SPOT'S POINTING MECHANISMS EXPERIENCE FEEDBACK

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ABSTRACT

Since the first generation back in early eighties, *Spot's* instruments have included steering mirror mechanism called "Mécanisme de Changement de Visée" _ MCV. Jointly with CNES, MMS has acquired over that program a broad and original experience on single-axis pointing mechanisms : 12 models were assembled and tested, 8 models launched, 6 models are today still operated in-orbit and last generation's 4 models are set to fly by 2001. The paper will highlight this experience focusing on evolutions due to steady performance improvement, new techniques emergence and integration. Conclusions will be extended to new MCV systems expected to equip new generation of imaging small satellites.

1. MCV'S FEATURES

1.1 Mission

Three generations of instruments have equipped the Spot satellites :

- HRV instruments – 'Haute Résolution Visible' - on Spot1/2/3
- HRVIR – 'Haute Résolution Visible Infra Rouge' - on Spot4 ;
- HRG – 'Haute Résolution Géometrique' - on Spot5.

On each of them, "out of track" imaging on both sides of the Nadir is performed by pointing the front-end mirror. That capability is fundamental both to carry out stereo imaging and to be less sensitive to the Earth cloud coverage. In case of emergency, MCV is also used to seal instrument's aperture by moving the mirror in a safe position.

1.2 Definition.

The MCV is a single-axis mechanism. MCV's definition consists of a mirror, a barrel for mechanical interface with the mirror, a stepper motor, an angular encoder, ball bearings and a structure called "Pyramide". One clamping device locks MCV's rotation around its axis during launch.
The stepper motor is used in direct drive. It is a SAGEM 57PPP60, 1200 steps per rotation. Torque capability is about 4.7 Nm.

On Spot1/2/3/4, a resolver manufactured by Sagem, measured the angular position. Its resolution was equal to 10 bits. On Spot5, an optical encoder jointly developed by CODECHAMP and CNES replaces this resolver. Its resolution is equal to 21 bits. Its static accuracy is equal to ±15 µrd. Its bandwidth is around a few hundred Hertz.
The ball bearings are manufactured by ADR. Their mean diameter is around 120mm.
The whole mobile mass is around 25 kg.

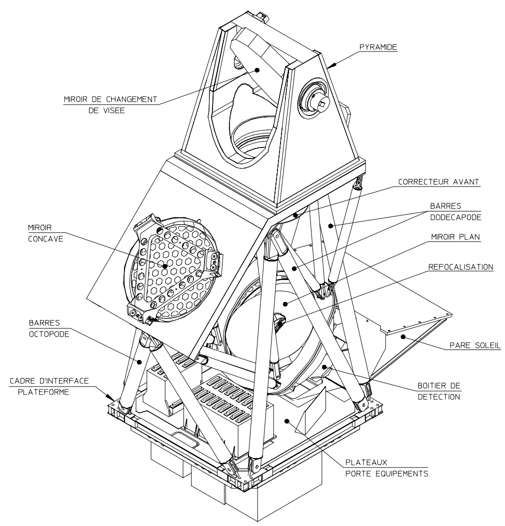

Figure 1 : HRG's instrument overview. MCV is placed at the top of the instrument. Its mechanical structure is called "pyramide".

1.3 Performances

The MCV performances are split in three classes relating to pointing, manoeuvrability and dynamic.

Pointing performances depends on "a priori" and "a posteriori" accuracy. "A priori" accuracy is needed to centre the images on assigned locations. It is also needed due to stereo imaging, which is processed by overlapping two images. Note that in that last case, MCV is the only contributor for the AOCS does not add any error.
Manoeuvrability is the capacity to swiftly carry out several imaging from several angles of sight. MCV is

the sole contributor to that performance which directly yields to instrument's effectiveness. The performance depends both on the motion velocity and the stabilisation duration. Stabilisation criteria, specified as a maximum oscillation magnitude is obviously fully linked to dynamic stability specifications, see hereafter.

Relating to ***dynamic***, the MCV is to be seen as both an emitter and a receiver of dynamic disturbances.
During motions, it generates dynamic disturbances towards the platform. Those disturbances should be broken down depending on their frequencies.

Low frequencies bring about wheels reactions and should so be taken into account in platform's budgets.

High frequencies, also called micro vibrations disturb the second MCV, playing then the role of a disturbance receiver.
During image acquisition, the MCV is a receiver of disturbances. Those disturbances come from the other MCV as seen just before. They also come from others emitters as satellite wheels.

1.4 Design constraints

There is only one clamping device to lock MCV's rotation around its axis during launch. As a result, overall design is simpler. However, ball bearing should then be sized to withstand launch vibrations along with meeting drastic safety margins.
That constraint is strengthened due to ball bearing lubrication. Wet lubricants were turned down due to optics closeness. So, ball bearings were dry lubricated with MoS2 that requires limiting loads to a relative low-level, typically 200 hbar.

2. FIRST DESIGN

The same design equipped on the three first generations of Spot's instrument called HRV.
The SAGEM57PPP stepper motor was used in direct drive. It was simply commanded in full step at a constant stepping rate by a voltage supply. The mechanic guidance used dry lubricated ADR's ball bearing. One ball bearing was left sliding to withstand axis's thermo-elastic dilatations.

A major feature was that mechanical friction was quite high. That friction was partially due to internal ball bearing characteristics as balls diameter, angle of contact and pre-load. Main frictions however came from contacts between balls and theirs separators, fine tubular parts in Teflon. Friction noise was high too, due to MoS_2 deposit process by simple burnishing.
That simple and robust design was fully in compliance with system needs. High friction was welcome to damp high oscillations generated by the rough full step command and stabilisation lengths were short enough.

Pointing budget could be simply broken down into a high "static angle", image of the ratio between the motor stiffness and the mechanical friction, and a magnetic "even-odd" effect (i.e. H2 harmonic). Compared to AOCS's pointing budget, MCV had comfortable performance margins.
Dynamic stability was not to be in-depth analysed for stability constraints were not acute due to "low" instrument's resolution. Furthermore, high friction helped to see MCV as motionless during imaging.
To conclude, mechanical frictions played a major role : in spite of a rough motor command, it allowed to get manoeuvrability performances while keeping enough margins with respect to pointing budget.

3. FIRST EVOLUTION

Spot4's instrument was called HRVIR. On the HRVIR's MCV, the main modification was brought on the mechanical guidance.
On one model, a fretting-corrosion effect was detected on the sliding ball bearing. That led to change the design.
New ball bearings were developed. One having a very low axial stiffness replaced the sliding ball bearing. This was obtained with a very high conformity (125%) and a low contact angle (5°).

First idea was to replace tubular separators by annular ones to better control the magnitude and the stability of the friction between balls and separators.
Finally, tubular separators were used once again : if not mechanical frictions were too low to damp MCV's oscillations.
Additional frictions brought by tubular separators being still too low, electronic command was modified to short circuit the not supplied phase during full step commutations. Friction brought by induction currents allowed meeting wanted
performances.

Due to HRVIR's increase in resolution, which led to strengthen stability constraints, pointing stability was much more analysed than before. It was indeed no longer possible to justify stability better than one micro radian without performing an acute characterisation.

After several analysis, Dahl's model of mechanical friction - see reference - was found as giving the best MCV's physical behaviour simulation in the micro oscillations' range.
It showed that MCV was no longer to be seen as motionless due to frictions. In spite of them, it could still oscillate on a higher natural frequency _ 10 Hz typically while the static motor frequency was around 7 Hz.

4. HRG'S IN DEPTH MODIFICATIONS

4.1 The reasons to change

Spot5's instrument was called HRG. Due to both technical and industrial reasons, design of HRG's MCV was in depth modified.
Industrial causes came from the number of models to manufacture. At the beginning of the program, three instruments were to equip Spot5 versus only two on Spot1/2/3/4. Two models were to equip Helios instruments. At last, the possibility to manufacture a second Spot5 satellite, called Spot5-b, should be taken into account. From two MCV's flight models on former satellites, it was then eight models to be manufactured.

It seemed difficult to meet such a manufacturing rate with the former design. Experience clearly showed how costly it was to tune a design performances of which depended on unsteady mechanical frictions. That design was well adapted as long as performance margins were high enough. But then, new specifications of pointing were too strengthened and induced margins too low. In the same time, technical reasons to change the design were numerous.

Firstly, HRVIR's mechanical guidance did not withstand new vibrations level required to be launched on Ariane 5 (31g taking into account design margins). High conformity made one ball bearing very sensitive in term of Hertz pressure.

Secondly, manoeuvrability requirement was strengthened to increase instruments' imaging rate for instance to allow Earth vignetting when no particular image is ordered. Less time was granted to perform low amplitude motions : 10s were allowed to HRV to perform motions from 0 to 27° ; only 4s were granted to HRG to perform low amplitude motions while up to 10s were granted to cover 27°.

Thirdly, pointing specifications were strengthened, in particular "a posteriori" accuracy.

Fourthly, Spot5 increase in resolution led to drastically strengthen dynamic stability requirements. Pointing stability hence became one major design driver.

4.2 Mechanical improvements

Former design was therefore in depth modified. Main idea was to better decouple functions and performances.

- First, mechanical guidance was to withstand new vibrations levels with comfortable safety margins. It was no longer to ensure oscillations damping thanks to its friction. Frictions should be as repetitive as possible from one model to the other and from the beginning to the end of the mechanism's life.
- Second, command was to be optimised to meet manoeuvrability and dynamic specifications.

New ball bearings were designed. To increase their load acceptance along with minimising frictions, the ball diameter was increased up to 6.35 mm and angle of contact was increased up to the 36°. Mean conformity came back to a more "standard" value, that is 7%. All mechanical interfaces were in depth analysed to get sure that no additional stress could increase frictions during ball bearings integration. Tubular separators were obviously replaced by annular ones. MoS_2 lubricant physical vapour deposition was used instead of burnishing process.

As a result of all those modifications, friction was limited to 0.040Nm in spite of a pre-load worth 650N. Ball bearing loads and gapping were less than 200 hbar and 10µm in spite of axial loads worth around 8000N.

The whole mechanical architecture was fully re-analysed. Purpose was to get down the degree of hyperstaticity known to be the source of important not mastered loads. Focusing on in-orbit operating, analysis took into account thermo-elastic dilatations and residual deformations. A "pyramide" axial stiffness worth around 2 N/µm allowed to withstand dilatations and others axial defects. To withstand misalignments, specific flectors were implemented to limit torques. That solution was found better than an "X assembly" of ball bearings. Flectors were 1.4 mm thick components. They were axially stiff but their flexion stiffness was less than 20 000 Nm/rd. This pseudo-isostatic solution is sketched hereafter. Thanks to it, increase in frictions after assembling was limited to 30 %.

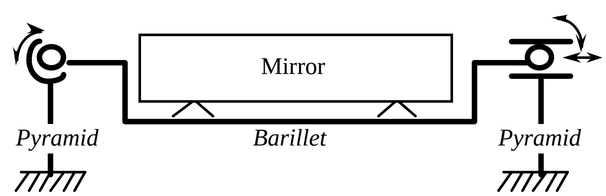

Figure 2 : Shaft assembling is pseudo isostatic thanks to flectors and pyramid's local axial stiffness

4.3 Command improvements

In the same time, electronic command was completely modified. The former full step command was replaced by a micro step one. Specific linear current amplifiers were designed by CRISA.
After analysis, amplifiers' characteristics were found to be at the feasibility limit. Performances, such as phase balances or harmonic distortion, directly entered harmonic disturbance budgets.
Velocity profiles were in depth analysed as well. On former design, full step command tuning only consisted to decouple commutation frequency from MCV's natural frequency. Tuning of the micro step command was far more complex.

Optimisation of the velocity profiles needed to very finely tune acceleration lengths _ at better than a few milliseconds typically.
Optimisation of the velocity profiles needed also to perfectly identify electronic and motor harmonic disturbances spectrum to decouple it from MCV's natural frequency.
Two algorithms were implemented to process optimised profiles. First algorithm was to control high amplitude motions, typically greater than 3°. It took benefit of MCV's natural cut-off to limit the motor harmonic disturbance effects by moving at high speed, typically 10°/s. Second algorithm was to control low amplitude motions, typically less than 3°. It took benefit of the low amplitude to cover to always keep harmonic disturbances less than the resonance and avoid then amplifications.
Note at last that a vacuum-thermal test allowed highlighting a slight shift of the natural frequency. Once well understood and quantified, that phenomenon was also taken into account in velocity profile tuning.
All that was possible thanks to a devoted 80C32 microcontroller implemented in the CRISA command electronics.

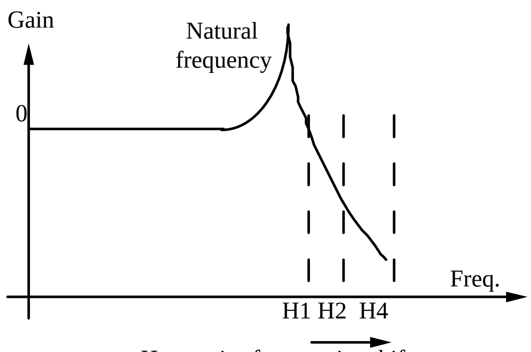

Figure 3 : Frequency of harmonic instabilities depends on the mechanism velocity. Velocity magnitude should then be set to avoid MCV's natural resonance.

The open loop command depicted just above was smooth enough to meet dynamic requirements. A close loop command was nevertheless tested in the early HRG development to get utmost performances.
According to the principle sketched hereafter, optical encoder data was used to add a command damping.

Note that this concept kept variable commutation angles as in classic micro step command. As a result, natural holding stiffness was kept, which was essential for pointing applications. Close loop's efficiency was experimentally proven for amplitude compatible with the encoder resolution that is 3 µrd.

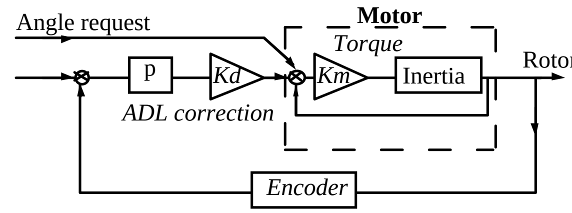

Figure 4 : Active Damping Loop is a very efficient option to increase oscillations damping.

4.4 Pointing stability

Spot5's increase in resolution tends to drastically strengthen dynamic stability requirements. Pointing stability thus became one major design driver.
Analysis led to split stability requirements in requirements on short and long term.
Short-term stability, typically a few milliseconds, was required to ensure "on-line" signal consistency on the several detectors, devoted to the different bands. Short-term stability was as well required to ensure "on-column» signal consistency on a few pixels, typically five, for "super mode".

On long term, typically a few hundreds of seconds, position stability was required to allow efficient images processing as localisation with respect to given points.
Instrument's resolution directly impacted short terms specifications. As a result, required stability, typically less than 0.5µrd, could be seen as a very stringent requirement.
As a dynamic device, MCV was the single contributor to instrument's pointing stability budget. At satellite level, MCV remained as well a major contributor : experience showed it took between 30% and 50% of the whole satellite budget.
All design improvements helped to get a repetitive and predictable dynamic behaviour even for micro oscillations worth typically less than 1 micro radian. Test campaigns allowed to build up the dynamic model initiated in the frame of Spot4. That model gave non-linear MCV's transfer functions applicable for oscillations' amplitudes worth less than a few tenths of micro radians. Dahl theory was found giving a right friction model : Dahl's stiffness was observed around 5000 Nm/rd providing a significant frequency shift between MCV emitter and MCV receiver. It was possible to measure magnification ratios, typically greater than 10. Those ratios were used to quantify impact of external disturbances as wheels' harmonics. They were as well taken into account to assess impacts of current amplifiers' noise.

As a result, it was found that amplifiers' performances had a great impact on the system's performances. A lot of analysis and tests focused then on linear current amplifiers. Performances such as low frequency noise or current drifts directly entered stability budgets.

To highlight orders of magnitude, current noise in the band [0 ; 30] Hz was to be less than 9µA rms as currents could vary from 0 up to 750 mA !
In the same time, test campaigns allowed to highlight non-foreseen phenomena, such as the so-called "middle term drift". Once well understood, it has been taken into account in on-ground image processing to cancel its linear content

4.5 Tests campaigns

Along with design modifications, analysis and characterisation efforts made a significant step.

A specific real time test bench was developed to be able to spy at high frequency (typically 200 Hz) synchronous data as high-resolution optical encoders, accelerometers as well as motor phases voltages and currents.
An electromechanical mock-up equipped with representative ball bearings, motor and encoder was built. To measure pointing stability, tests were performed under sharp environmental conditions : low enough seismic and air disturbances not to have any motion on the optical encoder's 25^{th} bits !

A complete qualification phase was carried out including 100 000 cycles to simulate on-ground cycles, a vibration test, a thermal vacuum test and 800 000 cycles to simulate in-orbit operational life.

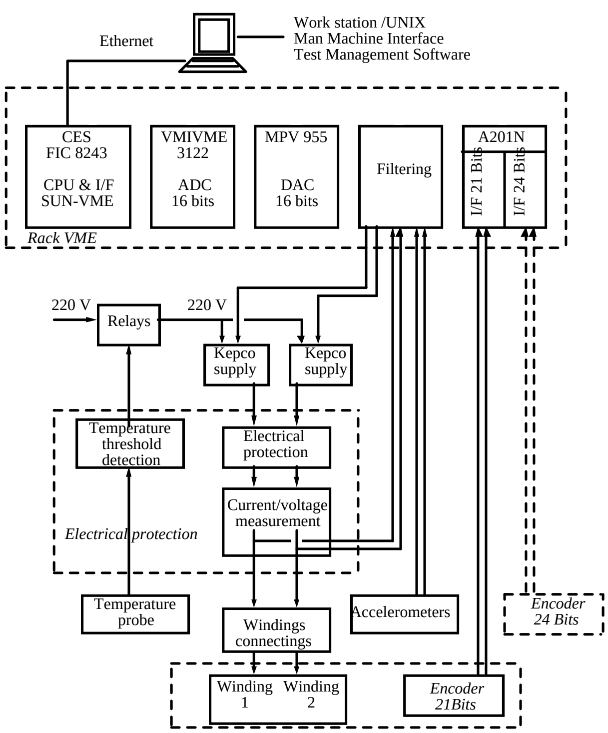

Figure 5 : A specific real time test bench allowed carrying out fine MCV's characterisatio

While performing operational cycles, a dry atmosphere was set in order to make ball bearings' dry lubrication work under conditions as representative as possible of in-orbit conditions. Those tests allowed gathering useful data as for MCV's model parameters. Above all however, those tests allowed checking the robustness and the repeatability of the new design.

5. CONCLUSIONS AND PERSPECTIVE

In conclusion, it should be emphasised that due to new always better instruments' resolution in particular, MCV became a major contributor taking between 30% and 50% of the whole satellite pointing stability budget.
From a simple single axis pointing application back to early Spot's program, MCV became hence a sub-system needing fine characterisations and optimisations. All that background is now very useful to design new pointing systems expected to be implemented on new generation of small imaging satellites. It will allow developing higher performances, simpler and cheaper pointing systems well fit to meet new requirements and economic constraints. In the meantime, new mirror material emergence is very promising for the next MCV generation, making possible even better pointing performances at a reduced cost.

KEYWORDS
Pointing, stepper motor, microvibrations, active damping loop, harmonic disturbances.

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