FINE STEERING MECHANISM FOR NEW GENERATION OPTICAL COMMUNICATION TERMINALS.

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ABSTRACT

MMS has gained a significant experience in the mechanism development for optical communication terminals in the frame of the Silex (Semi-conductor Interactive Link EXperiment) program led by MMS as Prime contractor for ESA. Many lessons have been learnt from this development : for new generation optical communication Terminals, they have been taken into account in the overall terminal architecture as well as in the mechanisms design.

Mass, volume and recurring cost aspects are the major design drivers regarding the implementation of optical communication terminals, particularly when considering candidate applications such as satellite constellations.

Optical terminal mission is to provide high rate intersatellite link based on optical technology between two spacecraft's. The link is maintained by continuously controlling the counter satellite laser beam direction. The Pointing, Acquisition and Tracking (PAT) system is in charge of reflecting the beams towards the telescope : it is one of the key assemblies of the optical terminal.

The analysis of the PAT system pointing requirements, presented in the first section of the paper has lead to the choice of a two stages mechanism architecture, which support the terminal Front Mirror Unit (FMU). These mechanisms are:
- the Large Range Azimuth Mechanism (LRAM) providing the complete azimuth angular range
- the Fine Steering Mechanism (FSM) which is a two-axis assembly.

The LRAM requirements and main performances will are discussed, prior to focus on the FSM requirements, design description and performances budget. The FSM activities have been initiated under MMS funding and a demonstrator detailed design was issued in the frame of the phase 1 of ESA contract 12792/98/NL/DS.

Hardware was developed and initial tests were performed. A LRAM demonstrator was fabricated and integrated by Mecanex and tested by MMS. FSM technology-critical devices were designed, fabricated and tested, such as the flex pivots. Characterization test results are presented.

1 - PAT FUNCTIONAL REQUIREMENTS.

The optical terminal mission is to provide high data rate intersatellite link based on optical technology between two spacecraft's. The link is maintained by continuously controlling the counter satellite laser beam direction.
One of the key systems in the optical terminal design is the Pointing, Acquisition and Tracking (PAT) system, which is in charge of the following functions.

i) *Beam Acquisition*.
This corresponds to the link initialization phase.
The terminal line-of-sight (LOS) must be aligned within the transmit beam divergence, in order to illuminate the counter terminal. Due to the initial pointing uncertainties (S/C attitude, mechanism pointing...), a specific phase is needed to achieve the initial alignment between the terminals.

At the beginning of the link initialization phase, both terminals are continuously pointing each other with open loop pointing uncertainties.
At the end of the link initialization phase, both terminals are able to continuously point each other with an accuracy well inside the transmit beam divergence.

ii) *Beam Tracking*.
This is part of the link phase. Beam tracking is a closed loop process which involves the measurement of the receive beam direction thanks to an optical sensor (ARTS). The PAT is controlled to maintain the desired receive direction.

iii) *Beam Pointing*.
Due to finite speed of light, the relative velocity of the spacecraft must be compensated. Therefore, the transmit beam direction is offset with regards to the receive beam. This offset is the point-ahead angle.

2 MECHANISM ARCHITECTURE

Following the lessons learnt from mechanisms development for the SILEX optical communication payload, developed by MMS as Prime Contractor for ESA, improvements have been implemented for future generation of optical communication terminals.

The telescope, optical bench and proximity electronics are now on the terminal fixed part, and only a large Front Mirror is mobile. This minimizes the mobile inertia, cantilever forces, motors power consumption, and makes integration and testability easier.

The LOS sensing architecture was improved (ARTS), allowing to delete the "Pointing Ahead Mechanism".

Mass, volume and cost aspects are the major design drivers particularly when examining the candidate applications, which are constellations of satellites. Therefore the following design rules were highlighted :

- Early implication of mechanisms designers into terminal project, in order to understand system requirements and find the best compromise between system and mechanisms requirements
- AIT operations simplification, at mechanisms level, and also at system level, when integrating the mechanisms
- Magnification of requirements in order to dramatically reduce recurrent cost of manufacturing processes
- Design to cost approach, including requirement compliant with the state-of-the-art available technologies performances

In order to establish and maintain the optical crosslink between two spacecraft's, the optical beam steering is obtained by the pointing of the Front Mirror Unit (FMU). The FMU motion is provided by the mechanisms of the Front Mirror Pointing Assembly (FMPA) ; the Fine Steering Mechanism (FSM) is one of the mechanisms of the FMPA.

The overall architecture of the Terminal is sketched on figure 1. This architecture is based on a hollow shaft LRAM, the rotor of which supports the Optical and Structural Baffle (OSB). The FSM Mounting Plate is mounted on a planar surface of the OSB. The FMPA includes:
- the Large Range Azimuth Mechanism (LRAM), which gimbals the front mirror around the azimuth axis, via the OSB supporting the FSM.
- the Fine Steering Mechanism (FSM), which provides the Front Mirror with elevation and fine azimuth rotations.
- the Front Mirror Unit (FMU).
- the LRAM and FSM electronics. These electronics are part of the terminal electronics.
- the FMPA software algorithms. The LRAM and FSM control algorithms are implemented in the terminal On-Board Software.

This paper is dedicated to the FSM. The LRAM is only briefly described in the following sections, reminding that the overall pointing performances are sensitive to the LRAM disturbing torque and the FSM rejection capabilities.

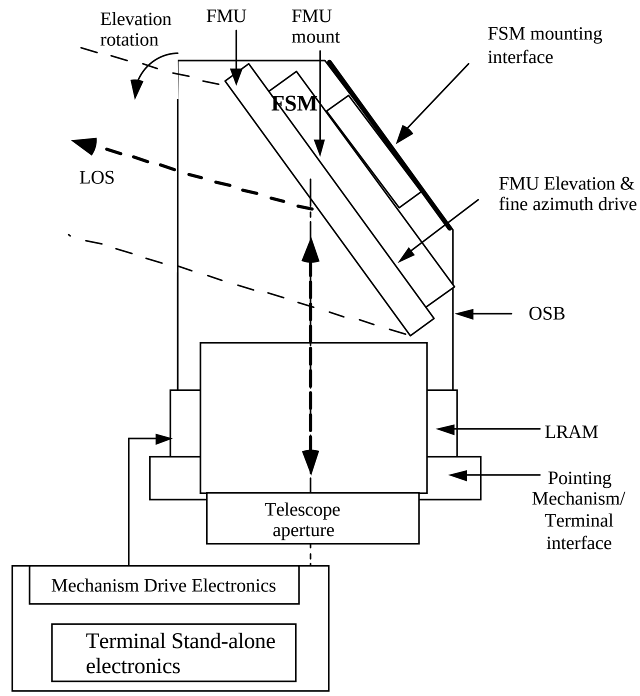


Figure 1 - PAT Mechanisms overall architecture

3 LRAM MAIN REQUIREMENTS AND DESIGN FEATURES

3.1 LRAM main requirements:

The LRAM and FSM requirements have been established in the frame of the TELEDESIC mission, but it is admitted that this class of requirements is applicable to any terminal suitable for low orbit satellite constellation.

The table 2 summarises the LRAM main requirements. To achieve the required performances, it is mandatory to specify very stringent torque requirements for the motor, the bearings and the cable wrap : acceptable torque noise and hysteresis are very limited.

3.2 Main design features

The LRAM is built according to a "hollow shaft" concept, implicating large diameter components.
The LRAM main constituents are:
- a direct drive brushless torque motor
- two rigid preloaded ball bearings
- a 21bit optical encoder
- a housing, which interfaces with the Launch Locking Devices linking the optical terminal to the spacecraft, and also with the terminal Optical Head Bench.
- a hollow shaft, which contains a thermal screen
- an optical structural baffle, which links the hollow shaft to the FSM assembly
- a cable wrap, which provide electrical connections from the terminal fixed part to the FSM assembly.

Requirement	Performance	Comment
Operating lifetime	10 years – 2800000 cycles	
Optical beam diameter	150 mm	
Pointing performances - Angular range - Speed - Acceleration - Pointing accuracy: * positioning * scanning * acquisition * tracking	 ± 125 ° 10 °/s 5°/s alternated 8°/s² 0.015° 0.015° 0.01° stability over 100 ms ± 1.4 µrd (3σ), speed 5°/s bandwidth > 0.01 Hz	End of life In slewing mode In other operational modes Stability : 0.005° over 30s, bandwidth <50 Hz The tracking performance is achieved thanks to the FSM
Mechanical misalignment	0.01°	Launch, thermoelastic and ageing effects
Mass	< 5.3 kg	
Structural performances	1st eigen frequency > 150 Hz 1st mode disturbing LOS[1] > 300 Hz	
Environment - Launch loads - Operating temp. - Radiation	 34 g -25°C to +60°C 50 krad	

Table 2 - LRAM main requirement summary

Internal mechanical stops limit the range, protecting the cable wrap from possible stress.

A rotational launch lock is fitted to the LRAM, preventing from possible azimuth rotation during launch phase.
The figure 3 illustrates the LRAM concept.

The encoder is based on the 21 bit CODECHAMP optical encoder qualified in 1998 (under CNES funding). This encoder is tolerant to a centering misalignment compliant with the centering tolerance given by the ball bearing assembly. Therefore the encoder integration process is straightforward, which is favorable for a low cost LRAM concept.

The torque motor is specially designed by ETEL (CH) in order to meet the stringent "low cogging" requirement.

A LRAM demonstrator has been manufactured by MECANEX (CH). It is based on commercial components, with exception of the motor, which is an EM manufactured by ETEL.
The LRAM demonstrator was partially tested at MMS, enabling to measure basic contributors to torque performance, and to compare them with predictions.

[1] L.O.S. Line Of Sight

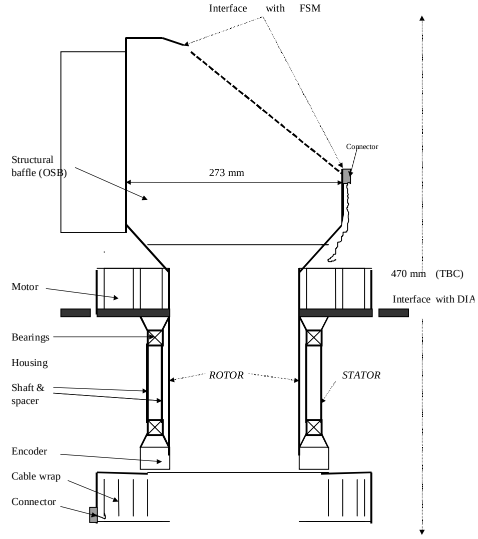


Figure 3 - LRAM architecture

4 - FSM REQUIREMENTS

The main FSM performances are listed table 4.

Parameter	FSM mode	Optical required performance	Opto-mecha. gain	Mechan. specif.
Azimuth angular range	*All*	-2° - + 2°	•2	~ ± 1.5 °
Elevation angular range		-28° ; -1°	2	~ ± 7°
Angular rate	*Slewing* *Positioning* *Scanning* *Acquisition[2]* *Pointing*	-8 /+8 °/s -0.5 / +0.5 °/s az: ±0.1°/s el ±0.6°s -8 / +8 °/s az: ±0.3°/s el ±0.5°s		
Angular acceleration	*Slewing* *Positioning* *Scanning* *Acquisition[1]* *Pointing*	-2 / +2 °/s^2 negligible *TBD* -1000 / +1000 °/s^2 negligible		
Pointing accuracy - Elevation	*Slewing , positioning & scanning* *scanning - stability over 30s* *scann.: - stability over 25ms* *Acquisition[1]*	0.02° 0.01° 20 µrd 0.01°	2 2 2 2	0.01° 0.005° 10 µrd 0.005°
Pointing accuracy - Azimuth	*Slewing , positioning & scanning* *scanning - stability over 30s* *scann.: - stability over 25ms* *Acquisition[1]*	0.015° 0.005° 14 µrd 0.005°	√2 √2 √2 √2	0.01° 0.003° 10µrd 0.003°
LOS error (3σ)	*Pointing*	1.4 µrd		

Table 4 -FSM main performances requirement summary

[2] *Acquisition is achieved over a restricted ±0.25° LOS range*

In addition, to fulfil the tracking operation phase requirements, the response of the FSM shall comply with the template figure 5 (next page).

The *pointing accuracy and stability* are the main FSM design driver.

To achieve *scanning* and *acquisition* pointing accuracy (absolute and relative responses), position sensors are mandatory. Stringent requirements apply concerning thermal sensitivity and measure stability over 30s.

Scanning pointing stability and *acquisition time response* require the utilization of torque command ensured by *current*_supply of actuators. The *3σ LOS error in pointing mode* is also very demanding. This parameter is sensitive to :

- electronic noise of the actuator command
- mobile part guidance : choice of flexible hinges instead of ball bearings
- parasitic torques, for instance electrical wire
- mechanism susceptibility to environmental micro-vibrations, constraining the balancing of the mobile part
- mechanism-induced mode impacting the LOS w.r.t. the control loop design (no mode below 300Hz). This is a severe constraint with respect to FSM mechanical design.

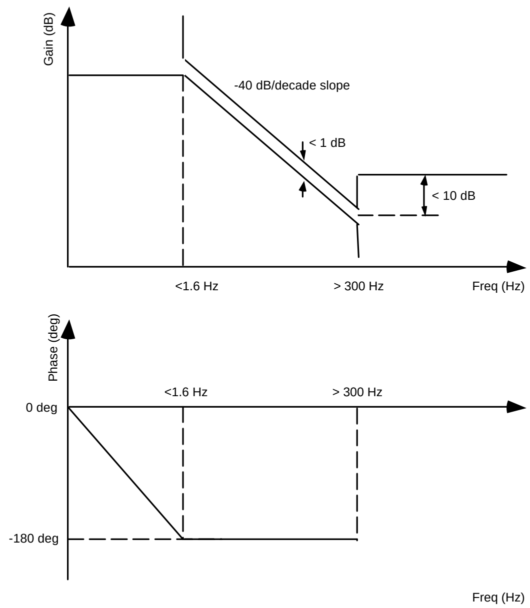


Figure 5 – FSM required frequency response

The main environment requirements are recalled in the table 6 :

Item	Requirement
Sizing level, lateral	40g
Sizing level, axial	23g
Thermal min. Non-op.	-40°C
Thermal min Op	-25°C
Thermal max Op	+60°C
Thermal max Non-Op	+70°C

Table 6 - FSM environment requirements

The main mechanical requirements are summarized in the table 7.

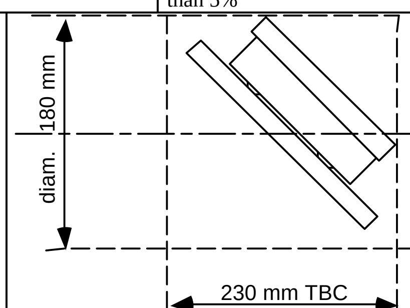
Item	Requirement
Mass, excluding Front Mirror Unit and FSM Electronics	< 2.0 kg
Mobile part inertia (including Front Mirror Unit) around the 2 actuation axis	$< 5.10^{-3}$ kg.m^2
Centre of mass of mobile part (including Front Mirror Unit) location wrt centre of rotation	< 0.1 mm
Inertia eigenaxes	Aligned with rotation axes Cross inertia wrt mechanical axes < 5%
Dynamic balancing	the inertia around three axes shall be equal, with an accuracy better than 5%
Volume	
Stiffness (Launch)	300 Hz for lateral and longitudinal modes
Front Mirror Unit interfaces	Mass 0.4 kg - Inertia around axes at CoM: Ixx ~0.001 kg.m² Iyy ~0.0025 kg.m²

Table 7 - FSM mechanical requirements

5 - FSM DESIGN

The main subassemblies of the FSM are:

- the mirror and the mirror structure (SiC)
- the barrel (Invar)
- the isostatic blade (mechanical link from barrel to mirror structure)
- the cross (Invar)
- the Flex-pivots
- the encoders
- the voice-coil actuator

The main mobile part comprises the mirror, its structure, the mobile barrel and the mobile rigid cross. The design of the mirror including a rigid SiC frame offers many advantages.

The closed frame structure allows to withstand residual thermo-elastic stresses from the mechanism, and induced stresses from the isostatic blades with minimum impact of the optical surface of the mirror (stringent WFE requirement).

The design of isostatic blades becomes easier : higher stresses are acceptable at the mirror interface, accepting higher flexural stiffness and finally thicker blades.

The drawing 8 illustrates the FSM architecture.

The mechanism /mirror interface is simpler. The blades are attached in the same plane, making easier the integration of the mechanism on the mirror.
The SiC structure offers a protection against radiation to the sensitive components (magnetic material, encoders, ...).
The structure carrying balancing masses is directly fixed to the mirror structure, featuring simple and stiff interface.

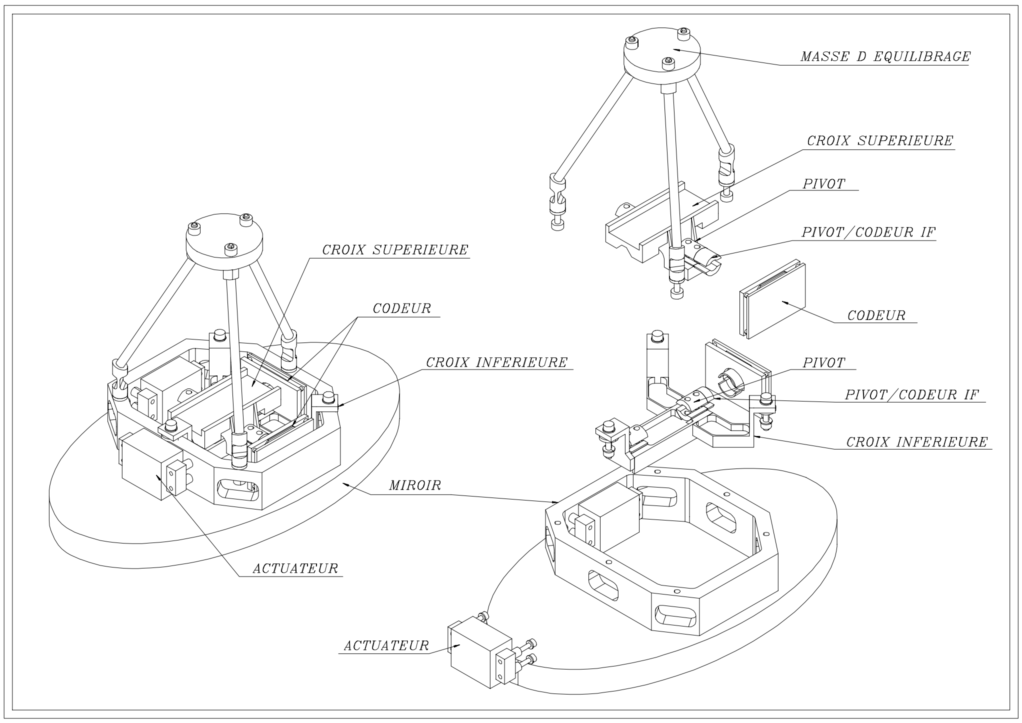


Figure 8 - FSM architecture

The voice-coils are installed directly between the mirror and the fixed structure, short-circuiting mechanically the mechanism structure and blades stiffness. This is a very favorable arrangement to satisfy the criteria "no mode below 300 Hz disturbing the LOS".
The mechanism itself is mounted to the SiC structure by three interface points, through the isostatic blades .

The mechanism structural parts (barrel and cross) are made of Invar, because it is necessary to interface with SiC with a material exhibiting a CTE as close as possible to SiC's.

The arrangement provides the two rotation axes in the same plane. The FSM mirror rotates around a virtual spherical link.

The closest rotation axis to the mirror is ‘Azimuth’, to minimize crossed inertia when operated.

The inertia around the two rotation axes and the normal to the mirror are made equal by adequate balancing masses, carried by a structure fixed to the mirror structure. The balancing mass is about 175g, located at 140mm of rotation axes plane, behind the mirror active surface.
Static balancing is also achieved thanks to the same balancing masses.
Finally, the electrical signals are routed from the fixed part to the mobile part through flexible "spring" wires.

The guidance is a key issue with regards to the FSM requirements.
Stringent noise requirement lead to choose flexible hinges for FSM mobile part guidance. This flexible element must fulfill the following criteria :
i) Guarantee a first rotational mode of about 1.6 Hz as imposed by the template requirement.

FSM requirement	RotationalStiffness	Translational.Stiffness	Load (N) - (assuming 30 g load)		
	0.81 Nm/rd	6.28N/µm	603 N		
Pivot requirement	Rotational Stiffness	Radial stiffness	Axial stiffness	Axial static load	Radial static load
	< 0.40 Nm/rd	> 6.28 N/µm	> 13.51 N/µm	> 373 N	> 280 N
MBD pivots	**0.19 Nm/rd**	**28** N/µm	**> 28 N/µm**	**500 N**	**500 N**

Table 9 - FSM flexpivots summary performances

ii) Guarantee a first translation mode greater than 300 Hz
iii) Withstand launch loads. A locking device, if any, has only to lock rotational degrees of freedom.

These requirements cannot be achieved by standard catalogue Lucas flex-pivots. The flex-pivots selected for the FSM mechanism are specifically designed and fabricated by MATRA BAe Dynamics (MBD-F). The performances of the pivots machined for the FSM are indicated figure 9, matching perfectly the FSM requirements.

These components have been tested at MMS and found compliant to their designed performances.

The selection of the actuators is another key issue; linear voice-coils are selected. The actuators design was completed by ETEL (CH). The proposed actuators have the characteristics table 10.

	Azimuth	Elevation	Comment
Mass mobile part	30 g	30 g	coil mass - a total mobile part < 100g is considered for both voice-coils (Az + El)
Total actuator mass	150 g	330 g	
Resistance (Ohm)	7.1 ±10%	6.1 ±10%	
motor thrust constant K_T	5.2 N/A mini	4.0 N/A mini	

Table 10 - FSM actuators overview

Concerning the sensors, a trade-off has been performed, involving linear inductive sensors and optical encoders. Linear inductive sensors exhibit major drawbacks :
1 – a high temperature sensitivity, which needs to implement a thermal drift compensation module in the detection electronics or software
2 - Errors due to the conversion of the linear measured motions into mirror rotation
3 - Errors due to the cross coupling effect between the two rotations.
The new qualified CODECHAMP encoder has been selected, because this encoder provides a direct rotation measurement for each axis. This arrangement is only possible thanks to the large centring tolerance allowed for this new design. It becomes possible to mount directly the encoder on the flex-pivot, without being disturbed by the flex-pivot ‘center-shift’ translation which occurs during rotation.

CODECHAMP has provided a special "compact" encoder design that fits the FSM available volume.

6 FSM PERFORMANCE BUDGET

The proposed FSM design is compliant with the mass, volume, moment of inertia, electrical and thermal interfaces requirements. The pointing performances are assessed as indicated hereafter.

"Open loop" performances. All operating modes, with exception of the "Acquisition mode", are performed in open loop at mechanism level. All the FSM components are selected to ensure the pointing performances are fulfilled.
The purpose of the phase 2 of the ESA contact is to manufacture, assemble and test the FSM demonstrator. Verification of the FSM actual performances is part of the phase 2 contract.

Acquisition phase. In this phase, the FSM is operated in a closed loop mode at mechanism level, using the encoder. The control law has been designed during the phase 1 of the contract, taking into account the characteristics of the FSM : mass/inertia, stiffness, components performances.
A mathematical model representing the FSM dynamical behavior has been first established.
This model illustrated figure 11 includes the measured flex-pivots torsion and radial stiffness, the encoder transfer function and the actuators performances predicted from the ETEL design. The structural parts design (cross, barrel, etc.) are stiff enough not to implicate intermediate modes.

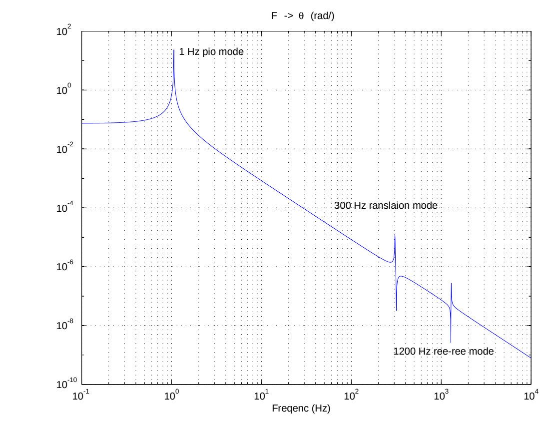


Figure 12 - FSM open loop transfer function

The FSM open loop transfer function is indicated figure 12. The control law has been designed based on this model, taking into account the following contributors (see figure 13) :

- Loop delays (from encoder, actuators, electronics)
- Specified acquisition performances ; to be achieved within a response time of 70 ms
- The potentially destabilising FSM 300 Hz mode

Because of the loop delays, a conventional PID controller does not provide a sufficient robustness. Therefore a 1 kHz 4th order digital controller is implemented. The closed loop characteristics are :

- bandwidth : 30 Hz
- damping : 0.7 (phase margin : 42 degrees ; gain margin : 7 dB)

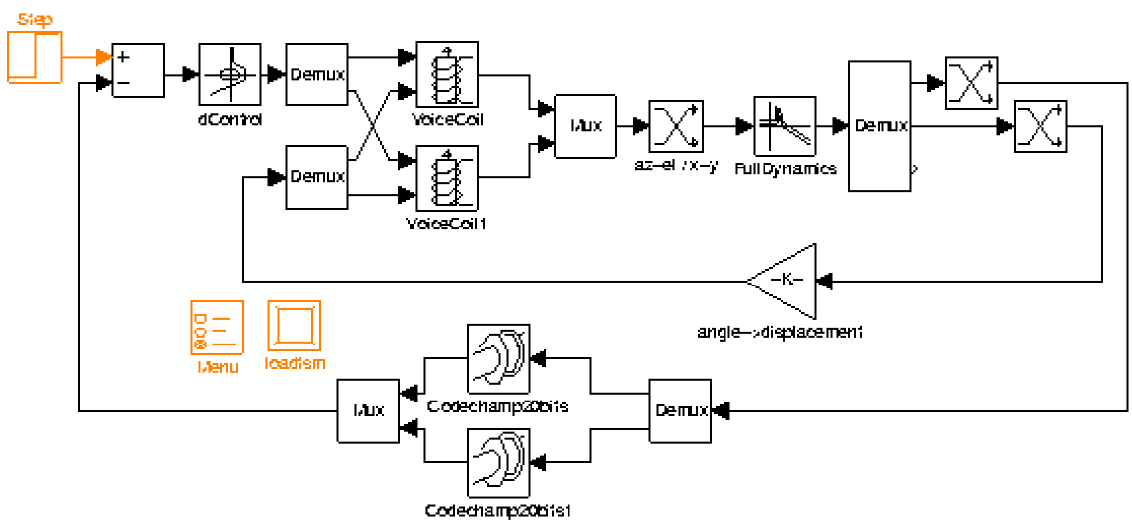


Figure 13 - FSM acquisition control loop model.

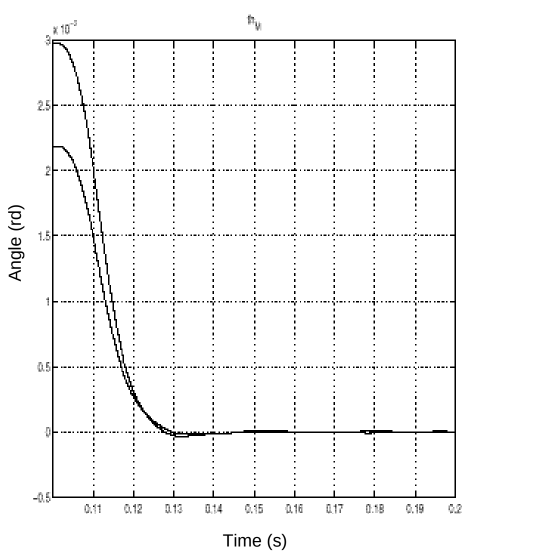


Fig. 14 - Simulated FSM acquisition performance

The acquisition pointing performance are assessed by simulation, as illustrated figure 14 steering angle versus time).

The simulations show an adequate behavior of the closed loop : fast convergence, good damping/ low oscillations and low residual noise

The achieved acquisition pointing performance is 24 µrad (1.3 10^{-3} degree) worst case, consolidating that the 3.5 10^{-3} degree pointing specification after 70 ms is achieved with margins.

It remains sufficient room to take into account some degradation due to further refinement of the model (effects not yet modeled), in particular the stiffness of the FSM structural parts.

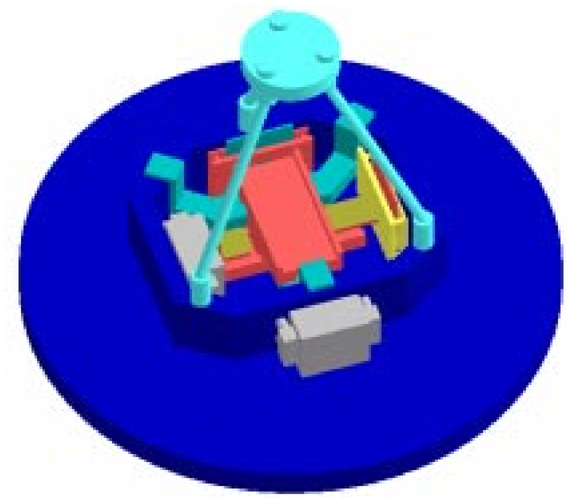
7 CONCLUSION

The work performed has demonstrated the feasibility of the mechanism fulfilling the stringent requirements of the pointing mechanisms dedicated to Optical Inter-Satellite Link Terminals.

This has in particular conducted to the design of an innovative two-axis pointing mechanism, the FSM, which presents the following advantages :
- compact two-axis pointing mechanism
- innovative position sensor integrated to the guidance bearing
- SiC and INVAR structure providing stiffness and temperature stability

Recurring cost is a design driver aspect for Constellation applications. The FSM concept was simplified as far as possible in order to reduce in particular the number of parts. The Launch Locking Device was removed from the design, making easier and simpler the detailed design and the fabrication of the mechanism.
Breadboards of key components and technologies were developed and tested (such as flex-pivots) ; other major issues took benefit of technological development program led by CNES (optical encoder).
The LRAM demonstrator was manufactured and component-level characterization was completed.
The next major milestone shall be the manufacturing and test of a representative FSM Demonstrator, allowing to confirm the expected performances.
The ultimate validation would implicate both the FMS and the LRAM Demonstrators integrated together, within a representative control loop using LOS sensor yet developed and validated. Mutual disturbances and rejection capabilities can be compared with the available performance budget based on mathematical modeling and simulation.

Finally, the FSM design features a wide application range capability and is adapted to missions where two-axes pointing, fast steering or scanning is necessary. High pointing stability – microrad scale or less – is achievable with European state-of-the-art technologies.



Acknowledgment.
The authors wish to thank T.T. NIELSEN (ESA) for his support during the FSM study, highlighted by his experience in Optical Terminal applications in particular.

Acronyms.
FMU : Front Mirror Unit
FMPA : Front Mirror Pointing Assembly
FSM : Fine Steering Mirror

LLD : Launch Locking Device.
LOS : Line-Of-Sight
LRAM : Large Range Azimuth Mechanism.

OISL : Optical Inter-Satellite Link

PAT : Pointing, Acquisition and Tracking

SILEX : Semi-conductor Interactive Link EXperiment.