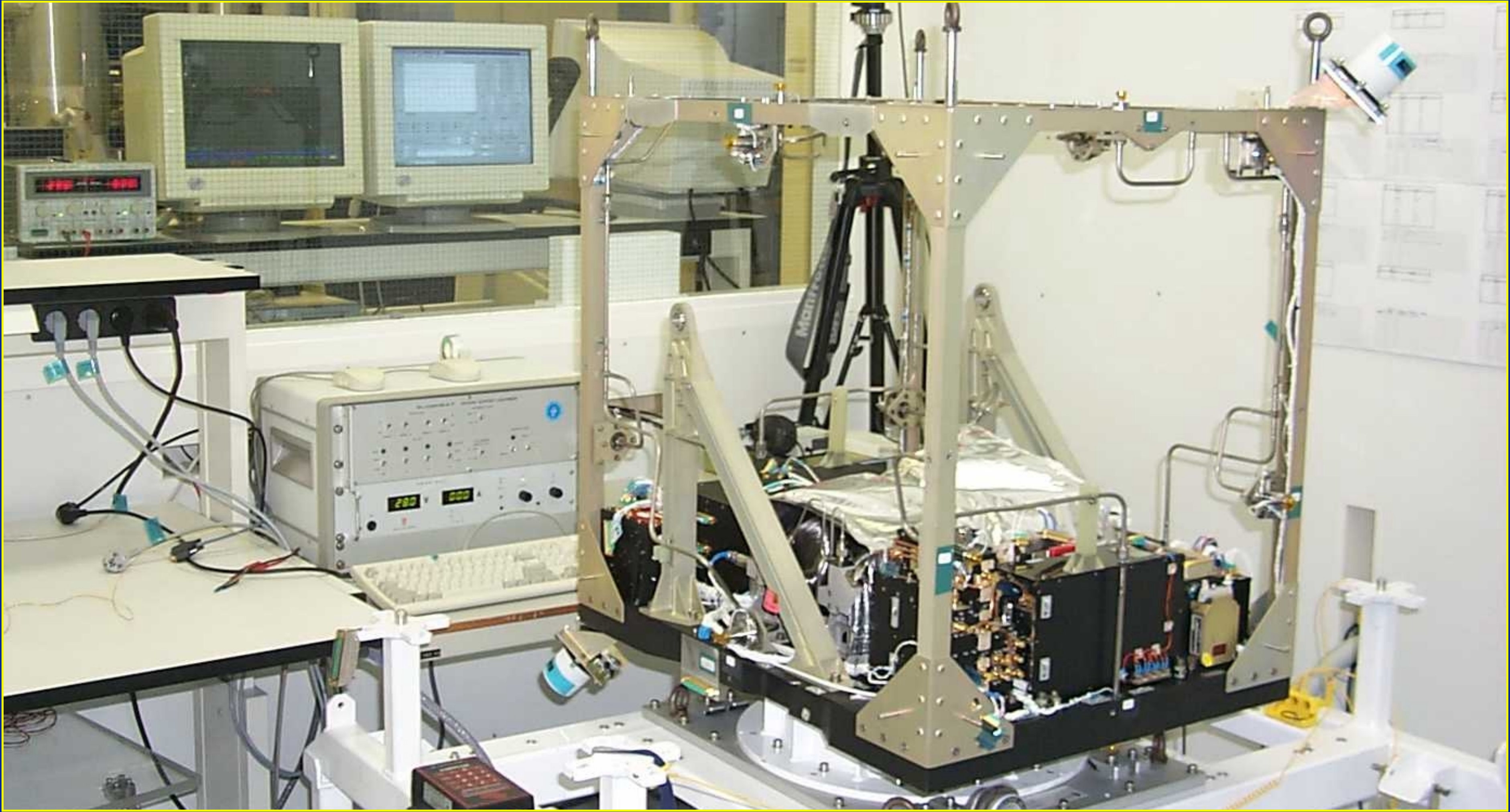
Sloshsat FLEVO Electrical Integration



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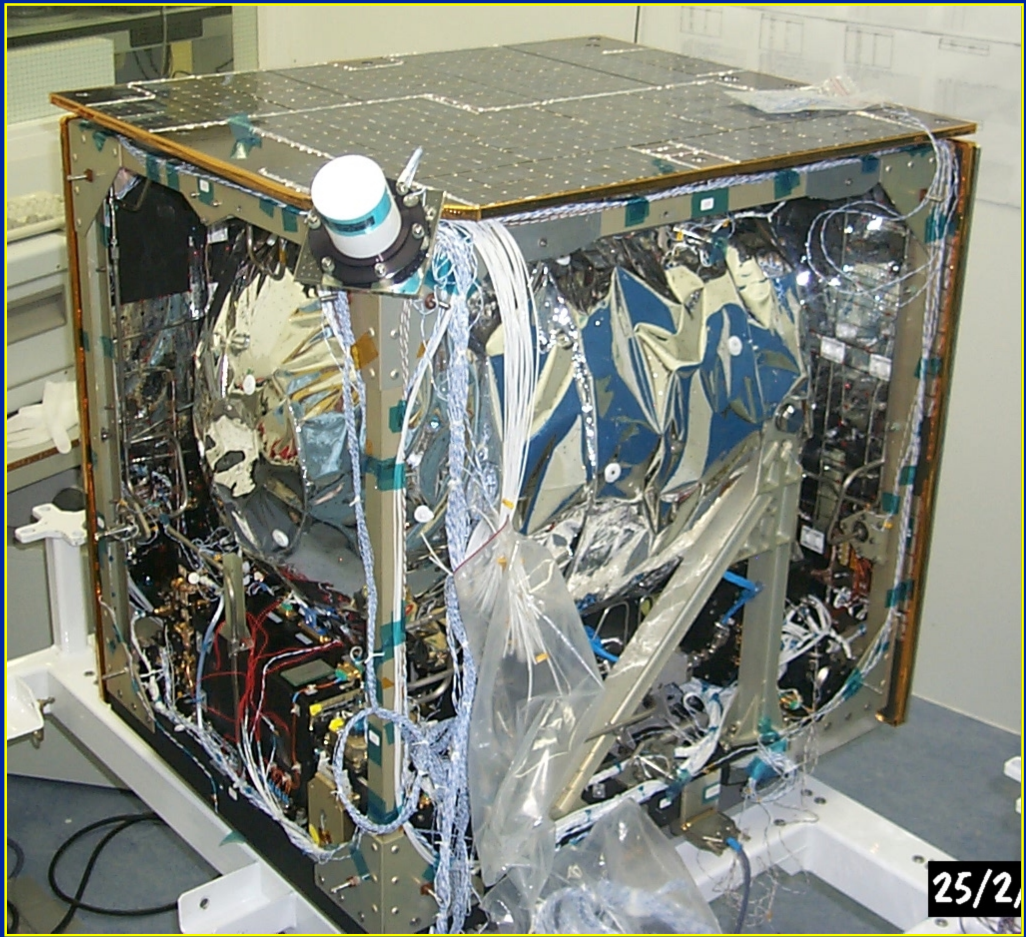
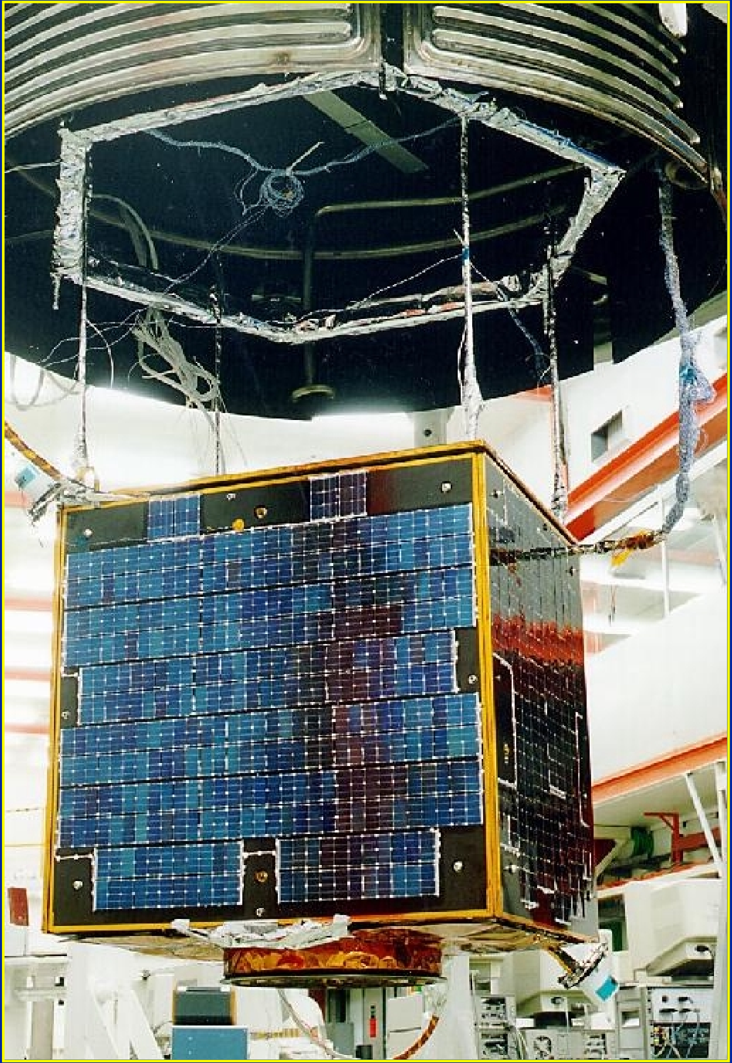
Sloshsat FLEVO
Thermal-vacuum test





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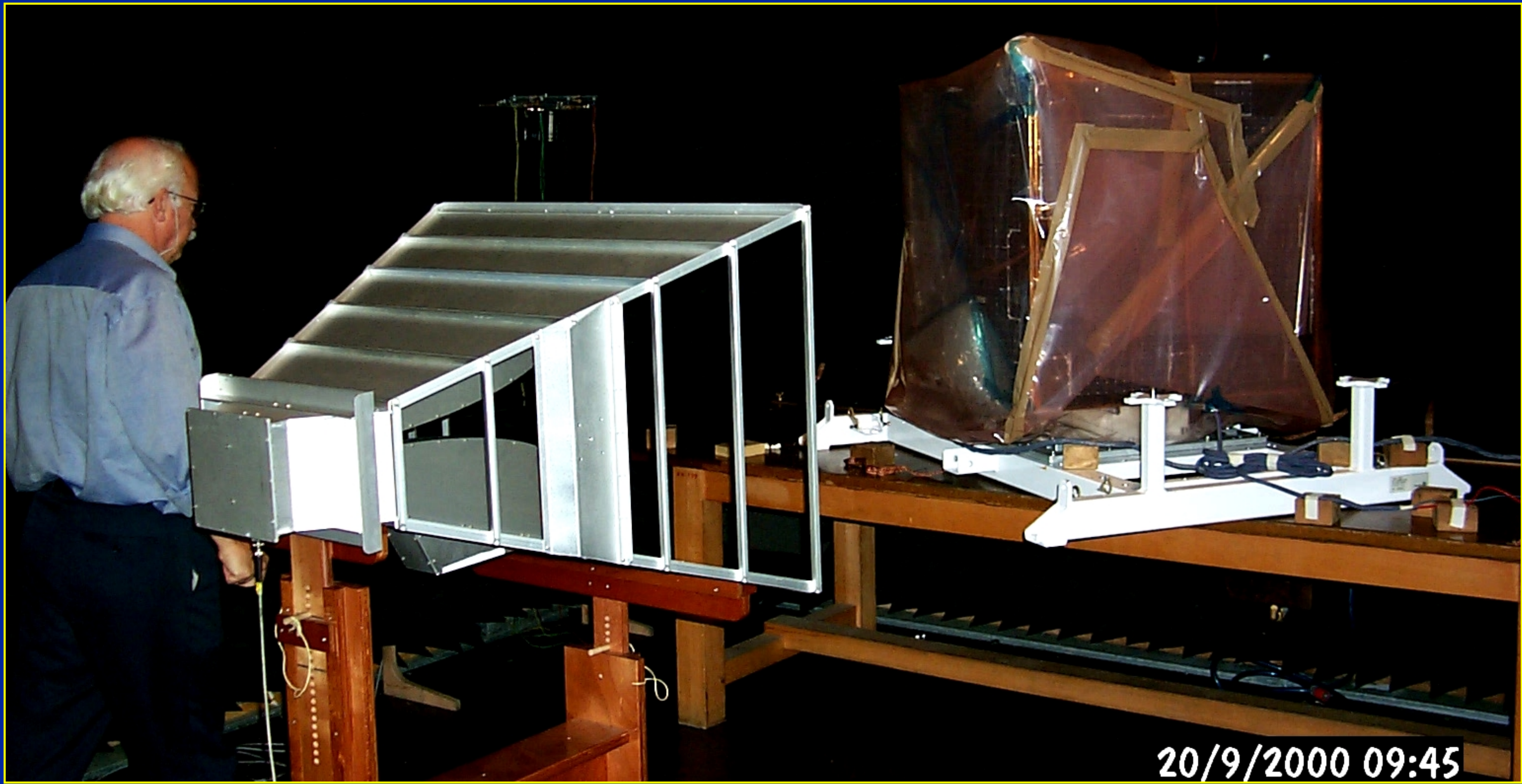
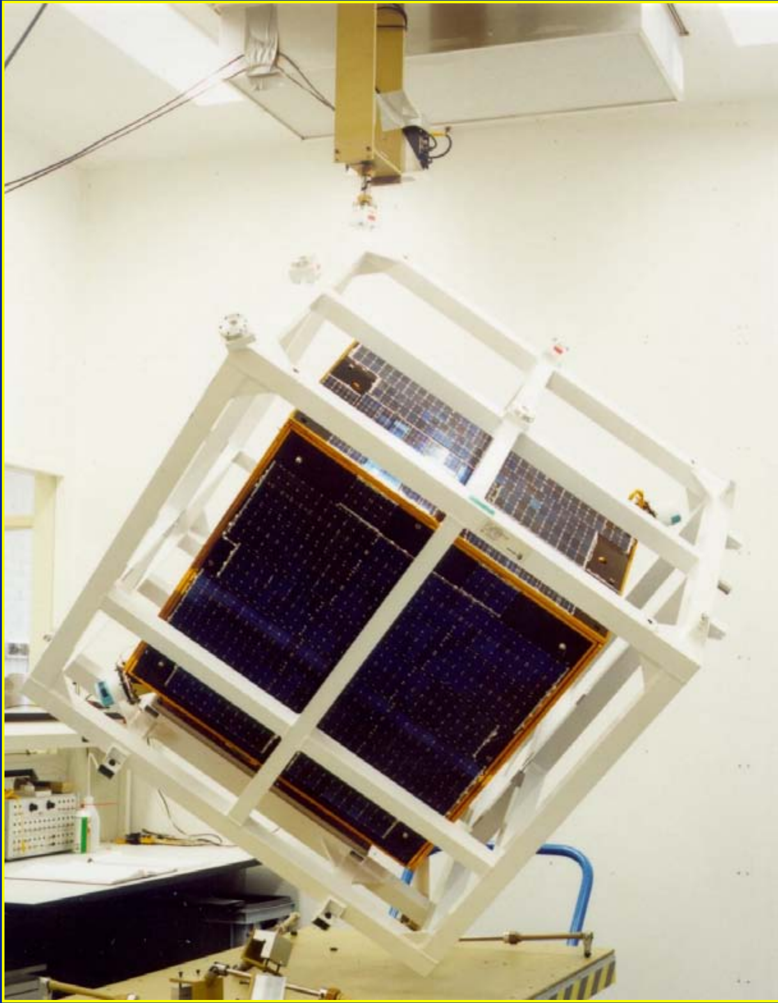
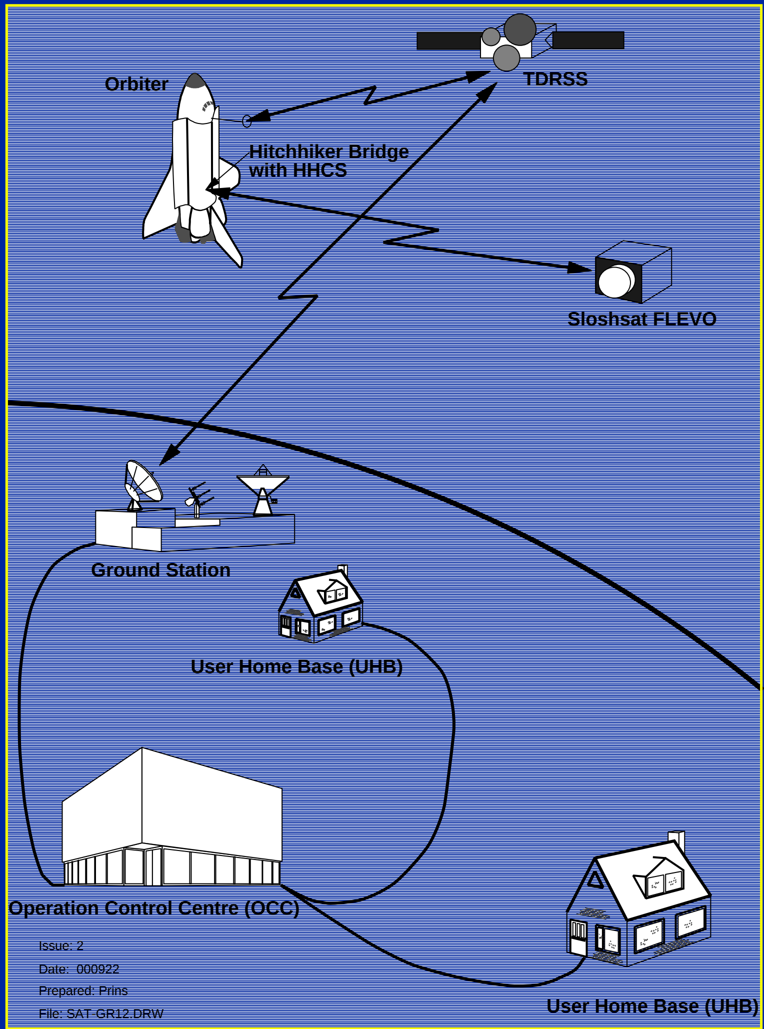
Sloshsat FLEVO
EMC test



Sloshsat FLEVO
Moment of inertia measurement

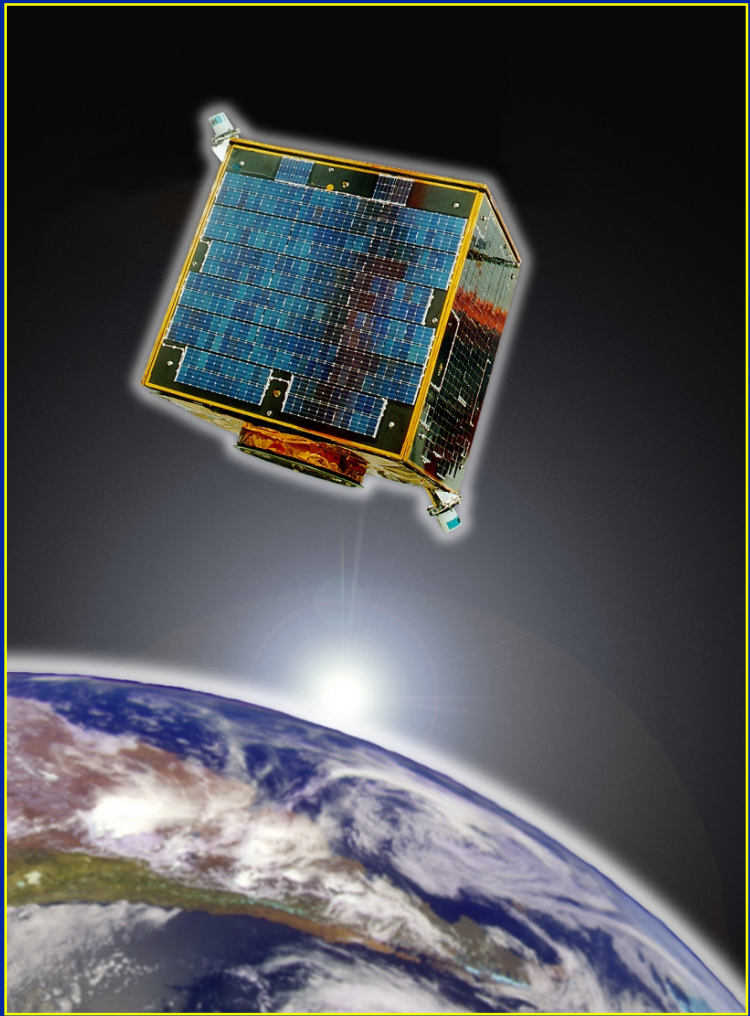


Sloshsat FLEVO Operations



- Operation from OCC at GSFC
- Orbiter attached and free-flying
- 24 hr experiment time
- Routing: Ground / TDRSS / Shuttle / HH / HHCS / Sloshsat
- Advance Crew Terminal ACT
- User Home Bases USB
- Internet science data distribution

Sloshsat FLEVO
Status and conclusion



Status:

- Qualification tests performed, except STOF mechanical test
- Flight currently foreseen April 2002 (R2 mission), or May 2003 (R3 mission)

Conclusions:

- Much interest in science data
- Rewarding small-sat development