SPACE SIMULATION TECHNIQUES AND FACILITIES FOR SAX STM TEST CAMPAIGN

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ABSTRACT

SAX is a satellite for X-Ray astronomy. It is a major element of the overall basic Science Program of the Italian Space Agency (ASI) and is being developed with the contribution of the Netherlands Agency for Aerospace Programs (NIVR).

The scientific objectives of SAX are to carry out systematic and comprehensive observations of celestial X-Ray sources over the 0.1 - 300 KeV energy range with special emphasis on spectral and timing measurements. The satellite will also monitor the X-Ray sky to investigate long-term source variability and to permit localization and study of X-Ray transients.

Alenia Spazio is developing the satellite that is intended for launch in the second half of 1995 into a low, near-equatorial Earth orbit.

At system level a Structural Thermal Model (STM) has been conceived to verify the environmental requirements by validating the mechanical and thermal analytical models and qualifying satellite structure and thermal control. In particular, the following tests have been carried out in Alenia Spazio, CEA/CESTA and ESTEC facilities:

Modal Survey, Centrifuge, Acoustic, Sinusoidal/Random Vibration and Thermal Balance.

The paper, after a short introduction on the SAX satellite, summarizes the environmental qualification program performed on the SAX STM. It presents test objectives, methodologies and relevant test configurations. Peculiar aspects of the test campaign are highlighted. Problems encountered and solutions adopted in performing the tests are described as well. Furthermore, test results are presented and assessed.

1. INTRODUCTION

The SAX satellite will observe celestial X-Ray sources in the broad energy band from 0.1 to 300 KeV to achieve a systematic, integrated and comprehensive exploration of galactic and extra-galactic sources, providing, with respect to previous missions, an astrophysics facility for more complete and extensive studies of known and new celestial X-Ray sources (see Ref. 1).

The SAX satellite development is part of the joint SAX program managed by the Italian Space Agency (ASI) and the Netherlands Agency for Aerospace Programs (NIVR), which decided to fund in response to the scientific interest of the Italian and Dutch scientific community.

The launch of the SAX satellite is planned for the end of 1995, for a minimum operative life of two years. The ATLAS 1 launcher will inject Sax into its operative orbit at 600 Km altitude with an inclination of less than 5° over the equator.

A pictorial view of the SAX satellite is shown in Fig. 1 (following page). In particular, it consists of three modules.

- The **Service Module (SVM)** which includes a central cone, lower and upper floors, eight side panels (the batteries are mounted on dedicated panels) and six shear panels. It houses all the electronic units, attitude control sensors and actuators, one S-band Antenna and provides the interfaces with the launcher.

- The **Payload Module (PM)** with a box structure which provides attachments for all the science instruments. The PDS is mounted internally, the HP-GSPC, WFCs and Concentrators externally. Three Star Tracker sensors are also externally mounted on dedicated supports.

- The **Shade Structure** consists of a panel framework surrounding the PM. It supports the third Sun Acquisition Sensor, the second S-band Antenna and the Science Instrument Thermal Baffles (HP-GSPC and WFCs).

The SVM and the Shade Structure provide the interfaces of two solar array wings and a body mounted solar panel.
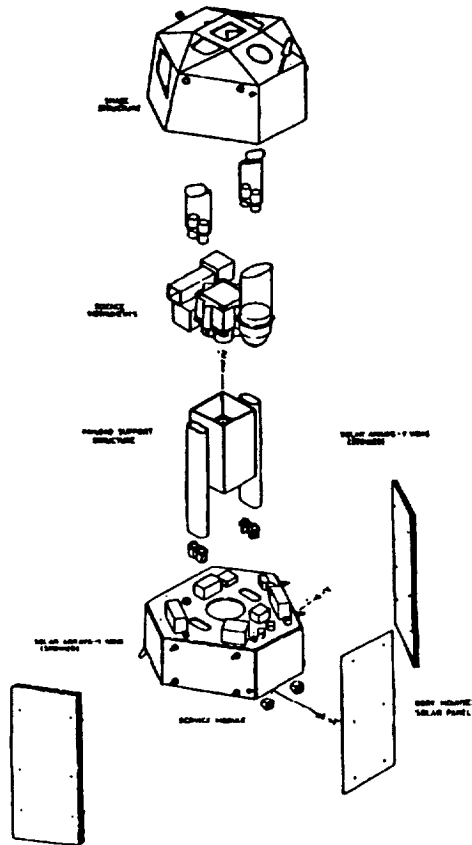
Fig. 1 - SAX Satellite Overall View

2. SYSTEM VERIFICATION APPROACH

The verification approach of the SAX satellite is based on three models (Ref. 2).

• Structural Thermal Model (STM) which was subjected to a full mechanical and thermal qualification test campaign.

• Engineering Model (EM) which is undergoing the electrical functional testing.

• Protoflight Model (PFM) which is intended for flight after environmental screening and final performance testing.

An overview of the system test approach is given in the table of Fig. 2 (see following page). Details of the SAX design, verification philosophy and system test approach are contained in Refs. 2 and 3.

In the frame of the system verification approach, a fundamental aspect is the STM activities. In fact, the overall satellite design, or essential portion of it, is governed by the thermal and mechanical requirements.

Qualification versus the above requirements is in this way a relevant part of the verification process.

Techniques used in simulating the environments acquire importance in providing the necessary confidence that the satellite meets the assigned operative role.

This paper will give evidence that methods and facilities used to qualify the mechanical and thermal design were adequate for its scope.

3. MECHANICAL REQUIREMENTS

The mechanical performances which have to be met by the SAX satellite can be split into two categories: one concerns the launch phase, and the other one the in-orbit life.

During the launch phase, the spacecraft structure must be able to withstand the high generated load environments. It must also be decoupled from the major low frequency excitation modes of the launcher, and the loads transmitted to the equipment must be acceptable to them.

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TYPE OF TEST	TEST DESCRIPTION	SAX STM	SATELLITE EM (S/C)	MODELS PFM
PHYSICAL PROPERTIES	Mass	X	- -	X
	Mol/CoG	X	- -	X
	Balancing	X	- -	X
STRUCTURAL TESTS	Modal Survey	X	- -	- -
	Acceleration	X	- -	- -
	Vibration	X	- -	- -
	Acoustic	X	- -	- -
	Pyroshock	- -	- -	X
THERMAL TESTS	Thermal Balance	X	- -	- -
	Thermal Vacuum	- -	- -	X
ALIGNMENT		X	- -	X
COMPATIBILITY	EMC\EMI	- -	- -	X
LEAK TESTS		X	- -	X
FUNCTIONAL PERFORMANCE TESTS	ISST	- -	X	X
	IST/SC	- -	- -	X
DEPLOYMENT/RELEASE	Solar Array	X	- -	X
	C/S Shutter	X	- -	X
SPECIAL TESTS	PA Calibration	- -	- -	X
	Ground Segment Comp.	- -	- -	X
	Match Mate Test	- -	- -	X
	Magnetic Field Measur.	- -	- -	X

Fig. 2 - System Test Approach Overview

During the in-orbit life, the mechanical performances to be traced are the relative dimensional stability existing between several pieces of equipment, especially belonging to the Attitude and Orbit Control S/S (AOCS) and science instruments. This part of the verification process will not be dealt with in this paper.

The mechanical development of the SAX satellite was performed with the strong support of Mathematical Models and Analysis and a Structural Mathematical Model of the spacecraft was built for this scope and validated through the Modal Survey Test.

Mechanical requirements applicable to the SAX satellite and relevant to the launch phase can be furtherly split into subcategories:

* stiffness requirements
* launch load requirements

The stiffness requirements were verified within the frame of the validation of the mathematical model as described in section 4.1.

The ATLAS 1 launcher imposes a complex combination of mechanical loads which can be split into three major constituents:

* Quasi-static loads
* High Frequency loads
* Shock loads

Quasi-Static Loads

The transient response environment during ATLAS 1 flight is characterized by a combination of low frequency dynamic and steady-state responses. Steady-state responses were specified in terms of equivalent design load factors for use in designing the Primary Structure.

These values were conservative for preliminary design purpose only and reflected the recommended frequency constraints. They were representative of the g-loading at the spacecraft centre of gravity and did not include a dynamic uncertainty factor. This load factor information did not replace the need for satellite/launch vehicle coupled Transient Loads and Clearance Analysis for the more critical flight events.

The response of the spacecraft to launch vehicle transients depends on its mass properties, stiffness, and amount of axial-lateral coupling.

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The above analyses are required to ensure that all the structural components have adequate margins.

A preliminary Transient Load Analysis was performed with a Spacecraft Dynamic Model representing the preliminary sizing of the hardware to provide a more accurate load distribution on the spacecraft for both Primary and Secondary Structure. These preliminary response data were used as a reference for the Stress Analysis Calculation and during the qualification test campaign on the Structural Model. A Dynamic Uncertainty Factor of 1.2, was applied to account for the potential design changes or modal correction prior to the final load cycle.

The final design load cycle is going to be run with the Test-Validated Dynamic Model for determination of the maximum expected flight loads. These response data will be used for calculation of the minimum margin of safety and therefore for the final verification of the qualification status of the spacecraft. The low frequency dynamic input was specified in terms of equivalent sinusoidal base acceleration.

Verification of minimum factor of safety was accomplished through a combination of static and sinusoidal base acceleration testing of the Structural Model. Primary structure interfaces are most easily loaded during Static Test, while the more complex dynamic responses are generated during the sinusoidal base acceleration test. For the Static Test it was chosen to perform a Centrifuge Test.

During the Vibration Test, notching of the base input was allowed in the 0 - 50 Hz range in order not to exceed the design loads and was based on flight equivalent levels as related to spacecraft damping.

High Frequency Loads

The high frequency random vibration that the spacecraft will experience is primarily due to the acoustic noise field, with a very small portion being mechanically transmitted from the engines. The acoustically excited random vibration environment is the design driver for component and small structure supports. The high frequency vibration level will vary from one location to another depending on the physical properties of each area of the spacecraft. Since the vibration level at the spacecraft interface depends on the adjacent structure above and below the interface, the exact interface level depends on the structural characteristics of the lower portion of the spacecraft, the particular Payload Launcher Adapter, and how the acoustic field is influenced by the particular spacecraft. The acoustic test of the spacecraft more accurately simulates the high frequency environment that it undergoes in flight than does a random vibration test. If the spacecraft is mounted to a test fixture that has structural characteristics similar to the Payload Launcher Adapter, then the vibration levels at the interface are similar to the flight levels.

Since the SAX satellite was attached to a rigid fixture during the Acoustic Test, a random test at low level was performed to provide evidence of the correct random vibration spectra specified for the unit located close to the spacecraft interface. The Launcher Adapter was not available at that time.

Shock Loads

There are four pyrotechnic shock events during flight on the ATLAS 1 Launcher. These are Insulation Panel Jettison, Payload Fairing Jettison, Centaur Separation from Atlas sustainer, and Spacecraft Separation. Since the system for Centaur Separation from Atlas is located far from the spacecraft, the shock is highly attenuated by the time it reaches the spacecraft and does not produce a significant shock at the spacecraft interface. The separation device for IPJ and PFJ are located closer to the spacecraft, and thus the shock at the spacecraft interface is noticeable. The Spacecraft Separation Device is at the Spacecraft/Centaur interface and produces the highest shock. Verification of the Spacecraft compatibility for Clamp Band Separation System will be performed on the Flight Model and as such it will not be described in this paper. This choice was dictated by the incomplete representativeness of both Structural and Engineering Models.

The launch load requirements verification tests are presented in sections 4.2 to 4.4.

4. STRUCTURAL MODEL TESTS SUMMARY

A summary of the mechanical tests performed on the SAX Structural Model is provided.

The Structural Model, as part of the STM, is fully representative of the Flight Model. It consists of a flight standard structure equipped with structural dummies of the several units, science instruments and mass representative harness.

An exception is the Solar Array -Y wing which was replaced by dedicated dummy masses.
The STM in full configuration is shown in Fig. 3 (following page).

Fig. 3 - SAX Structural Model
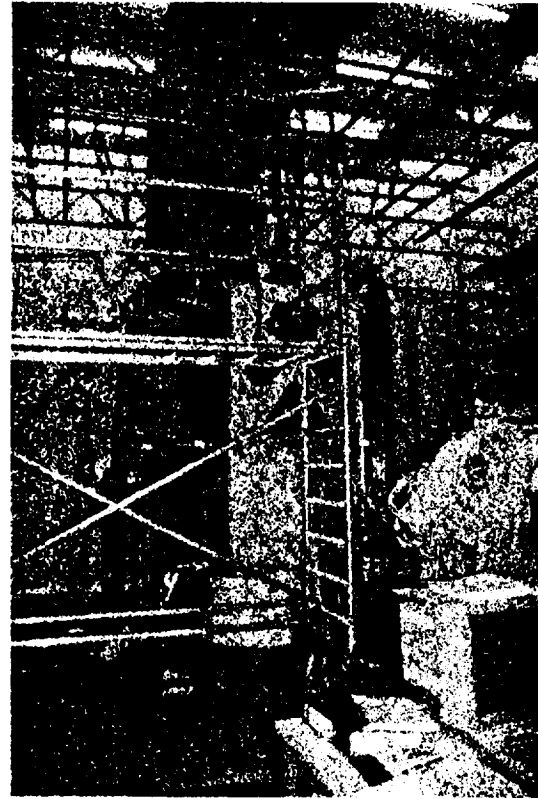
Fig. 4 - Modal Survey Test Set-up

4.1 Modal Survey Test

The primary purpose of the SAX Modal Survey Test was to measure all significant vibration modes over the frequency range 5 - 60 Hz and therefore the verification of the stiffness constraints. An additional purpose was to acquire frequency response functions up to 100 Hz. The test data were used to validate the SAX Structural Mathematical Model and to achieve a full understanding of how it behaves dynamically.

The test was carried out at the Integration Hall of Alenia Spazio in Turin using IABG's Modal Survey Test System. Modal Survey Test Set-Up is shown in Fig. 4.

The Flight Mathematical Model was modified to the STM Modal Survey Test Configuration. The changes introduced were mainly concerned with the missing hardware, mass distribution, modelling of the mass dummies instead of equipment, and the incorporation of the adapter used to realize the fixed-free conditions. It is worth mentioning that the missing hardware was responsible only for some local modes and had no influence on the global modes of the structure. This was necessary to operate a reasonable reduction of the modes limiting the number to that of particular interest for the subsequent correlation analysis and to guarantee a more uniform and significant energy distribution within the structure through a direct excitation of internal structural parts. The applied test technique was the Phase Separation Method with Multipoint Random Excitation.

Nine excitation points and 310 measurement points (response acceleration and excitation forces) were used. Applying random excitation forces, preparatory single points tests with the nine exciters and final multipoint tests with two exciter configurations were carried out. Additionally, measurements for linearity checks, Frequency Response Function measurements with an extended frequency range (5 - 100 Hz) and measurements for integrity checks were performed.

There were 28 modes expected in the frequency range to be examined. The number of the target mode was 18. From the two data sets from multipoint excitation, 17 and 18 modes were identified. For all these modes the modal parameters were determined. During the test, the results were carefully checked and comparisons were made between test and analysis results.

In general, the model was approximately 10% too flexible because of manufacturing contingencies. Minimum thickness and nominal Young's Module values were used. This is a conservative approach necessary for the Stress Analysis.

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DESCRIPTION : Global Y first lateral mode											
MODE NUMBER 1	FREQ. [Hz]	DEVIATION (%) TEST 1	TEST 2	DAMPING	Effective Mass (%) MX	My	Mz	Mrx	Mry	Mrz	Generalized Mass [Kg*m^2]
TEST 1	16.58	-	-	0.009	9.60	50.20	0.00	83.80	16.00	0.00	396.80
TEST 2	16.57	-	-	0.009	11.90	48.40	0.10	79.30	20.20	0.00	470.20
PREDICTION	14.74	-11.10	-11.04	-	16.20	43.90	0.00	72.40	28.90	0.00	371.92
CORRELATED	16.38	-1.21	-1.15	-	18.92	37.33	0.00	66.14	33.88	0.00	422.49

DESCRIPTION : Global X first lateral mode											
MODE NUMBER 2	FREQ. [Hz]	DEVIATION (%) TEST 1	TEST 2	DAMPING	Effective Mass (%) MX	My	Mz	Mrx	Mry	Mrz	Generalized Mass [Kg*m^2]
TEST 1	16.71	-	-	0.007	53.40	7.90	0.10	13.00	88.20	0.00	415.10
TEST 2	16.69	-	-	0.007	56.60	3.90	0.10	6.80	92.30	0.00	396.90
PREDICTION	14.70	-12.03	-11.92	-	43.20	16.40	0.20	27.30	72.60	0.00	431.18
CORRELATED	16.43	-1.68	-1.56	-	37.08	19.12	0.00	33.50	65.64	0.00	430.96

DESCRIPTION : Global X second lateral mode											
MODE NUMBER 3	FREQ. [Hz]	DEVIATION (%) TEST 1	TEST 2	DAMPING	Effective Mass (%) MX	My	Mz	Mrx	Mry	Mrz	Generalized Mass [Kg*m^2]
TEST 1	31.30	-	-	0.013	2.50	0.00	1.40	0.00	0.00	0.00	185.30
TEST 2	31.24	-	-	0.014	2.70	1.00	1.40	0.00	0.00	0.00	179.60
PREDICTION	28.53	-8.85	-8.67	-	4.40	0.00	1.00	0.00	0.20	0.00	185.59
CORRELATED	31.03	-0.86	-0.67	-	3.23	0.00	1.20	0.00	0.19	0.00	184.19

DESCRIPTION : Global Y second lateral mode											
MODE NUMBER 4	FREQ. [Hz]	DEVIATION (%) TEST 1	TEST 2	DAMPING	Effective Mass (%) MX	My	Mz	Mrx	Mry	Mrz	Generalized Mass [Kg*m^2]
TEST 1	31.64	-	-	0.007	0.20	1.10	0.00	0.00	0.00	3.30	161.50
TEST 2	31.60	-	-	0.008	0.10	1.10	0.00	0.00	0.00	3.10	157.30
PREDICTION	29.92	-5.44	-5.32	-	0.00	1.60	0.00	0.00	0.00	1.10	164.83
CORRELATED	31.44	-0.63	-0.51	-	0.11	1.80	0.00	0.00	0.00	0.64	161.47

Fig. 5 Comparison between Test, Prediction and Correlated Modes

In addition, the idealization of the Adapter to Launch Vehicle Adaptor (LVA) Ring connection allowed local rotations which did not occur in practice.

The stiffness of each area of the model was increased altering the thickness and Young Module's to average or top tolerances values. As a result the frequencies of the global satellite modes were accurate to better than 2 %.

Local Models of the Hydrazine Tank, Batteries and Concentrators were affected by the modelling of the cleats, straps and brackets. The assumptions used to derive their stiffness were introduced in the model. In particular, the Payload Support Structure Cleat Tension/Compression stiffness was increased in line with the values obtained during dedicated development tests. The idealization of the Concentrator Upper Trunnion Brackets was found to be too simplistic and coarse models were replaced by detailed models of each component.

During the correlation, no changes were made to the mass distribution and modelling. In general, the modifications which have been outlined result in uniform stiffness changes. In the areas in which the stiffness is increased locally it will be necessary to review the analysis. However, none of the modifications which have been introduced will affect the overall load distribution and behaviour of the model. The results of the correlation activity are reported in Fig. 5 together with the test predictions and frequency constraints.

All the above modifications were reflected into the Flight Mathematical Model which was provided to General Dynamics for the final Coupled Load Analysis.

Detailed information about the test, test results and correlation activity are contained in the documents of Ref. 4., Ref. 5. and Ref. 14.

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4.2 Centrifuge Test

The second step of the mechanical verification was the demonstration of the capability of the primary structure to withstand the quasi-static loads. For this purpose a centrifuge test was performed.

The test was carried out at the CEA CESTA Facility in Bordeaux (F). The centrifuge facility has the capability of generating a static acceleration, including those associated with satellite launches, in a fast and reliable way. It is constituted by a rotating arm with, at one extremity, 8.4 m from the rotating axis, an interface to the adaptor-specimen. It provides a static acceleration from 0 to 100 g corresponding to about 0.01 to 0.2 rad/sec^2.

The specimen is located inside a container (Nacelle) at the above defined interface. The most important aspects to be solved in using such a facility are related to the correct load distribution and the combination of axial and lateral loading.

The former is due to the different distance of each piece of hardware from the rotating axis which gives different accelerations along the satellite. This can be solved by increasing the masses locally to achieve the more realistic load distribution. The latter is due mainly to the dimensional constraints of the Nacelle (3 meters max diameter).

Detailed stress analyses were conducted in order to solve the above two problems.

First of all the stress analysis revealed the most critical load condition for each structural part. Only these load conditions were to be simulated by test because all the others were well enveloped by them. As it is not possible to reproduce the worst load case relevant to each structural part simultaneously, because they require different tilting angles, and because of the limited dimensions of the Nacelle, the following approach was followed:

* to identify the maximum obtainable tilting angles
* to compensate the reduced lateral load factor by increasing the axial load factors and by introducing dedicated compensation masses.

Two test cases corresponding to two different STM configurations and together providing the best possible coverage of the qualification load envelope were identified. Taking into account the STM shape, different rotation angles were used to cover a wider spectrum of lateral load factors.

The first test case was carried out with the fully integrated STM as shown in Fig. 6. Dummy masses were installed at the interfaces of the missing Solar Array Wing. The STM was inclined by 10° and rotated by 30°. The effective load factors at the CoG of the STM were:

* Axial Load Factor   = -9.24 g
* Lateral Load Factor = 2.64 g

The second test case was carried out without the Shade Structure, Body Mounted Solar Panel and Solar Array Wing. Furthermore the dummy units installed inside the Concentrator Tubes were replaced by increased dummy masses. Dedicated dummy masses were also installed at the lower interfaces of the Body Mounted Solar Panel.

The STM was inclined by 36° but not rotated (see Fig. 7). The effective load factors at the CoG of the STM were:

* Axial Load Factor   = - 4.69 g
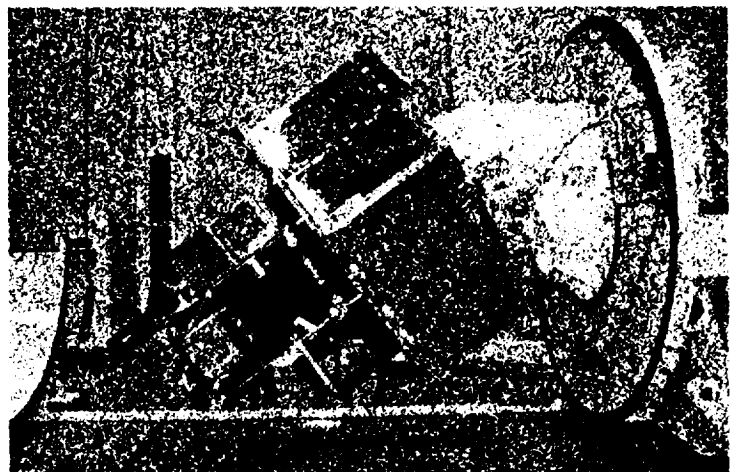* Lateral Load Factor = 4.64 g

Fig. 6 - First Test Case Test Set-up

Fig. 7 - Second Test Case Test Set-up

NOMINAL/TEST LOAD CASES	S/L - LVA RING		S/M		PSS		C. TUBES		SHADE S.		HPGSPG S.S.		PDS BRKTs	
	AX	LAT	AX	LAT	AX	LAT	AX	LAT	AX	LAT	AX	LAT	AX	LAT
BECO 1	-9.15	0.3	-9.15	0.3	-9.15	0.75	-9.15	0.75	-9.15	0.75	-9.15	0.75	-9.15	0.75
BECO 2(*)	-4.2	4.5	-4.2	4.5	-3.75 / -1.48	7.05 / 4.68	-3.75	7.05	-4.5	9.75	-3.75 / -1.48	7.05 / 4.68	-3.75 / -1.48	7.05 / 4.68
BPJ (*)	-3.6	3.45	-3.6	3.45	-2.85 / -1.48	5.55 / 4.68	-2.85	5.55	-4.5	7.2	-2.85 / -1.48	5.55 / 4.68	-2.85 / -1.48	5.55 / 4.68
MECO	-8.1	0.6	-8.1	0.6	-8.1	1.95	-8.1	1.95	-8.25	4.05	-8.1	1.95	-8.1	1.95
1°TEST CASE	-9.24	2.65	-9.62	2.71	-8.78	2.56	-8.82	2.5	-8.63	2.53	-8.89	2.58	-8.73	2.55
2°TEST CASE	-4.69	4.64	-4.87	4.77	-5.31	5.33	-7.47	7.61			-4.52	4.52	-4.44	4.46

(*) Non-bold values are relevant to coupled analysis results for non-time consistent events

Fig. 8 - Comparison between Nominal Qualification and Test Load cases

The STM was supported by a special inclined adapter constituted by two dismountable elements necessary to provide the correct orientation for the two test cases. The adapter was fitted with a flight standard interface flange.

The STM was equipped with 91 uniaxial and 30 triaxial strain gauges, with 9 displacement transducers and four accelerometers. Four runs were performed for each test case.

Detailed information about the test is contained in the documents of Refs. 6 and 7.

Using these test cases the nominal qualification loads were reached at the important interfaces. In particular, the first load case covered the qualification envelope relevant to flight conditions with high axial loads, while the second one covered the qualification envelope relevant to flight conditions with high lateral loads.

The comparison of the test load factors with the nominal ones is reported in Fig. 8.

The strain gauges behaviour, with the exception of 4 installed on the LVA Ring, was linear. The non-linearities were caused by local effects of Clamp Band tensioning and settling effects. However, even if non-linear effects were detected the measured strains were well below the yield limit.

All the test results are contained in the report of Ref. 8. No anomaly with the structure was detected.

4.3 Acoustic Noise Test

The objectives of the Acoustic Noise Test were:

* to qualify the secondary structure, including MLI and SSM's bonding vs the high frequencies broad band random vibration
* to verify the qualification random vibration criteria specified for the various equipments/instruments
* to verify alignment stability requirements of the item of interest.

The test was carried out in the Large European Acoustic Facility at ESTEC. The test set-up is shown in Fig. 9 (see following page).

The STM was instrumented with 251 accelerometers. They were located at areas expected to give high responses, or placed adjacent to equipment in order to confirm acceleration responses at these critical locations. Furthermore the acoustic noise spectrum was controlled by averaging the outputs of 13 microphones installed all around the Test Article (T/A).

The Acoustic Test consisted of the following runs:

* reverberation chamber preparation and equalization runs (chamber empty)
* low and intermediate equalization runs (T/A inside the chamber)
* qualification level run
* low level final run

Detailed information about the test is contained in the document of Ref. 9.
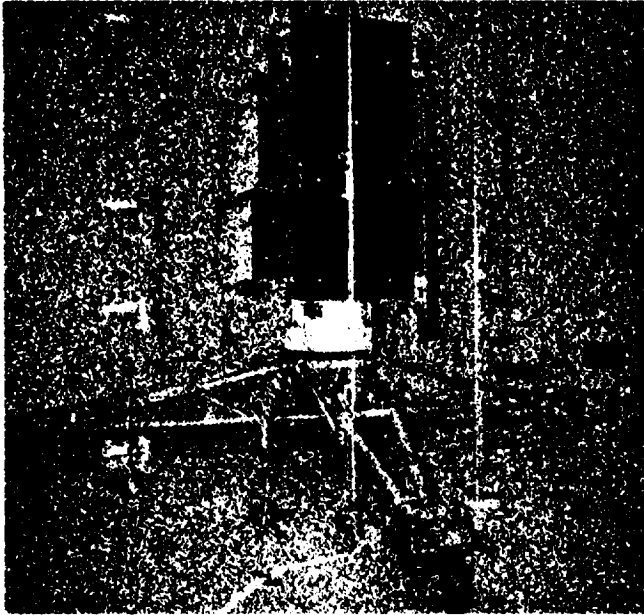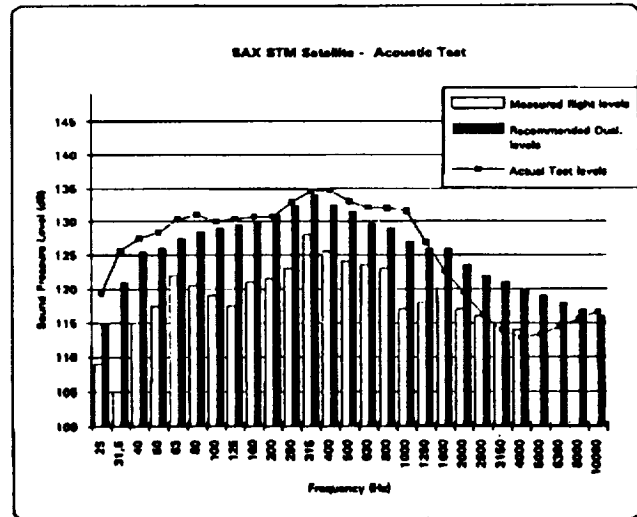
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Fig. 9 - Acoustic Test Set-up

Fig. 10 - Acoustic Noise Levels

The comparison between nominal and qualification acoustic noise spectra is shown in Fig. 10. The in-flight measured noise spectrum is included as well. The sound pressure levels were well controlled within the required test tolerances with the exception of some unimportant frequency bands. The goal was to reproduce the correct sound pressure levels over the frequency range 31.5 - 2000 Hz neglecting higher frequencies. The sound pressure levels between 2000 to 10000 Hz are very low and component responses are significantly attenuated at these frequencies. The overall sound pressure level was exceeded by some 1.5 dB. No anomaly with the structure was detected.

The acceleration responses were compared to the spectrum specified for equipment/instruments qualification random vibration test. Apart from only a few units, both external and internal, a close agreement between the measured and predicted responses was detected.

As expected, because of a rigid test adapter, the Acoustic Noise Test did not induce a realistic and adequate excitation at the areas close to the mounting interface. The measured response accelerations at the interface areas were well below the typical ones. Furthermore, an essential reduction of the qualification input spectrum for all the P/L instruments was detected.

All the test results are contained in the report of Ref. 10.

4.4 Vibration Test

The Sinusoidal Vibration Test was performed to qualify the structure for the low frequency transient peak responses by applying an equivalent sinusoidal base input.

Even if not specifically required by the Launcher Authority, a Low Level Random Vibration Test was also performed. This was to complete the verification of the random vibration criteria of those units installed close to the mounting interface (mainly the ones located on the Tank Support Floor) and not adequately excited by the Acoustic Noise Test.

The vibration tests were carried out at the ESTEC Test Facility. The STM in full test configuration is shown in Fig. 11 (see following page).

For the Sinusoidal Vibration Test, the SAX STM was instrumented with 224 accelerometers. They were located at selected locations in order to provide information of either local and overall behaviour of the structure. The strain gauges, mainly located on the LVA Ring and PM and already used for the Centrifuge Test, were reutilized.

The same accelerometers as used for the Acoustic Noise Test was reutilized for the Random Vibration Test. The input spectra were controlled by 4 Pilot and 12 Copilot accelerometers installed on the Dynamic Adapter.

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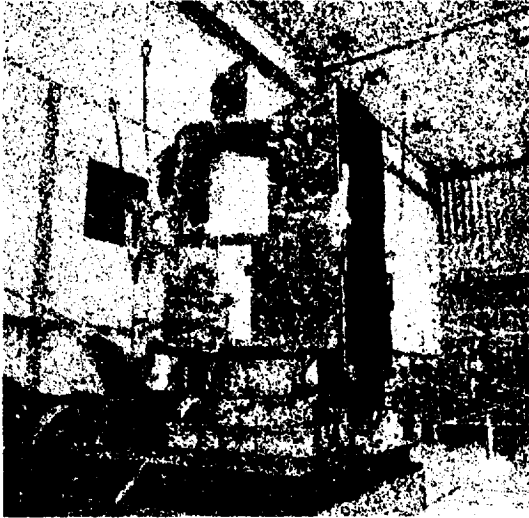
Fig. 11 - Vibration Test Set-up

The STM was subjected to the following test sequence for each axes:

Sinusoidal Vibration Test

- Low Level Run (0.2 g over the frequency range 5 - 2000 Hz)
- Intermediate Level Run (flight level over the frequency range 5 - 100 Hz)
- Qualification Level Run (flight level x 1.5)
- Final Low level Run

Random Vibration Test

- Low level Run (10 dB below the in-flight measured spectrum)

The vibration test was performed on the basis of the ATLAS 1 input spectra. Nevertheless, the sinusoidal input spectrum was reduced (notching) in order not to overstress the overall satellite, local structures and equipment.

Two different procedures were adopted depending on the frequency range:

Frequency range up to 50 Hz

The input spectrum was reduced in the frequency bands of the resonance of the primary structure such that the test loads experienced at each critical location of the structure did not exceed the design load.

Frequency range from 50 to 100 Hz

The input spectrum was reduced so as not to exceed at each critical location of the structure the maximum responses based on the amplification factors as provided by the Launcher Authority. A safety factor of 1.25 was used in this frequency range.

No notching was performed for the Random Vibration Test. A detailed description of the test is given in the document of Ref. 11. The input spectra together with the nominal ones are given in Fig. 12 a/b/c/d (see following page).

The Sinusoidal Vibration Test allowed to successful completion of the qualification of the primary structure against a safety factor of 1.5. A comparison between experimental and analytical base fluxes is reported in Fig. 13 (following page).

The results of the Random Vibration test were used only for the units of interest, i.e., the ones located on the Tank Support Floor. They were extrapolated at qualification level, considering a realistic damping factor coming from the results of the Sine Test. Higher levels than the ones obtained during the Acoustic Noise Test, but still enveloped by the specified random vibration criteria, were detected. All the test results are contained in the Report of Ref. 12.
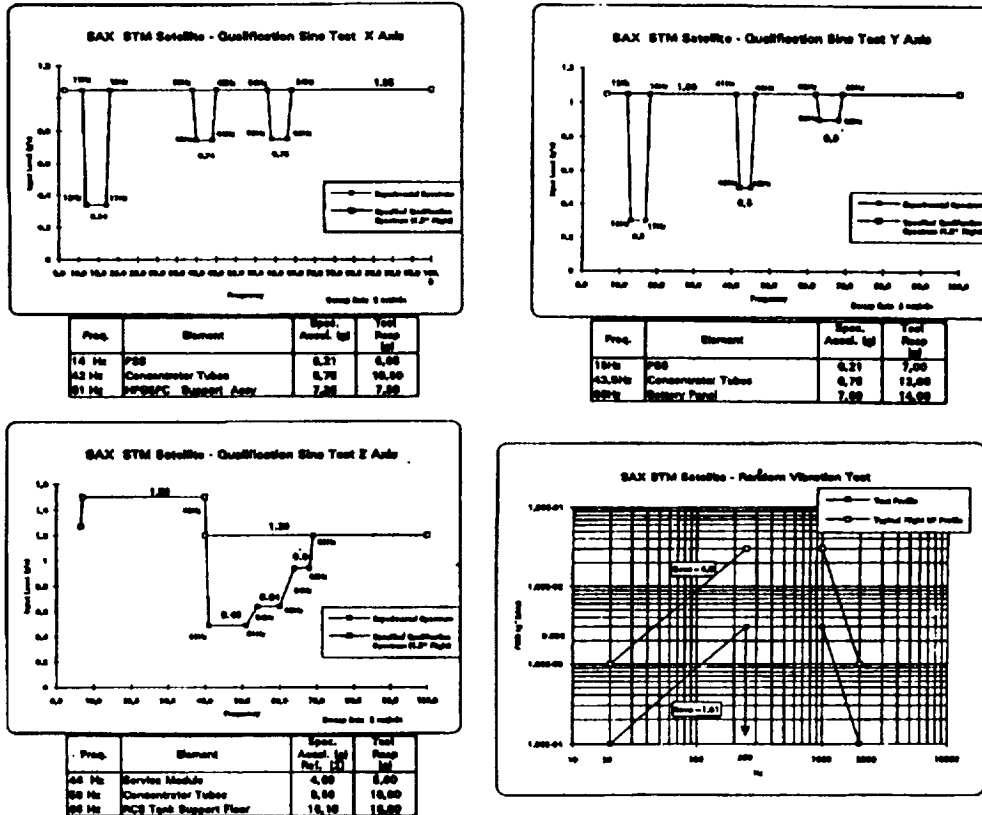
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Fig. 12 - Qualification Input Spectra

5. THERMAL REQUIREMENTS

During its life, the SAX satellite is subjected to thermal induced environments which drive the design of thermal control. These environments are strictly related to the mission profile to be performed and they can be split mainly into launch and operative conditions.

Launch conditions were evaluated by using a dedicated Thermal Mathematical Model and judged of low importance with respect to the operative conditions because of the short duration of the tranfer phase.

The SAX operative mission profile includes several cases differing from each other in boundary conditions or attitude.

A Thermal Balance Test was performed in order to evaluate the satellite behaviour, but only the extreme cases were covered, identified by the analysis, simulating as far as possible the real flight condition. The test included both steady state and transient phases to correlate the TMM and to evaluate the Thermal Control design performances respectively.
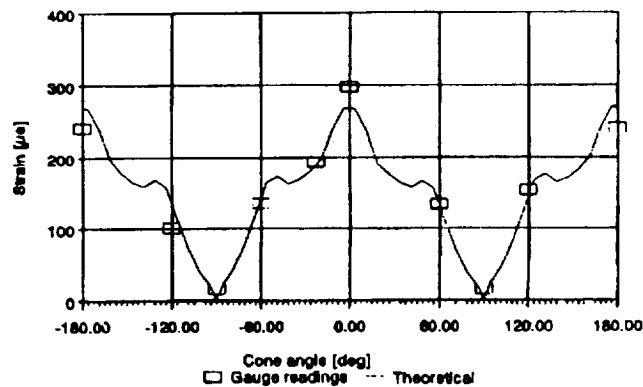

Fig. 13 - Comparison between Analytical and Experimental Base Fluxes (X axis)

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TASK N°	1	2	3	4	5	6	7
PHASE DESCRIPTION	PUMP DOWN & COOL. DOWN	0° SAA COMMISSIONING SUMMER SOLSTICE	+ 45° SAA SUMMER SOLSTICE	SUMMER SOLSTICE ECLIPSE	+ 30° SAA WINTER SOLSTICE	- 30° SAA WINTER SOLSTICE	CHAMBER RECOVERY
TEST CASE	REACHING TEST COND	STEADY STATE	STEADY STATE	TRANSIENT	STEADY STATE	STEADY STATE	REACHING AMBIENT C.
ESTIMATED DURATION	15 HRS	65 HRS	50 HRS	9 HRS	30 HRS	30 HRS	15 HRS
SPACECRAFT ORIENTATION AND ATTITUDE							
SOLAR INTENSITY	FROM 0 TO 900 W/m2	840 W/m2	840 W/m2	0 - 1320 W/m2	900 W/m2	900 W/m2	0 W/m2
CHAMBER VACUUM	FROM AMBIENT TO 10e-5 mbar	10e-5 mbar OR BETTER	10e-5 mbar OR BETTER	10e-5 mbar OR BETTER	10e-5 mbar OR BETTER	10e-5 mbar OR BETTER	FROM 10e-5 mbar TO AMBIENT
SHROUDS TEMPERATURE	FROM AMBIENT TO 100 °K	100 °K	100 °K	100 °K	100 °K	100 °K	FROM 100 °K TO AMBIENT
COMMENTS		COLD CASE FOR P/L	COLD CASE FOR S/L	VERIFICATION OF TRANSIENT ECLIPSE PERFORMANCE	HOT CASE FOR P/L	HOT CASE FOR S/M	

Fig. 14 - Thermal Balance Test Phases

6. THERMAL BALANCE TEST

The objectives of the Thermal Balance Test (see Ref. 15) are:
* to validate the Thermal Mathematical Model
* to demonstrate the validity of the Thermal Control Subsystem (TCS) design
* to anticipate any possible manufacturing/assembling problems.

The Thermal Balance Test covered only a few extreme mission cases which are considered significant for all the susequent correlation analysis. In particular the STM was subjected to the following test phases (see Fig. 14):

* **Commissioning Case - 0° Sun Aspect Angle (SAA)**
  (Steady State, worst cold case for the Payload Module)

* **Summer Solstice: 45° SAA**
  (Steady State, worst cold case for the satellite)

* **Summer Solstice Eclipse: 0° SAA**
  (Transient, orbital simulation)

* **Winter Solstice: 30° SAA**
  (Steady State, worst hot case for the Payload Module)

* **Winter Solstice: -30° SAA**
  (Steady State, worst hot case for the Service Module)

The test has been carried out in the Large Space Simulation Chamber (LSS) at ESTEC (NL).

The STM was fully representative of the Flight Model (see Fig. 15, following page) with the exception of the solar array wings which were replaced by shadowing panels (truncated panels) sized to avoid a direct sun impingement on the satellite during the summer solstice phase. They simulated the thermo-optical properties of the flight wings. The effect on the view factors of the reduced length of truncated panels was negligible. The dummy unit heaters were set at fixed power levels with the exception of the orbital simulation phase where for some units, mainly of the Electrical Power Subsystem (EPS), the same profile of the flight units was implemented. Also the Thermal Control heaters were set to a fixed level.

The S/L was installed on the Spin Box/Gimbal Stand via Thermal Test Support Rig. The Test Adaptor was designed such that it had minimum shadowing effects during the test phases and heat flux from S/L. In order to avoid heat exchange with the S/L it was also equipped with Guard Heaters. A thermostatic control was implemented for the Guard Heaters.
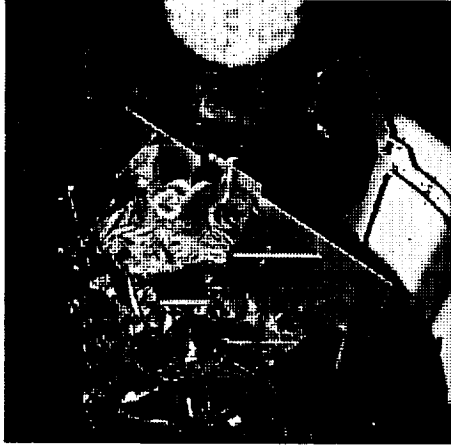
Fig. 15 - Thermal Balance Test Set-up

Radiative Plates were installed partially all around the satellite and in front of SVM Lower Platform in order to reproduce the Albedo and Earthshine effects. Thermostatic control, based on the average of two thermocouples for each plate, was implemented. The solar intensity, during the steady cases, reproduced the average value of the orbit for the summer solstice and winter solstice cases.

During the eclipse phases the real value of the Sun intensity along the complete orbit was simulated. The effect of Deep Space was simulated by Chamber Shroud (cooled by liquid nitrogen) all around the S/L. A stabilization criteria of $1^\circ/22$ h was used. This allowed to reach the equilibrium temperature with an accuracy of 0.5 °C.

Test results were not directly comparable with the analytic ones because of the slight changes occurring in the boundary conditions. A new Thermal Analysis including the actual boundary conditions was run. The modelling of the Thermal Test Adaptor was included and a more detailed model of the truncated panels substitued the coarse model. Comparison was made between the new analytical data and experimental results. This is documented in Ref. 16. In spite of this, in general, the STM was colder than the prediction. Differences for some units were detected between the two data sets. For the time being, the correlation activity is still in progress.

It is involving both the refinement of the modelling (refinement of the values of the thermo-optical properties, contact conductances, view factors, etc.) and modification of thermal control hardware. Local modifications were already identified, for example the Concentrators tubes will be completely covered by multilayers and heater supports will be modified, Second Surface Mirror area in correspondance of the batteries will be reduced to allow an higher temperature, etc.

Furthermore, a new allocation of the Thermal Control Power could be possible. Anyway, it is worth mentioning that the modification of the Thermal Control hardware as well as the power allocation will be such to confirm the thermal environments specified in the equipment design documentation.

5. CONCLUSIONS

An extensive test campaign was performed on the Structural Model of the SAX satellite. The test program was fully compliant with Launcher Authority recommendations but tailored to the specific technical needs and program constraints of the SAX program.

- The validation of the Mathematical Model as well as the successful verification of the stiffness requirements were accomplished through the classical Modal Survey Test. Slight differences between the experimental and analytical test results, mainly caused by the manufacturing contingencies and an underestimate of the stiffness of some structural components, were detected. An additional survey was performed over an extended frequency range (up to 100 Hz). The measured data were used in conjunction with the results of the Frequency Response Analysis to get more reliable predictions for the Sinusoidal Vibration Test. The mathematical model was updated and provided to the Launcher Authority (General Dynamics) for the final load cycle.

- The qualification against the static loads was reached through the Centrifuge and Sinusoidal Vibration Tests. They were conducted on the basis of the maximum acceptable loading as derived from the coupled load analysis with the launcher.

  * **Centrifuge Test**
    Two test cases corresponding to two different STM configuration and together providing the best possible coverage of the qualification load envelope were performed. Using these test cases the qualification was reached at the important interfaces.

  * **Sinusoidal Vibration Test**
    Purpose of the Sinusoidal Vibration test was to apply the maximum expected low frequency quasi-sinusoidal loads and to complete primary structure qualification.

  The qualification against SAX project requirements was correctly met. However, the final confirmation of the correct qualification against the quasi-static loads has still to be made based on the results of the final coupled load analysis with the launcher.

- Concerning the high frequency loads, the STM was successfully subjected to a complete qualification against the Acoustic Noise Test. Apart from only a few units, a good agreement between the predicted and measured response accelerations was detected. An essential reduction of the qualification input spectra of the Science Instruments was possible.
  Due to the presence of a rigid adapter, the Acoustic Noise Test did not induce a sufficient excitation over the areas near the mounting interface. In order to overcome this problem and therefore to verify the random vibration criteria of the units/equipments mounted on the Tank Support Floor correctly, a random vibration test, at low level, was performed. The extrapolated spectra of the units of interest were well enveloped by the specified random qualification spectra.

  No problems arose with the structure all along the test campaign.

  Test results allow to conclude that the SAX structural design conforms to the ATLAS 1 requirements. Nevertheless, the mechanical verification process will be completed only on the Flight Model which will undergo the Separation Shock Tests.

  In order to cope with the thermal requirements derived by the particular SAX mission, a Thermal Balance test was performed on the Thermal Model refurbished from the Structural Model.

  Only a few critical cases of the mission profile were simulated, providing anyway the necessary confidence in the capability of the satellite to meet thermal requirements. The test included both steady state and transient phases to correlate the Thermal Mathematical model and to evaluate the Thermal Control design performances. The Thermal Balance test was carried out with some deviations, but they were understood and a more reliable Thermal Model was implemented and run.
  The new data set was the basis of the correlation analysis which, even if it is still to be completed, provided good evidence of the Thermal Control Subsystem performance.

  Nevertheless, the thermal verification process will be completed only on the Flight Model where, during the Thermal Vacuum test, a thermal cycle will be used to verify the Thermal Mathematical Model correlated on STM and so definitevely provide confirmation of the requirement satisfaction.

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