Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

Line-of-sight jitter of SILEX optical terminals, analysis and verification activities

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Abstract

The Semi-Conductor Laser Inter-Satellite Link Experiment (SILEX) is a very innovative program of the European Space Agency. Two optical terminals, PASTEL and OPALE, respectively on the SPOT4 satellite (low Earth orbit) developed by MATRA MARCONI SPACE under CNES contract, and on the ARTEMIS satellite (geostationary) developed by ALENIA under ESA contract, must be pointed to each other to within 2 microradians in the communication phase.

To achieve this very high accuracy pointing, the Pointing, Acquisition and Tracking (PAT) system of each terminal provides high bandwidth (above 100 Hz), fine control capabilities so as to decrease the pointing jitter induced by host spacecraft disturbances. In this frequency band, the spacecraft and the optical terminal are no more rigid bodies, and the coupling of structural modes is a performance driver that requires detailed analysis and verification tests. The aim of the paper is to describe the activities carried out at MATRA MARCONI SPACE to predict and verify on the ground the high frequency line-of-sight pointing performances of the SILEX terminals, essentially focusing on the case of PASTEL.

Due to the complexity of the problem (flexible bodies in a high frequency range, large angle azimuth/elevation motions of PASTEL, PAT control loop, on-board disturbing environment...), the pointing verification logic was built on a combined tests/analyses approach. A series of modal tests have been performed at terminal level, completed by a microvibration test on the SPOT4/PASTEL assembly. Their exploitation has led to Finite Element Model update, and definition of worst case transmissibility envelopes. In addition, the detailed characterisation of the main on-board disturbance sources (SPOT4 Reaction Wheels and Oblique Viewing Mirror mechanism) has provided the

performance prediction analyses with realistic input. All these experimental lessons has been gathered for the final coupled pointing performance analysis, which concludes the verification process.

List of Acronyms

AOCS	:	Attitude and Orbit Control System
CPA	:	Coarse Pointing Assembly
CPMA	:	Coarse Pointing Mechanism Articulation
FEM	:	Finite Elements Model
FPA	:	Fine Pointing Assembly
HRVIR	:	Haute Résolution Visible et Infra-Rouge
GEO	:	Geostationary Orbit
LEO	:	Low Earth Orbit
LOS	:	Line Of Sight
MCV	:	Miroir de Changement de Visée (oblique viewing mirror)
PAT	:	Pointing, Acquisition and Tracking
RRPM	:	Roue de Réaction à Palier Magnétique
SILEX	:	Semi-Conductor Laser Inter-Satellite Link Experiment
STM	:	Structural and Thermal Model

1 - Introduction

The Semi-Conductor Inter-Satellite Link Experiment (SILEX) is a programme of the European Space Agency involving two optical terminals : PASTEL on the SPOT4 satellite in low Earth orbit (LEO), and OPALE on the ARTEMIS satellite in geostationary orbit (GEO). The SILEX terminals are developed by MATRA MARCONI SPACE under two contracts, one directly to ESA (PASTEL), the other (OPALE) to ALENIA as ARTEMIS satellite prime contractor. The SILEX terminals will be delivered by the end of 1996.

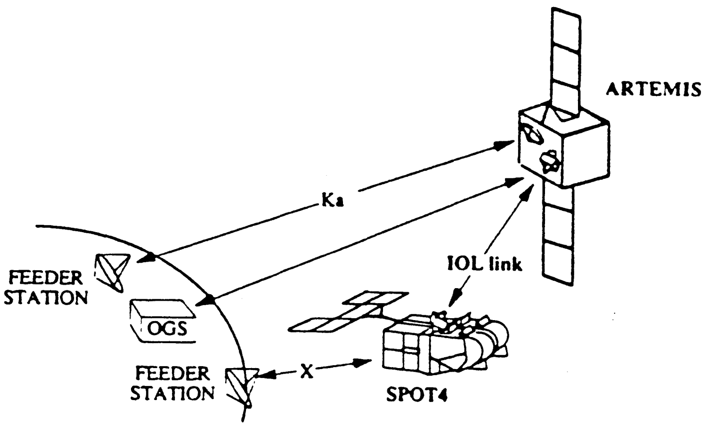

Figure 1 : SILEX System Configuration

The communication scheme is designed for a very high data rate (50 Mbit/s, with significant growth potential) Inter Orbit Link between the LEO and GEO satellites, with also the possibility for an optical transmission between the GEO and a ground station (see figure 1). In the SPOT4/ARTEMIS application, SPOT4 images, normally stored on a magnetic tape recorder and downlinked once per orbit during ground station visibility, will be transmitted in real time to the ground via ARTEMIS (see Ref. [1]).

The Pointing, Acquisition and Tracking (PAT) subsystem of each terminal ensures by design the large coverage and the high pointing accuracy required to maintain the communication link (figure 2). The PAT is based on a two-stage architecture, combining active control and passive design optimisation :

- a large angular range mechanism, the Coarse Pointing Assembly (CPA), allows to gimbal the Mobile Part (optical head, structure and electronics) with a low bandwidth around two articulations (azimuth and elevation)
- inside the Mobile Part, the Fine Pointing Assembly (FPA) can deflect the laser beam with a small, two-axis mirror, controlled by a high bandwidth tracking loop (100 Hz), using dedicated sensors and electronics.

To acquire the communication link between the two terminals, an open loop pointing accuracy of about 2 microradians must be ensured throughout the co-operative tracking phase. The Line-Of-Sight jitter induced by the on-board disturbance sources is a major contributor to the overall pointing performance : the host spacecraft disturbances are significant (reaction wheels, payload mirror mechanisms, ...) and cover a large frequency domain from DC to some hundred Hz. In addition, the spacecraft and terminal dynamics exhibits large amplifications on structural resonances, and the PAT control bandwidth is limited : no disturbance rejection capability is available above 100 or 150 Hz - and even below 100 Hz, the rejection capability is finite, although the control loop is optimised for the host spacecraft disturbances (notch filters, ...).

The study and verification of the microvibrations impact on PASTEL and OPALE pointing stability is thus of prime importance for the validation of the SILEX system performances.

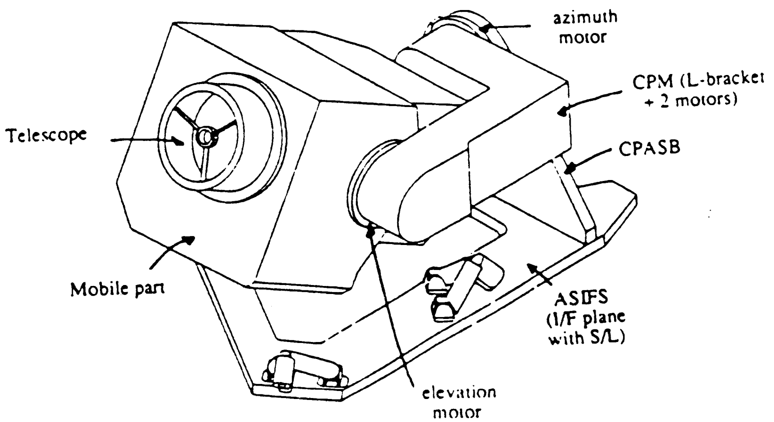

Figure 2 : The PASTEL Optical Terminal

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2 - SILEX Jitter Assessment - The Verification Logic

The microvibrations are due to the amplification, by the spacecraft or terminal structure and optics, of the dynamic disturbances induced by moving parts of the spacecraft/terminal assembly : reaction or momentum wheels used for the AOCS, SPOT4 oblique viewing mirrors and tape recorders, ARTEMIS antenna pointing mechanisms... When a disturbance spectral line falls in coincidence with a structural mode, the effect of the disturbance is amplified by a large factor with respect to rigid body motion. The structural mode can be either a pure SPOT4 mode, a pure PASTEL mode, or a coupled SPOT4/PASTEL mode. Due to this possible interaction of structural dynamics, the methods originally studied for "decoupling" the microvibration analysis did not prove fully satisfactory.

It was thus concluded that the reference microvibration analysis for the development phase had to be an "integrated" analysis (also called "coupled analysis" in the following), in which the effect of spacecraft disturbances on PASTEL Line-Of-Sight is directly evaluated using a complete model of the spacecraft/terminal assembly. The microvibration verification logic was established accordingly, based on coupled analyses updated with test results at disturbance source level, terminal level and spacecraft/terminal level.

This verification logic is based on combined analyses and tests as illustrated on figure 3. In this logic, the tests are used to verify, validate and/or update the mathematical models involved in the SPOT4/PASTEL coupled analyses, and to perform end-to-end performance assessments based on assumptions "as close as possible" to the real world (disturbance models, structural FEM).

Tests are essential in particular to identify modal damping factors (not predictable by the FEM analysis) and to define worst case assumptions and system margins. At last, since the microvibration analysis is limited in frequency below 150 Hz typically by models representativeness, ground tests give an opportunity to estimate the performance above this limit.

According to this verification plan, several coupled analyses have been performed during PASTEL development, alternately with tests at terminal or spacecraft/terminal level. The test logic was the following :

• TEST OF SPOT4 AND PASTEL DISTURBANCE SOURCES (see section 3) : microdynamics disturbance characterisation tests were performed at equipment level, in order to validate and complete the mathematical models and the corresponding numerical assumptions.

• TESTS ON PASTEL STRUCTURAL AND THERMAL MODEL (see section 4) : different complementary tests were performed on structural elements of the terminal (Optical Assembly, Mobile Part), on the terminal alone, and on the spacecraft/terminal assembly (with a SPOT4 Engineering Model). These tests were essentially dedicated to the validation and update of the terminal FEM and to the qualification of the terminal design for microvibrations matters. In addition to "classical" modal survey tests, some dedicated sequences were devoted to the assessment of the structural behaviour in the microvibration domain (i.e. for very low excitation levels) ; and for the PASTEL CPM, the non-linear transmissibility of microvibrations through the articulations was investigated in detail.

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To conclude, tests are also foreseen on PASTEL Flight Model (on the terminal alone and on the spacecraft/terminal assembly, including SPOT4 Flight Model). They will be dedicated to the ultimate verification of the in-orbit microvibration performances.

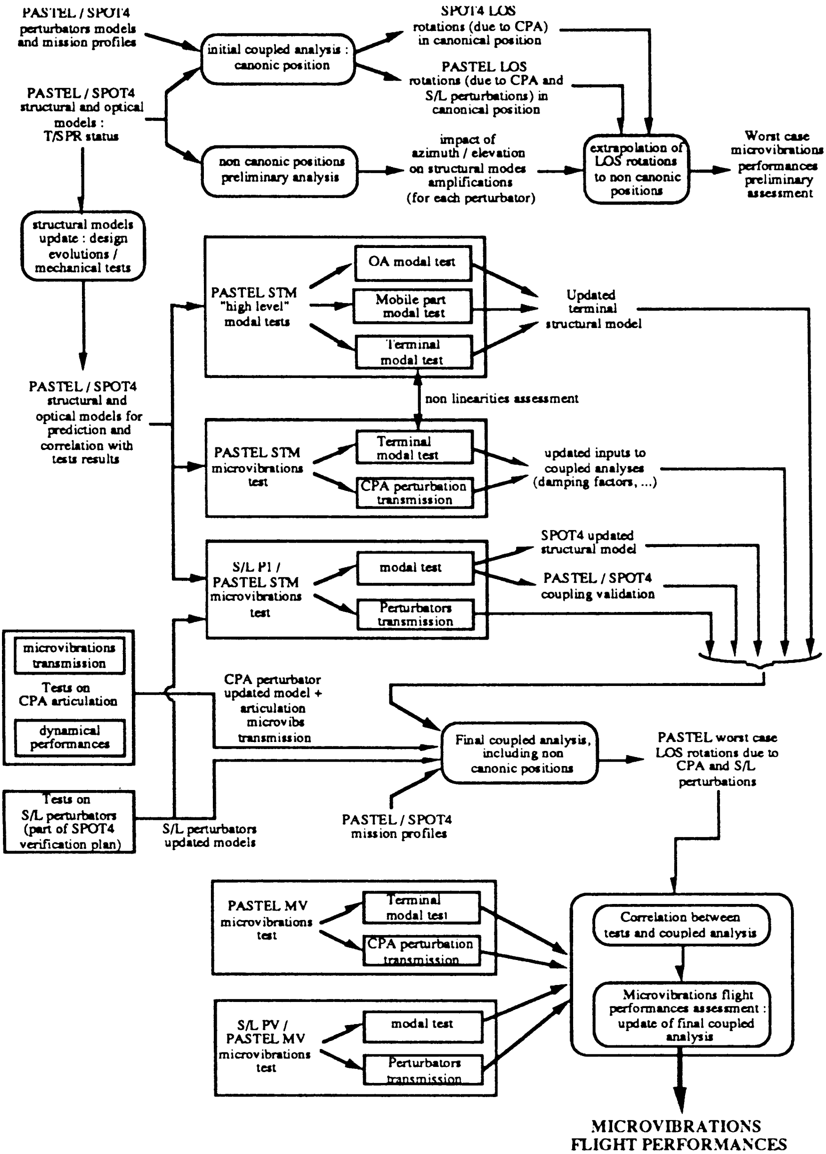

Figure 3 : PASTEL Microvibrations Verification Plan

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3 - Characterisation/Verification of the On-Board Disturbances

All moving parts on-board SPOT4 are potential microvibration sources, although a number of them are shown to be negligible (Earth sensor scanning mechanism, gyroscope mechanical heads, solar array drive mechanism,...) or are not operated during PASTEL communication sequences (thrusters for example). The most significant sources are the three SPOT4 reaction wheels (RRPM), the two oblique viewing mirrors (MCV) of the HRVIR instruments. The two SPOT magnetic tape recorders (EMS), and the two PASTEL Coarse Pointing Mechanism Articulations have also been investigated.

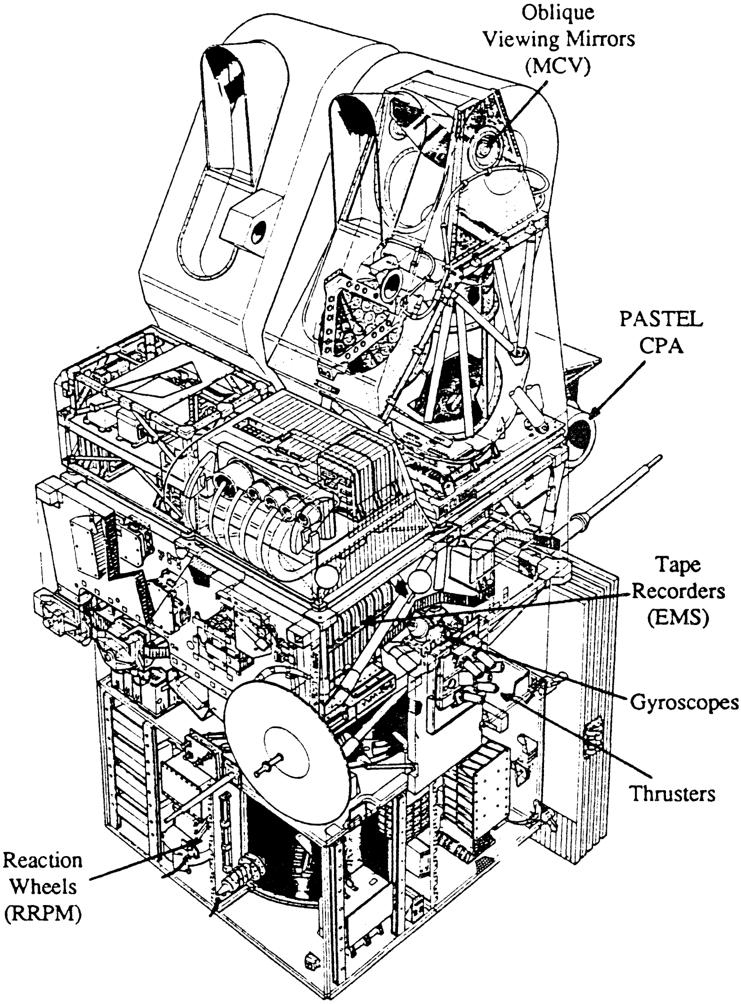

Figure 4 : SPOT4/PASTEL Microvibration Sources

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3.1 - The SPOT4 Reaction Wheels (RRPM)

Three magnetically suspended reaction wheels are used by the AOCS to control the spacecraft's attitude. These 40 Nms wheels, developed by Aerospatiale, are based on an innovative magnetic bearing architecture, where the two axes perpendicular to the rotation axis are actively controlled : the relative rotor/stator position in the radial plane is detected by inductive sensors, measuring the position of a circular track mounted on the rotor ; a feedback force is applied through a current sent to electromagnetic actuators. The remaining degrees of freedom are passively stabilised by permanent magnets. The disturbances are due to the following physical causes :

- an offset between the rotor centre of mass and the magnetic centre leads to a rotor-synchronous rotating force *(magnetic unbalance)* ; an offset between the rotor centre of mass and the detection centre (geometric centre of the detection track) leads through the active control loop to a rotor-synchronous rotating force *(detection unbalance)* ; a misalignment between the rotor principal axis of inertia and the magnetic axis generates a rotating rocking torque, rotor-synchronous *(dynamic unbalance)*
- circularity defaults of the detection track generate harmonic disturbances through the active control loop, at frequencies that are integer multiples of the rotor rate *(detection harmonics)*

These wheels were identified early in the programme as a major contributor to the microvibration performance ; therefore an effort was done to understand, model and validate by tests their dynamic behaviour. A very fruitful test was based on the measurement of the 6-axis interface torque generated by the wheels, rotor in rotation, and to analyse its variation versus rotation speed :

• TEST PRINCIPLE : the wheels were successively rigidly mounted on a 6-axis Kistler dynamometric platform (designed to measure interface forces with an accuracy better than 1 milli-N), integrated inside a vacuum chamber, itself mounted on a massive seismic concrete block - isolated from the ground by low cut-off frequency spring systems. Taking into account the need for characterisation of the disturbances on the whole operational range of rotor rate, the following method was used :

- run-up with full motor torque, up to the maximum operational rate
- spin-down at zero motor torque ; the wheel rate decreases due to internal friction. The force channels are recorded in the time domain

Due to the low level of friction, the wheel rate decreases very slowly ; over a short period of time (1 or 2 seconds), it can be considered almost constant. The spin-down phase can thus be processed as a series of "quasi-steady states" : "waterfall" spectra vs. time all along the run-down phase, identification and tracking of the harmonics as a function of the rotor rate... This method is particularly well adapted to microdynamics tests involving a reaction or momentum wheel. It allows a comprehensive characterisation of the disturbance through one unique test sequence (see Ref. [5] for other examples).

• TYPICAL TEST RESULTS : an example of spectra in "waterfall" representation is given for the radial force on figure 5 over a spin-down phase. This plot shows the harmonic contents of the disturbance, which can be interpreted as the "image" of geometric imperfections of the position detection ring (used as reference for the active radial control). The frequency of the harmonics decreases in the time, following the decrease of the rotation velocity.

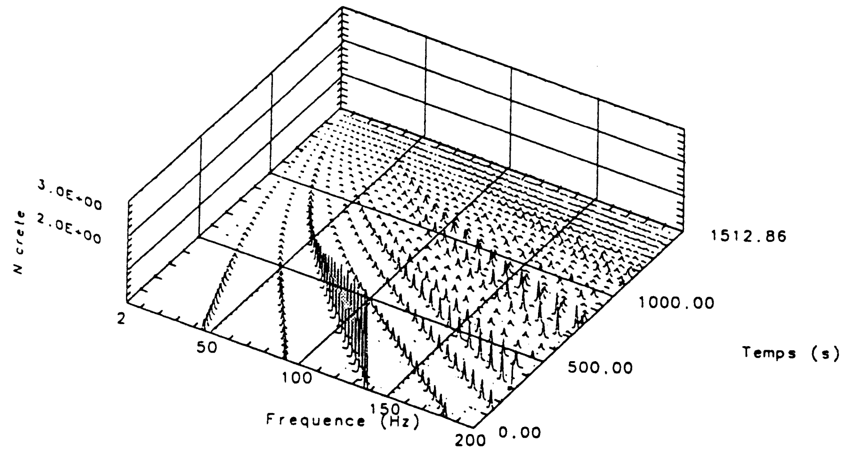

Figure 5 : RRPM Radial Signature ("Waterfall" Spectra)

Thanks to the combined test/analysis approach applied to the case of the RRPM, the simulation models and the associated parameters have been identified with a high level of reliability. Simulation results can now be used directly for microvibrations performance predictions.

3.2 - The HRVIR Oblique Viewing Mirrors (MCV)

The SPOT4 MCV (Miroir de Changement de Visée, or Oblique Viewing Mirror) is an important element of the HRVIR payload (Haute Résolution Visible et InfraRouge). This steering-front mirror allows out-of-track imaging with a tilt capability around the roll axis ; it is powered by a SAGEM stepping motor in "full step" mode. The switch frequency is 16 Hz, the step amplitude is 0.3°, and the nominal angular position in imaging mode is within ±13.5° from Nadir. Just like the RRPM, the MCV actuation is a major contributor to the microvibration performance. Therefore its dynamics has been investigated in detail over the past few years, by series of tests and analyses. The aim of the tests performed since 92 on different models of the MCV was to validate our analysis models, to identify its critical parameters and to correlate simulation and analysis results in terms of disturbances and dynamic behaviour.

• TEST PRINCIPLE : several tests were performed at MMS since 1992 on a flight-representative MCV, mounted on the HRVIR instrument. The angular motions of the mobile part were measured by two high sensitivity linear accelerometers, mounted tangentially on the side of the mirror. The current in the stator windings was also available. This instrumentation was able to provide a very complete and accurate overview of the status of the hinge (angular acceleration, torque on the mobile part, electrical status of the motor) :

- angular motions, disturbing torque and stator currents were measured during rallying phases (MCV actuation over 90 motor steps)
- the stabilisation profile (after the last commanded step) was investigated to characterise the internal friction effects.

• TYPICAL RESULTS : experimental measurements and simulations using a detailed model of the motor confirm the presence of harmonics of the switch frequency (16 Hz and multiples), up to high orders (10th harmonics and higher have been observed). They also show "inter-harmonics" components, with a very different behaviour following the specimen :

- in some cases, they are transient and vanish during the rallying motion. Here they correspond to the axial hinge eigenfrequency f_0 and to combinations with 16 Hz and harmonics, due to non-linearity of the motor ($N \times 16$ Hz $\pm f_0$)
- in other cases, they keep excited at high level all along the rallying motion. Here they correspond exactly to multiples of 1/3 of the switch frequency ($N/3 \times 16$ Hz)

This phenomenon has been correlated by non-linear simulation and analytic approach. It is known as "1/3 subharmonic resonance" of a cubic non-linear system : the second cases present subharmonic resonance, and the first do not. To simplify, such a behaviour may occur when the switch frequency is "close to" three times the hinge natural frequency : this is the case for the MCV.

A last test campaign on the SPOT4 MCV is now under completion, in order to characterise the effects of a new motor command mode : the motor phases are in short-circuit, instead of open. The additional electrical dissipation in the short-circuit phase prevents from subharmonic resonances, and reduces the tranquillisation time of the MCV at the end of a rallying sequence.

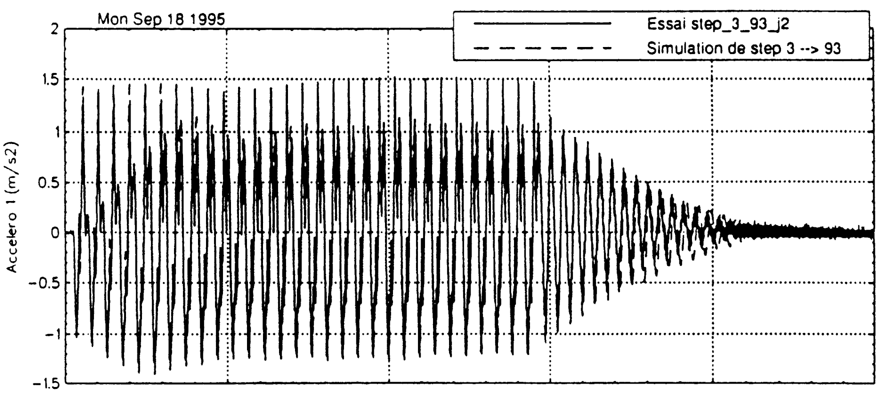

Figure 6 : MCV Test/Simulation Correlation (Example)

Just like in the case of the RRPM, the combined test/analysis approach chosen for the MCV has given fruitful results. Well-adapted model identification methods have been worked out, and a fully validated simulation model is now available (see an example of test/simulation correlation on figure 6).

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4 - Verification of the Structural Dynamics

In order to validate and correlate the Finite Element Model (FEM) of PASTEL, a modal survey test campaign has been carried out on the SILEX LEO STM. The logic of this campaign is directly derived from the structural architecture of the terminal ; it is based on the successive verification and update of substructures of growing complexity, leading eventually to the update of the whole terminal model.

4.1 - Simplified Description of the PASTEL Structure

PASTEL (see figure 2) is made of a Telescope Assembly (TA), transmitting and receiving data from the Optical Head Bench (OHB). These two items constitute the Optical Assembly (OA), and are isostatically mounted to a closed box : the Mobile Part Carrier Structure (MPCS). Thermal insulation of the optics is ensured by the Optical Head Thermal Hood (OHTH) covering the OHB, and the baffle for TA protection.

The MPCS is pointing toward ARTEMIS thanks to a two axis Coarse Pointing Mechanism (CPM). This mobile arm is fixed on SPOT4 through the Coarse Pointing Support Bracket (CPASB) and the Aerial to Spacecraft InterFace Structure (ASIFS). To withstand the launch dynamic environment, the MPCS is maintained by three Launch Locking Devices. A pyrotechnique cut-off leads to the operational configuration of the terminal.

4.2 - PASTEL Modal Test Campaign

The modal test campaign has been divided in three steps, concerning each of the following substructures of the terminal :

- the Optical Assembly, made of the telescope and the optical bench,
- the Mobile Part Carrier Structure, supporting the OA and optical equipments,
- and finally, the whole PASTEL terminal.

After each modal survey test, the associated FEM correlation is performed and used for the following FEM update. This "step-by-step" procedure allows to update the critical modes for the LOS pointing performance. On another hand, this methodology, consisting in modal survey tests on each substructure, makes easier the final FEM correlation which is too complex to correlate in a single modal test (due to the high number of complex interfaces and coupled modes).

This comprehensive modal test campaign allowed to perform a fine PASTEL FEM verification and update up to 150 Hz. The correlated FEM has been coupled to SPOT4 in order to perform the flight microvibration performance prediction.

4.3 - Focus on the Aerial Modal Survey Test

For this test the SILEX LEO aerial is clamped on a seismic mass via a dedicated test set-up (rigid up to 180 Hz). The ASIFS is placed in a vertical position, simulating the SPOT4 interface (see figure 7). The anti-gravity device is fixed on the MPCS to compensate the mobile part mass. The specimen is equipped with 176 accelerometers, located on the whole structure. Before the aerial modal survey test itself, a FEM of the anti-gravity device is made to know the impact of this device on the low frequency eigen mode of PASTEL.

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The following table presents a comparison between the tests and the FEM results :

Mode Description	FEM without 0g Device	FEM with 0g Device	FEM Updated	Test	Damping Factor
CPM bending Zs	6.4 Hz	5.5 Hz	6.4 Hz*	7.1 Hz	2.4 %
CPM bending Zs	not predicted	6.4 Hz	7.4 Hz*	7.4 Hz	0.7 %
CPM bending Xs	7.5 Hz	7.5 Hz	8.7 Hz*	8.5 Hz	2.1 %
CPM translation Ys	13.8 Hz	13.6 Hz	15.8 Hz*	15.9 Hz	1.7 %
CPASB bending Ys	41.1 Hz	40.5 Hz	45.1 Hz	45.7 Hz	1.7 %
TA mode Zs	83.2 Hz	83.1 Hz	81.0 Hz	83 Hz	2.5 %
TA mode Xs	89.3 Hz	88.8 Hz	90.0 Hz	90 Hz	2.9 %
OHB translation Xs	123.7 Hz	123.0 Hz	141.5 Hz	144.8 Hz	0.5 %

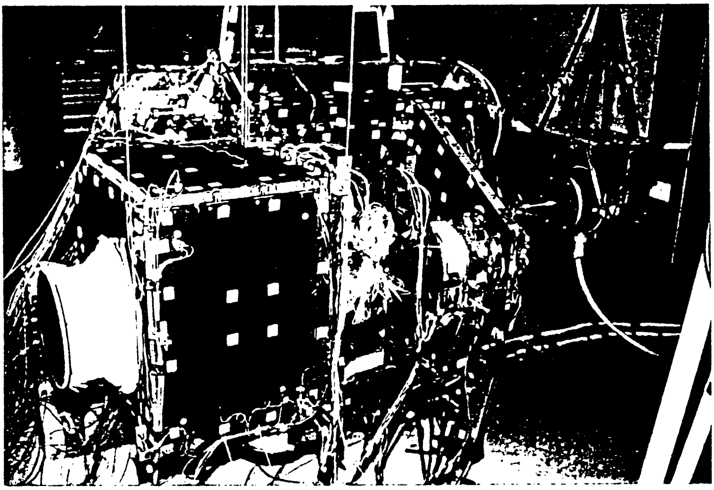

Figure 7 - Aerial Modal Test Configuration

The values with a * are eigen modes driven by the CPM stiffness ; this stiffness was refined by rule-of-the-thumb calculations from static and sine test results at CPM level (since no modal survey test was run on the CPM alone). The splitting effect on the first CPM bending mode was well predicted by the FEM ; it is due to the mass added to the Mobile Part by the anti-gravity device.

The PASTEL FEM correlation is now completed. Figure 8 shows a test/FEM transfer function comparison at the TA top side.

4.4 - Structural Characterisation in the Microvibration Domain

In addition to the "classical" modal survey tests performed on the different PASTEL substructures, some tests were dedicated to the characterisation of the structural behaviour in the microvibration domain :

- MICROVIBRATION TEST ON PASTEL STM, in parallel with the modal tests described in section 4.3. The principle was similar to the modal test sequence, with a very low excitation force level, the accelerations being measured by high sensitivity accelerometers. A good overall linearity was demonstrated.

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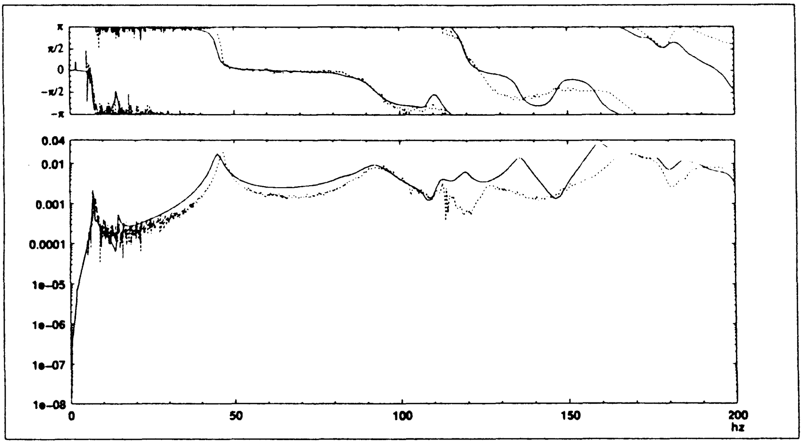

Figure 8 : Test/FEM Comparison (Telescope Top Side)

• MICROVIBRATION TEST ON THE CPMA : the aim was to characterise the transmissibility of microvibrations through the SILEX articulations. The principle was based on the angular response of the rotor to an angular displacement excitation of the stator, applied through a dedicated equipment driven by a piezoelectric actuator. The angular responses were measured by Systron-Donner Inertial Angular Displacement Sensors, with a threshold of some nanoradians. This test has demonstrated that the transmissibility at very small amplitudes (below 10 microradians) depends on the excitation level (a set of transfer functions is given in figure 9). The cause of this non-linear behaviour has been accurately modelled as a Dahl's friction phenomenon.

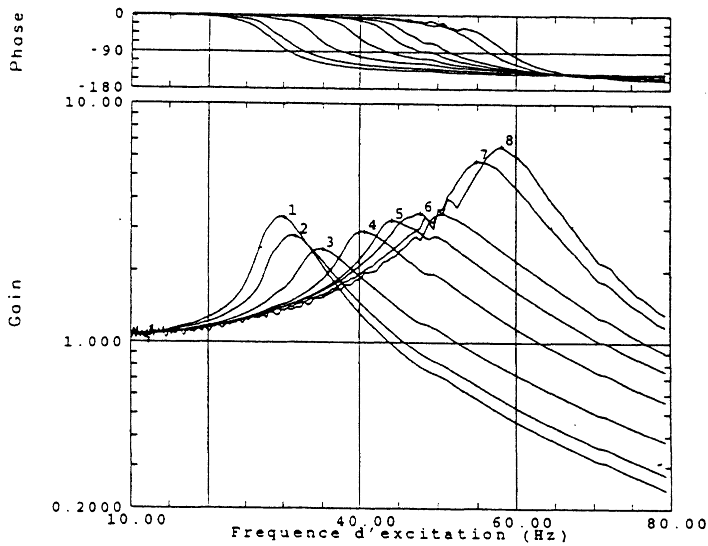

Figure 9 : CPMA Non-Linear Transmissibility

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4.5 - Tests on SPOT4 P1 / PASTEL STM

A microvibration test was performed in December 1993 on the SPOT4 P1 engineering model / PASTEL STM assembly. The essential objective was to measure reference transfer functions to validate the coupled FEM ; a secondary objective was to measure the effects of actuation of on-board disturbance sources to estimate the jitter induced on the PASTEL LOS. The satellite was suspended by soft slings, representative of free-free boundary conditions above some Hz ; PASTEL was unlocked, azimuth and elevation motors powered in canonic position, Mobile Part suspended by its own anti-gravity rig.

• THE TRANSFER FUNCTIONS measured allowed to refine the structural damping assumptions. The damping ratio was found roughly equal to 1% below 50 Hz (except for one particular PASTEL mode : 1.7%), and to 1.5% between 50 and 200 Hz. Besides, this test enabled to draw lessons to build a realistic margin policy :

- below 20 Hz, a 20% margin was directly applied to the Frequency Response Functions.
- between 20 and 50 Hz, a method of modal hybridisation is applied. The principle is to combine all the modes which appear in an "uncertainty window" and to allocate the maximum reached level for the centre frequency. This allows to take into account a strong SPOT/PASTEL modal coupling, observed in test, but not predicted by the "nominal" FEM.
- between 80 and 100 Hz, a multiplicative factor is applied (3 on Rx LOS)
- above 100 Hz, the test/model correlation was good in terms of level, but not in terms of frequency. It was thus decided to replace the transfer functions by their maximum gains (flat transfer functions).

These assumptions were directly applied to the final flight prediction analysis.

• THE JITTER ESTIMATION extracted from the test was rather below the final flight prediction (see section 5.5). Note that this test was performed on a hardware not fully representative of the flight (engineering models of SPOT4 structure and of the reaction wheels) ; in addition, only the canonic position of PASTEL could be investigated ; finally, the prediction corresponds to a research of worst case coincidence between modes and disturbances, which cannot be done in tests on ground - but which might happen in flight.

5 - Final Coupled Performance Prediction and Verification

The final coupled microvibration budget for SPOT4/PASTEL gathers all the lessons learnt from the previous analyses, models and test results. The previous sections have explained how each element contributing to this budget (disturbance sources and structural models) has been verified and validated. Assembling these elements ensures a high level of reliability to the final performance prediction.

5.1 - Structural Modelling - Assumptions and Margins

As indicated in the microvibration verification logic, the final prediction was made using an updated SPOT4/PASTEL coupled FEM, with the uncertainty margins derived from experimental results, as justified in section 4.5 :

• The PASTEL FEM was validated and updated in detail, as presented in section 4. The Line-Of-Sight was introduced by linear combinations of physical degrees of freedom, validated on the rigid modes. Obviously, the FEM is representative of the flight configuration (Launch Locking Devices released, azimuth and elevation articulations powered).

• The SPOT4 FEM includes updated models of the two HRVIR instruments. It is representative of the orbital configurations : the Solar Arrays are deployed ; the MCV are unlocked, motor powered on a fixed step ; the tanks have been modified from elementary tests. In addition, a physical model of the reaction wheels has been introduced : the radial active control (see section 3.1) has been described as a spring-damper system with a high damping ratio (typically 30%). Indeed, tests and analyses have demonstrated the need to model accurately the wheels/structure interactions (the presence of the wheels can reduce the local transmissibilities by a factor 5 in some frequency bands). As a consequence, the damping matrix of the system was not diagonal - this was a noticeable specificity of this FEM.

• To take into account the large motions of the PASTEL terminal, the assembly of the PASTEL and of the SPOT4 FEM was performed for a series of 35 different azimuth and elevation fixed positions, varying from 5° to 185° in azimuth, and from -38° to 75° in elevation. As a consequence, 35 NASTRAN FEM models were built for this "multi-positions" analysis.

5.2 - Analysis Method and Tools

For each of the 35 PASTEL positions, the LOS response to RRPM and MCV disturbances are calculated (in frequency domain), leading to a set of forced frequency responses. A "worst case position" is determined from this set, for which the complete final performance budget is established (see figure 10). The whole analysis processing is performed by the in-house IPANEMA software (Integrated Performance Analysis Environment for Microdynamics Applications), developed under MATLAB.

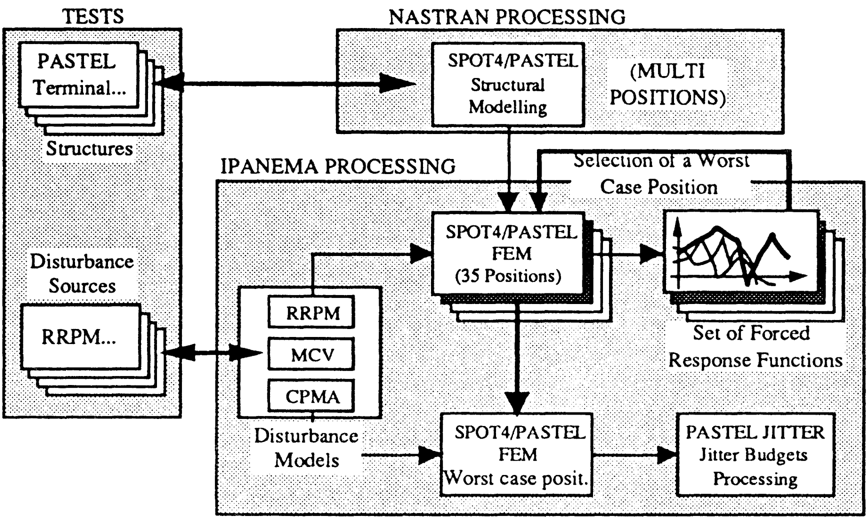

Figure 10 : Principle of the Final Coupled Performance Analysis

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5.3 - Disturbance Sources Models

Only the main disturbance sources are considered : the RRPM, the MCV ; the CPMA (although known not critical) is also processed for verification.

• MAGNETIC BEARING REACTION WHEELS (RRPM, see section 4.1) : only the disturbances produced by radial forces are important to PASTEL. The harmonics are given by a worst case envelope of experimental measurements ; the maximum velocity varies from 3.3 Hz (for wheel X) to 6 Hz (for wheel Y). The other force and torques can be neglected.

• OBLIQUE VIEWING MIRROR (MCV, see section 4.2) : the disturbance profile used in the study is based on the validated stepping motor model. Two kinds of components take part in this profile : a *transient component* (which contains low frequency disturbances) is considered in a specific study, based on time domain simulations with a simplified SPOT4/PASTEL dynamics ; and a *steady-state component*, composed of a series of harmonics of the motor stepping frequency (16 Hz). A conservative harmonics envelope is applied in input to the FEM, taking also into account the MCV unbalance forces.

• COARSE POINTING MECHANISM ARTICULATIONS (CPMA) : the two CPMA (azimuth and elevation) are based on a stepping motor. The main disturbances are generated by the drive electronics at 100 Hz (although smoothed by a built-in Butterworth filter). This disturbance level is simply applied to the structure ; a worst case coincidence with a structural mode around 100 Hz is searched.

5.4 - Analysis Results

The step of "worst case" position research gave the evidence of a significant dependence of the performance on the PASTEL position. The worst position found corresponds to an azimuth angle of 65°, and an elevation angle of 75° (as it appears on figure 11).

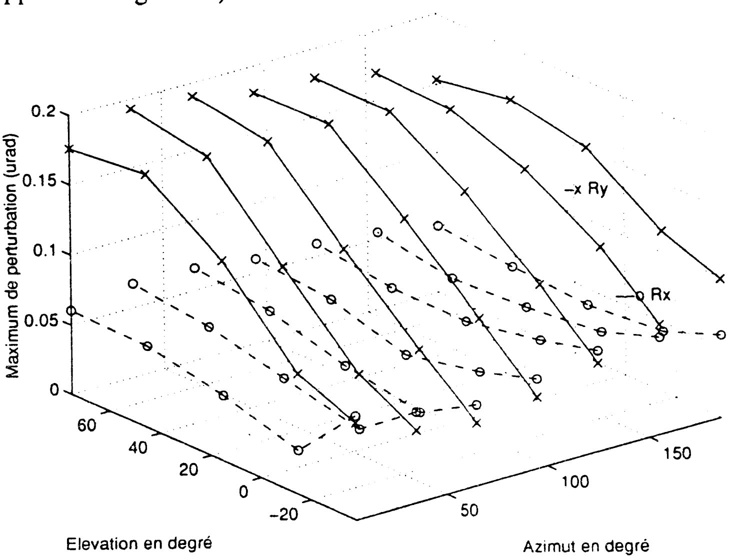

Figure 11 : Maximum Disturbance vs. PASTEL Position (Wheel Y)

The final pointing budget has been worked out for this worst case position. It shows that the jitter level reaches 0.27 microradians (value 1 σ) after rejection by the PAT control loop. This figure includes all the disturbance contributions (summation of wheels and MCV harmonics and CPMA disturbances) and margins due to structural uncertainties. It is thus known to be conservative.

5.5 - Final Verification Tests

A final verification test is foreseen on the SPOT4/PASTEL Flight Model assembly. Its principle is similar to the one already performed in December 93 on a SPOT4 Engineering Model and the PASTEL STM (see section 4.5).

6 - Synthesis and Conclusions

The analysis and verification activities performed by MATRA MARCONI SPACE in the frame of the assessment of SILEX terminals Line-Of-Sight pointing stability cover a wide technical spectrum in the domain of microvibrations. The very demanding system requirements (in the range of the microradian) have led to develop a comprehensive performance verification logic, based on a combined experimental and analytic approach, including the characterisation and modelling of the disturbance sources, of the structural behaviour, and the working out of the final pointing budget. The results now available on the PASTEL terminal show significant jitter levels, but still acceptable for the system performances.

This SILEX experience constitutes an important breakthrough for prediction of microvibration effects on complex space missions. the lessons (verification logic, models, methods and tools) drawn from this activity will be an asset for a pragmatic and efficient approach on present and future demanding applications (GOMOS, SPOT5, METOP, ...).

Acknowledgements

The work described in this paper has been performed under ESA and CNES contracts. The authors wish to thank ESA, ITG and CNES engineers for their very helpful contributions.

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