High accuracy image stabilization system
Executive Summary Report

Written by	***Responsibility*** *+ handwritten signature if no electronic workflow tool*
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CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
1	09/06/2021	First issue of the document	FLIP FLAP Team

1.1 Applicable documentation

DR	Reference	Issue	Title
AD01	ESSB-HB-E-003	1	ESA pointing error engineering handbook
AD02	ECSS-E-ST-60-10C	1	Space engineering - Control performance
AD03	ECSS-E-HB-60-10A	1	Space engineering - Control performance guidelines
AD04	TEC-ECC/159.16/	1	Statement of work of the the study

1.2 Reference document

RD	Reference	Issue	Title
RD01		1	Fast Loop Image Processing for Line of Sight Accurate Pointing – Statement of Work
RD02		1	Fast Loop Image Processing for Line of Sight Accurate Pointing – TAS Full Proposal
RD03	0005-0008149017	1	TN1-1 Mission Selection Analysis
RD04	0005-0008408579		TN1-2 System requirements and trade-offs analyses
RD05	0005-0008994214	1	TN2-1 System design
RD06	0005-0008408579	1	TN2-2 Image Processing Design and Analysis
RD07	0005-0010007111	1	TN2-3 Product components specifications
RD08	0005-0012764406	1	TN2-4 Product performance analyses
RD09	0005-0010006648	1	TN3-1 Flip Flap Breadboard test plan
RD10	0005-0010006690	1	TN3-2 and TN3-3 Breadboard requirements and design
RD11	0005-0013315936	1	TN 3-4: Breadboard test results
RD12	0005-0012764391	1	TN4-1 & TN4-2: Development and Verification Plan
RD13	0005-0013774823	1	TN4-3 Business Plan
RD14	0005-0013774848	1	TN4-4 Performance synthesis and recommendations

1.3 Abbreviations

Acronym	Definition	Acronym	Definition
AOCS	Attitude and Orbit Control System	MTG	Meteosat Third Generation
APE	Absolute Performance Error	ODC	Optimized Delay Control
CCD	Charge-Coupled Device	OF	Optical Flow
CTEC	CEDRAT Technologies	PDE	Performance Drift Error
DoF	Degree of Freedom	RMS	Root Mean Square
FCI	Flexible Combined Imager	ROI	Region Of Interest
FEM	Finite Element Model	RPE	Relative Performance Error
FGS	Fine Guidance Sensor (or System)	RVCM	Rotational Voice Coil Mechanism
FLIP-FLAP	Fast Loop Image Processing For Line-of-sight Accurate Pointing	RW	Reaction Wheels
FOV	Field Of View	RWA	Reaction Wheels Assembly
FPGA	Field-Programmable Gate Array	SA	Solar Array
FSM	Fast (or Fine) Steering Mirror	SADM	Solar Array Drive Mechanism
IP	Image Processing	SNR	Signal to Noise Ratio
KDE	Knowledge Drift Error	SOW	Statement Of Work
L3S	Line of Sight Stabilization System	SZA	Solar Zenith Angle
LPTC	Large Pulse Tube Cooler	TAS	Thales Alenia Space
LoS or LOS	Line Of Sight	TDI	Time Delay Integration
MTF	Modulation Transfer Function	WFE	Wave Front Error

2 INTRODUCTION AND WORK LOGIC

The general demand for higher resolution satellites is driving complex designs not only at payload level but also at platform level, with very accurate sensors and expensive means to compensate the platform perturbations. This is becoming very critical for up-to-date missions, like EUCLID or MTG and will become a show stopper for future very high demanding missions. The very high costs driven by this complexity are also a brake for the accessibility of the high resolution data to a larger number of customers.

The objective of the study consists in the design of an active line of sight stabilization product for LEO and GEO Earth observation and Science missions. The development of a breadboard with COTS elements has been performed to demonstrate the feasibility and to increase the TRL of the designed solution.

The product to be developed in the frame of this project will demonstrate the line of sight image stabilization concept presented below:

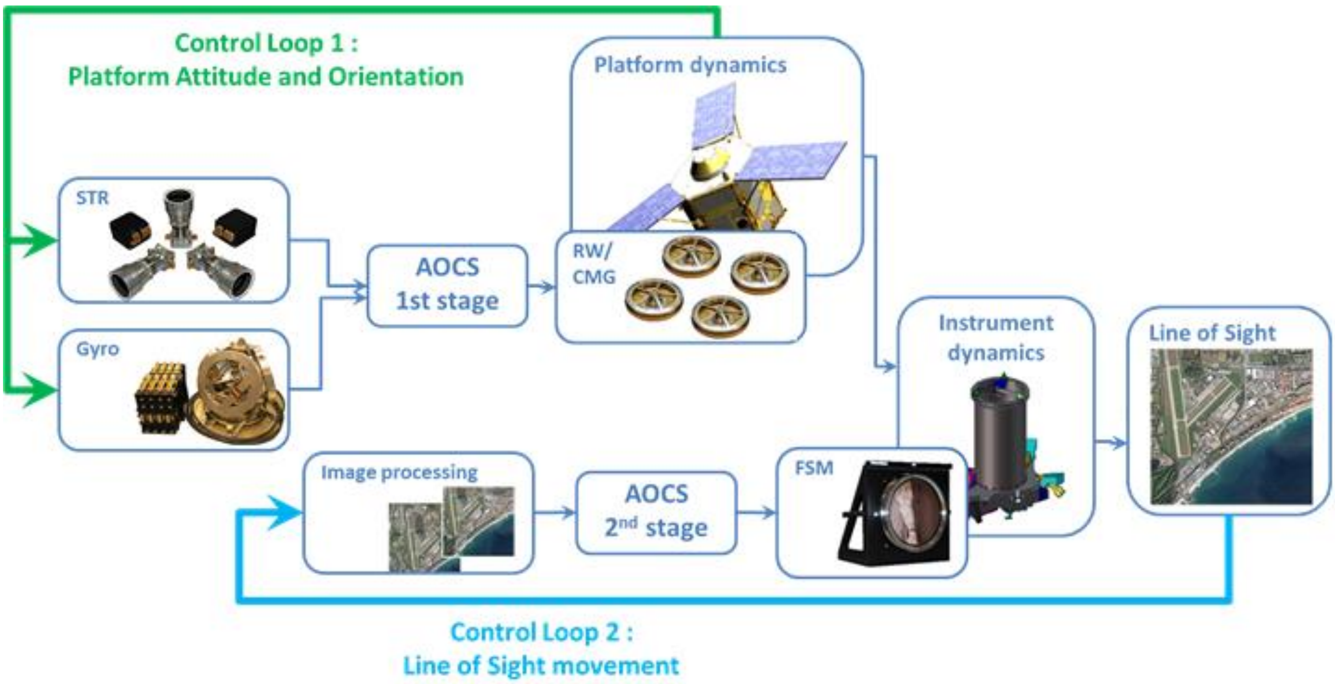


Figure 2-1 Line of sight image stabilization concept for FLIP FLAP

With this concept, the platform attitude is controlled with a usual AOCS and the line of sight is stabilized at payload level by the proposed product, using image processing to measure the line of sight rotations and a Fast Steering Mirror (FSM) as actuator to control them.
The benefits of FLIP FLAP concept rely on 2 major points:

- It enables an end-to-end measurement of the line of sight rotations
- It enables the compensation of pointing disturbances with a very high bandwidth

To reach the objectives, four major work packages are defined, with the following logic:

WP1000 consisted in the mission scenario selection, the requirement analysis and the initial architecture trade-off.
WP2000 objective is to design of the Flip Flap product, to assess its performance, especially at image quality level, to specify the Flip Flap components, and finally to validate the Flip Flap concept through correlation of the tests.
The WP3000 allowed to design the Flip Flap breadboard using COTS components, and to perform the required tests especially at performance level, to validate the Flip Flap concept.
WP4000 included the development and qualification plan of the Flip Flap product, to provide recommendations for the next development stages.

3 SYSTEM REQUIREMENTS AND TRADE-OFF

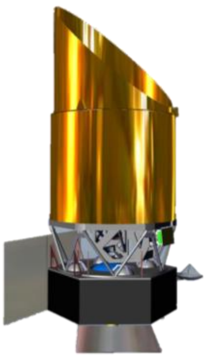
The first part of the work consisted in the selection of the mission scenario and the analysis of the pointing requirements. Three scenario have been studied, a geostationary high resolution mission, a LEO medium resolution class mission and a science mission such as Ariel.

3.1 Geostationary Earth observation

The geostationary scenario selected as application case for Flip Flap is the GEOHR satellite. This satellite is the object of preliminary system study, aiming to develop an Earth observation system from geostationary orbit; very stringent requirements are derived at pointing level.
A high performance AOCS system has been foreseen for this mission:

- Attitude determination is provided by a gyrostellar filter with 3 optical head star trackers Hydra and an Astrix FOG 200.
- The actuators are 6 Ball bearing reaction wheels mounted on isolators, and with an internal loop for friction instabilities compensation.
- The satellite design includes disturbance mitigation solutions such as body mounted solar arrays.

Pointing stability and agility requirements are presented in the following table:



Performance index		Requirement
Pointing stability	RPE 5 ms	0.037 µrad (3σ)
	RPE 14 ms	0.09 µrad(3σ)
	RPE 100 ms	0.037 µrad (3σ)
	RPE 200 ms	0.09 µrad(3σ)
Repointing capability		
Slew duration		13 deg in 600s

Table 3-1 : GEO-HR pointing requirements

The main objective of a LOS stabilization is to extend the instrument exposures time and to relax the design by adding solar array driving mechanism, allowing mass reduction and a simplification of operations. Another possible point concerns the downgrade of the platform gyroscope, the use non isolated reaction wheels.

The solution retained for the accommodation of the Fast Steering mirror is to add an additional mirror right before the focal plane, the distance from the focal plane is the one that allows for a reduced Wave Front Error degradation. An additional high frequency detector is placed on the focal plane to measure the line of sight.

3.1 LEO Earth observation

The LEO mission chosen for the study of FLIP-FLAP is a high resolution Earth observation satellite. The AOCS architecture consists in 4 Ball bearing reaction wheels, offloaded by magneto torques bars, and with an attitude determination performed by 3 optical head star trackers without any gyroscopes. Table 3-2 presents the pointing accuracy requirements in terms of APE, RPE and RKE driven by image quality.

AOCS Requirements	Notes	Root	performance
AOCS RPE	Relative platform stability over integration time	PAN FTM	0.264 µrad 3ms per axis 90%
AOCS APE	Absolute pointing error	Target pointing	700 µrad per axis 90%
Slew performance		50deg in 40s	

Table 3-2 : LEO mission pointing requirements

The objective here is to improve the performance of the spacecraft and to increase the agility by reducing the tranquilization time.
Here the fast steering mirror can be placed in an intermediate pupil, and the detector will be adjacent to the mission detector in the focal plane. An increase of the telescope Field of View is necessary to illuminate the detector.

3.1 Science mission

The science mission selected is Ariel, which is a future universe observation spacecraft that will observe hundreds of planets in the visible and infrared bands with its meter class telescope. The objective of the FLIPFLAP system here is to increase the pointing stability over long durations and also to decouple payload fine guidance sensor from AOCS.
The fast steering mirror here replaced one of the existing mirrors, without introducing too much wave front error degradation for the allowed stroke. The sensor part consists in the mission fine guidance system itself.

4 SYSTEM DESIGN AND PERFORMANCE ASSESSMENT

The objective of Task 2 is to define the system design for the three missions, in particular concerning the controller and image processing design.

4.1 System design

The following architecture is proposed for the GEO-HR system, showing the interface with the attitude control loop.

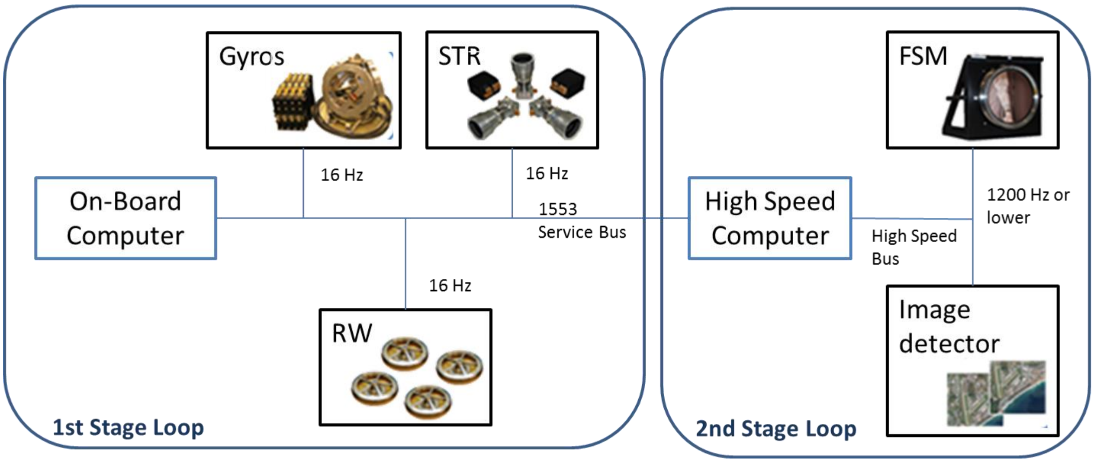


Figure 4-1 System architecture for the GEOHR mission

The image processing has been designed for LEO and GEO application. For the GEO mission the algorithm consists in the selection of multiple regions of interests over the image and the estimation of the image displacement from a reference image. For the LEO mission the design takes into account the scene displacement due to satellite motion by estimating an average angular rate over a certain number of images. The following figure shows the image processing architecture proposed.

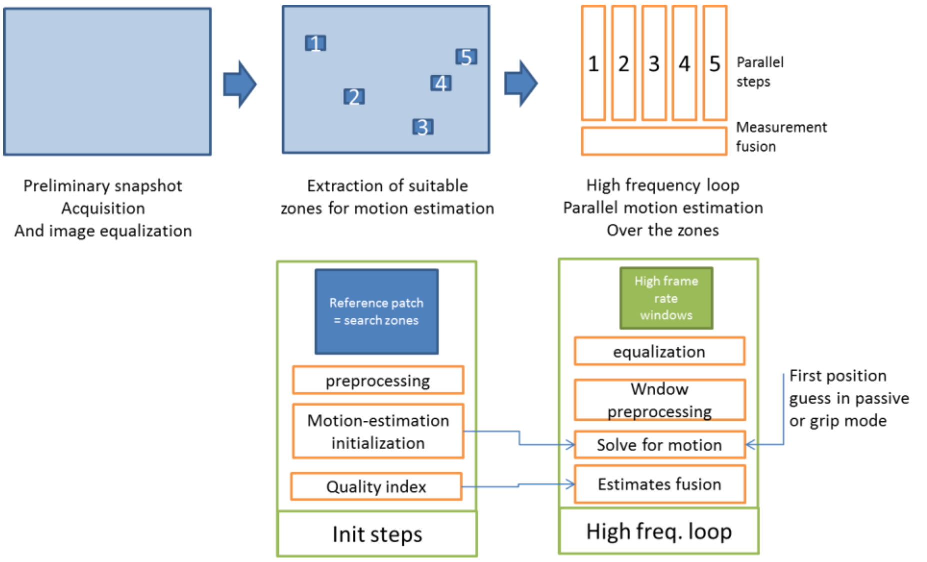


Figure 4-2 Image processing architecture for the GEOHR mission

The following figure gives an overview of the GEOHR control loop for the AOCS (1st stage) and the FLIP FLAP system (2nd stage).

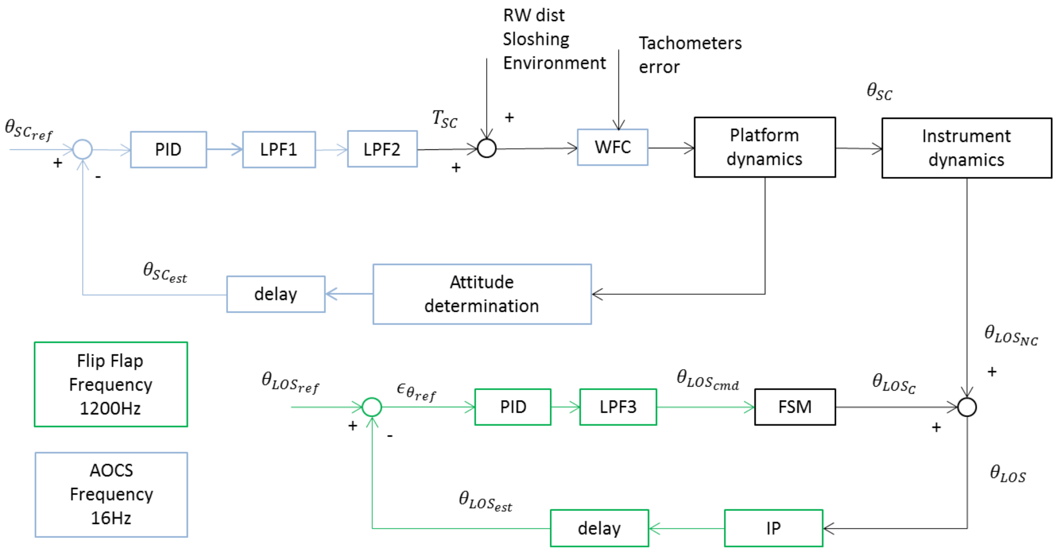


Figure 4-3 Control loop overview for the GEOHR mission

4.2 Performance assessment

A performance campaign over a large number of images has been performed to characterize the algorithms and to generate a performance model for the environment.

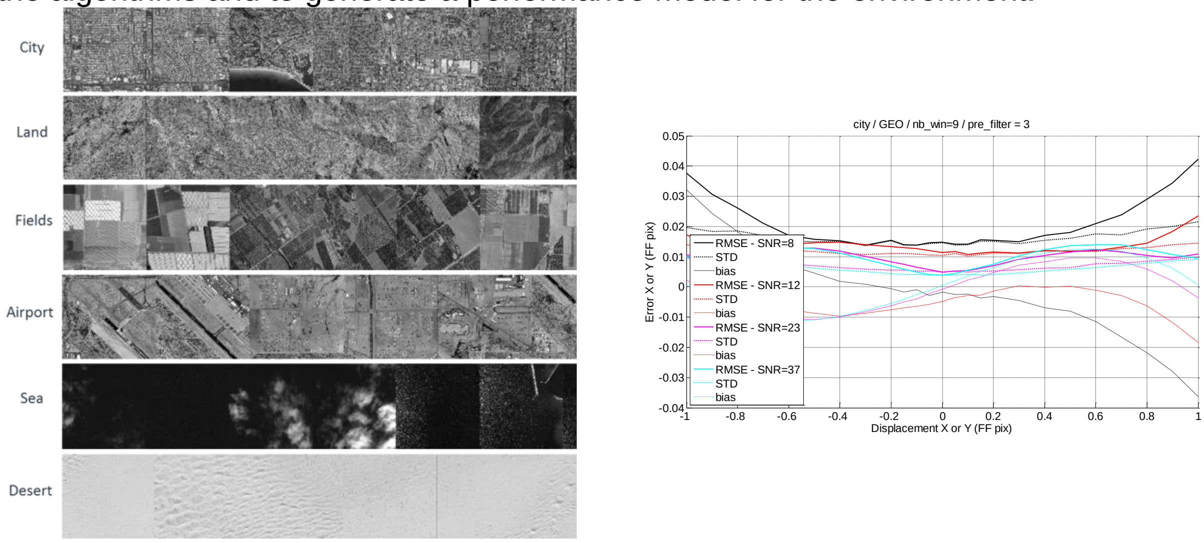


Figure 4-4 Image performance model from typical scenes

To assess the performance of the product three high fidelity simulators have been developed for each mission. The main conclusions are:

- For the GEOHR mission the FLIPFLAP system allows to improve the performance over long exposures by a factor 5, thanks to the high accuracy of the telescope itself. The tests show also that the use of a rotating solar array does not impact the pointing performance thanks to FLIPFLAP. The reaction wheel isolator on the other hand cannot be removed because of the high frequency disturbances involved.

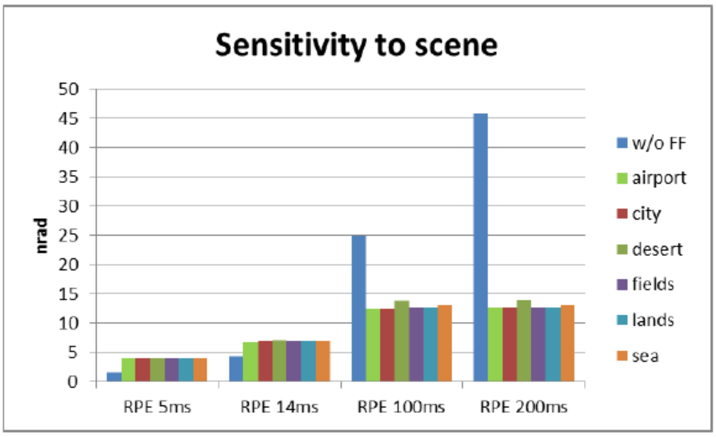


Figure 4-5 Performance overview of GEOHR for typical scenes

- The improvements brought by FLIP FLAP in the science case are limited, since the baseline ARIEL design is already compliant with the fine pointing requirement, without a very complex AOCS design. In the case of the FGS use on the AOCS, the FLIPFLAP main improvement is the compensation of the wheel friction jumps, with a better performance than the wheel friction compensation, for bright object observation. The decoupling of the FGS and AOCS is possible thanks to the fast steering mirror and the performance of the fine pointing mode is comparable to the baseline architecture.
- For the LEO case, the results have confirmed that the best control bandwidth, which does not worsen the platform performance, is relatively low, smaller than 2Hz, due to image processing noise injection in the loop and the very short term stability requirement (3 ms). Two additional RPE 50 and 100 ms have been considered in order to assess the performance gain for longer term requirements. The sensitivity to the scene and SNR has shown that the performance of all performance indexes is improved, except for Desert SNR 8 case. An agility test confirmed that large slews require still a short tranquilization time to allow the correction with FLIPFLAP due to the FSM stroke.

5 BREADBOARD DESIGN AND PERFORMANCE ASSESSMENT

The third task consists in the development of an experimental breadboard representative of the GEO high resolution mission and the performance assessment and correlation with simulation results.

5.1 Breadboard description

Figure 7 presents the FLIPFLAP breadboard elements. One can note the following elements:

- A halogen light source with an integrating sphere simulates the scene illumination.
- The observed scenes, consisting in an engraved silica mask representing typical GEO image scenes from sea, city, airports, lands or desert.
- Four lenses that simulates the optical path of the GEO-HR telescope.
- Two fast steering mirrors from Piezo System Jena PSH-2. The FSM-1 is used for the disturbance generation and the FSM-2 is the stabilizing steering mirror.

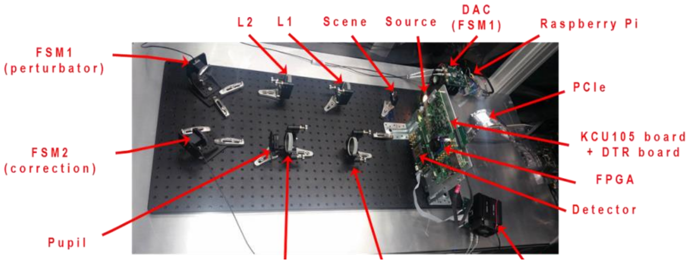


Figure 7: The FLIPFLAP breadboard

- The CMOS CMV12k mounted on the Xilinx evaluation board KCU105 of the FPGA Kintex Ultrascale KU040.
- The control computer, connected to the disturbance generation fast steering mirror using a Raspberry Pi board and a Ethernet connection, and to the FPGA evaluation board through a PCI express cable

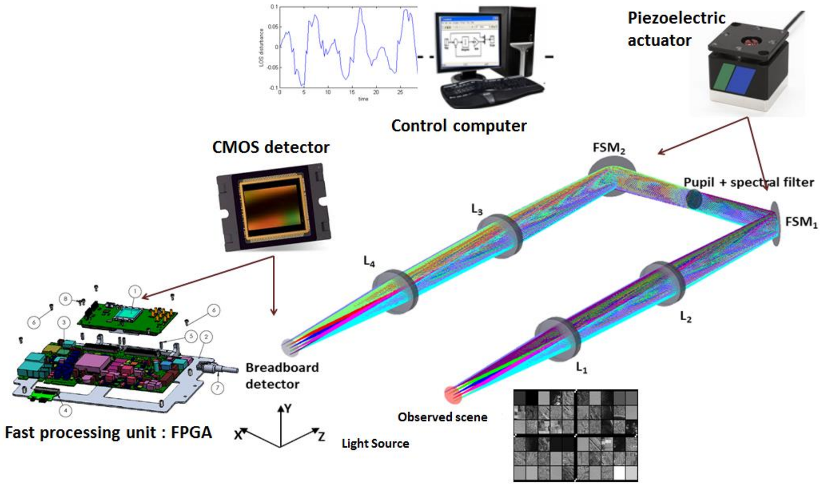


Figure 7: Overview of the FLIPFLAP LoS stabilization breadboard

The principle of the test is to generate the expected GEO-HR AOCS residual motion due to control errors or high frequency microvibrations using the FSM-1. The FPGA acquires the images at 1200Hz, estimates the motion by comparing the current image to the reference image with the described image processing algorithm, and eventually computes the command for the stabilizing fast steering mirror. The control function consists in a proportional integrator controller without FSM position control loop, as shown in Figure 8, tuned with the robust control approach. The image processing algorithm corresponds to the GEO-HR presented design, but implements only the high frequency mode, without the ROI selection algorithm. The controller bandwidth reached by the FLIPFLAP breadboard corresponds to a disturbance rejection of -6db at 45Hz, even if the value can be optimized to reduce the noise in the loop.

5.2 Performance results

The following test presents the city, sea, lands and desert images generated with the breadboard.

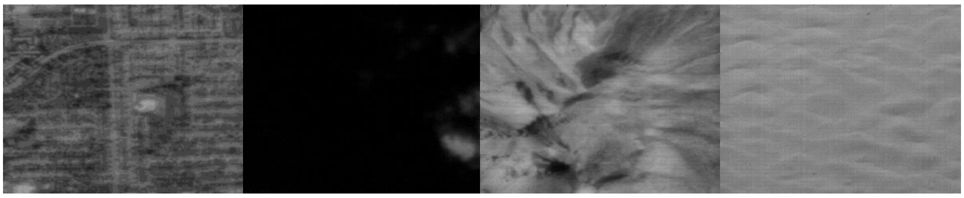


Figure 8: FLIPFLAP breadboard scenes

Figure 9 shows the comparison between the GEO-HR AOCS error, the FSM command and the residual LoS stabilization error, with a zoom on the residual error. The results show that the residual error is well below 10% of pixel, corresponding to the expected performance.

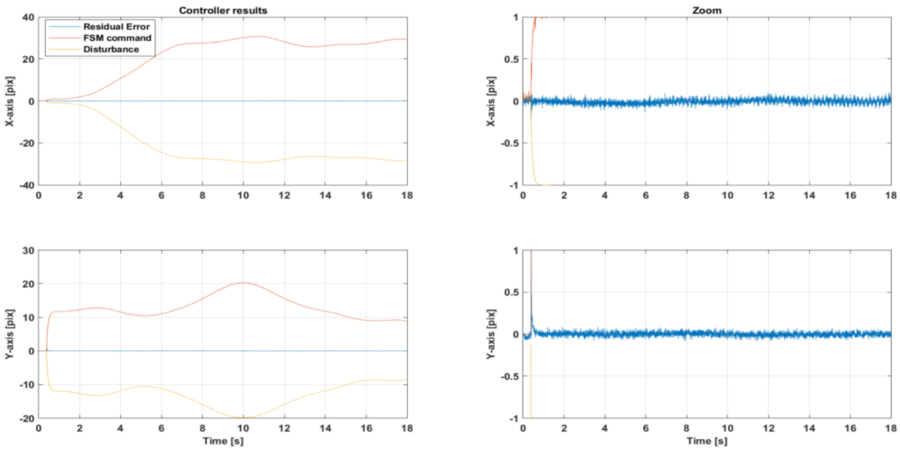


Figure 9: Comparison between GEO-HR disturbance, FSM command and residual error (left) and zoom on residual error (right) with city scene

The Figure 10 shows the residual error for a sinusoidal disturbance at 10 and 20Hz with +/-2 pixels amplitude. A rejection factor of 6.6 and 4.2 is observed respectively for the 10Hz and 20Hz disturbance.

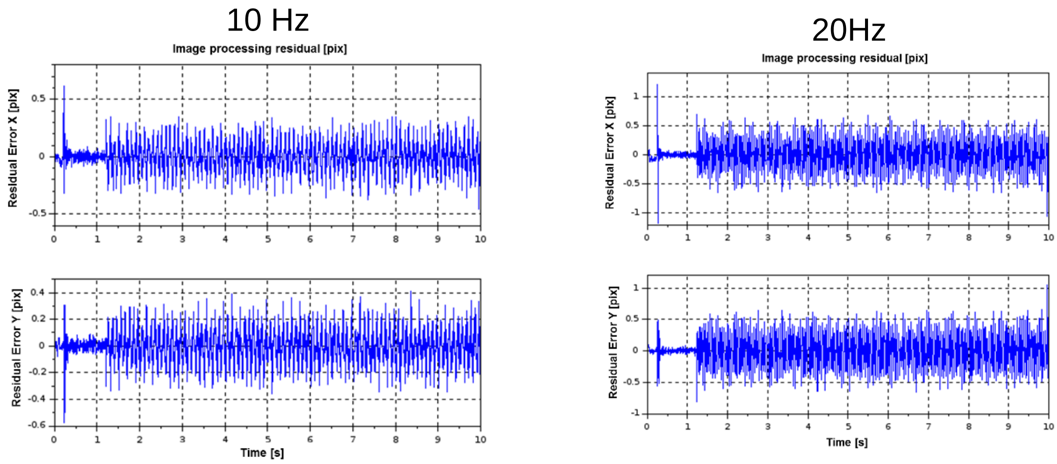


Figure 10: Residual image processing for closed loop microvibration at 10 and 20Hz

Figure 11 presents RPE performance comparison between breadboard and simulations, for a typical SNR, assuming that the breadboard has the same pixel angular resolution than GEO-HR. The values are computed as the norm of X-Y axes of the error at 99.7% confidence level. A real world is estimated by a more accurate, but still imperfect, image processing algorithm running offline on the control computer. The results show a good correlation with the simulated results, a small difference is visible for low contrasted scenes.

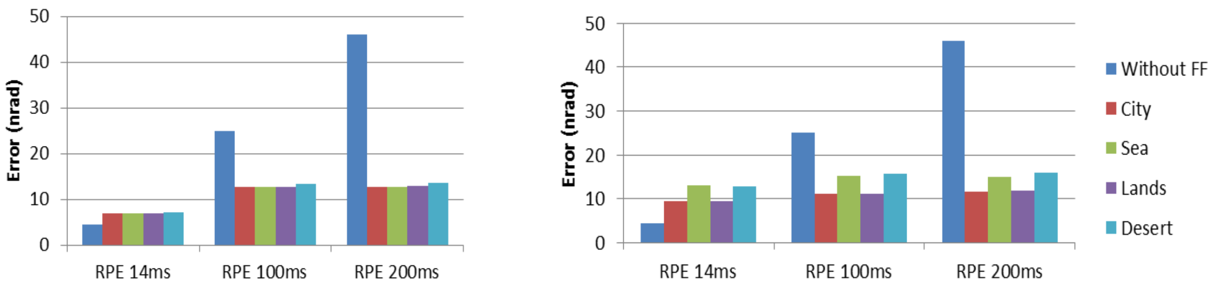


Figure 11: Performance summary in simulation and breadboard

6 DEVELOPMENT PLAN AND RECCOMMENDATIONS

The work performed in this task allowed to define the FLIP FLAP product current development state and to propose a development and verification approach and planning. The following figure shows the product tree of FLIP FLAP.

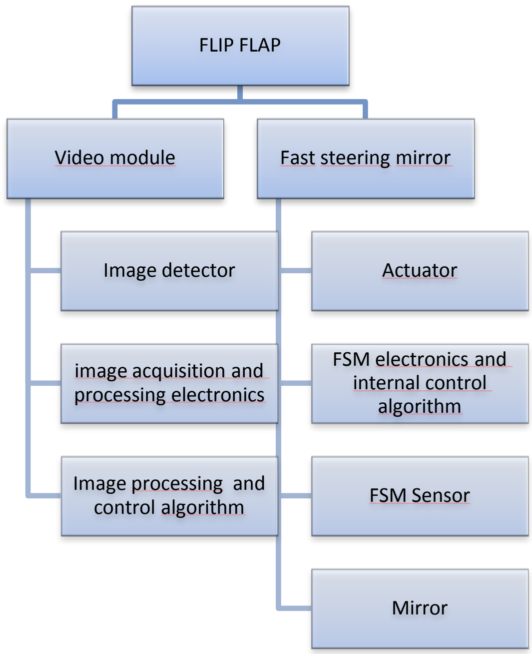


Figure 12: FLIP FLAP product tree

In this task, the requests for information (RFI) for the equipment have been performed to identify the potential supplier and get an estimation of the system cost and development plan. The next activities to reach the maturity of the product consist in the Request for Quotation (RFQ) in order to obtain the committing prices and the elaboration of a qualification plan for the remaining components non-space qualified. Once the subsystem reaches independently the TRL 8, through their qualification process, the whole system can be qualified. The logic of the tests involves the model-in-the-loop, software-in-the-loop, and hardware-in-the-loop tests to validate the performance of the product. Software development activities need to start as soon as possible, even with draft models in order to de-risk the hardware in the loop test.

The development of a FLIP FLAP breadboard with Engineering Models of the equipment provided by the selected suppliers, during their development and qualification activities, is necessary to complete performance assessment campaign and the qualification of the product. This Engineering model is used to validate electro-magnetic compatibility, design, tuning and performance validation and the calibration needs. The vibration and thermal vacuum tests at Flip Flap level are performed directly after the integration on the satellite and the instrument. The breadboard can be reused as a spare component to support the flight operations and in orbit tests.
A planning of 2-3 years is expected for the qualification of the product and their sub components.

7 CONCLUSIONS

The study allowed to design and assess the performance of FLIP FLAP product for three main scenarios targeted, highlighting the main advantages of the system in terms of performance, and AOCS design simplification and potential cost reductions. The results have shown the important advantages of using FLIPFLAP on GEO and LEO earth observation missions, while limited benefits for the Ariel Mission. For Earth Observation, thanks to the use of the satellite telescope, FLIPFLAP allows reaching a very good accuracy of the line of sight knowledge and stability at high frequencies. The extension of observation duration and the compensation of higher frequencies disturbances, such as solar arrays driving mechanism exported torques, are the key advantages of FLIPFLAP. Moreover, the development of an experimental breadboard allowed increasing the maturity of the system, by demonstrating the high frequency image acquisition and processing, and by correlating the results with the GEO-HR simulations for the typical scenes and SNRs.