ISABELA

Image StAbilization BrEad-boarding for hosted PayLoAd

(High Accuracy Image Stabilization Bread-boarding)

Executive Summary

Written by	***Responsibility*** *+ handwritten signature if no electronic workflow tool*
ISABELA Teams	
Verified by	
ISABELA Teams	
Approved by	

List of Abbreviations

AIT	Assembly, Integration and Test
AOCS	Attitude and Orbit Control System
APE	Absolute Performance Error
AQ	Air Quality (mission)
ARMD	Angular Rate Measurement Device
ASD	Amplitude Spectral Density
Disp	Dispersive spectrometer
DoF	Degree of Freedom
DVM	Design Verification Matrix
FCI	Flexible Combined Imager
FLIP-FLAP	Fast Loop Image Processing For Line-of-sight Accurate Pointing
FOV	Field Of View
FPGA	Field-Programmable Gate Array
FSI	Fixed Stare Imager
FSM	Fast (or Fine) Steering Mirror
FTS	Fourier Transform Spectrometer
GSD	Ground Sampling Distance
HRPB	High spatial Resolution Push Broom
KDE	Knowledge Drift Error
IFSI/IF2	In Field Spectral band Separation (Imager)
ISABEA	Image StAbilization BrEad-boarding for hosted PayLoAd
LPTC	Large Pulse Tube Cooler
LS	Line of Sight
LSOS	Line of Sight Optical Sensor
MPE	Mean Performance error
MSI	Multi-Spectral Imager
MTF	Modulation Transfer Function
MTG	Meteosat Third Generation
NIR	Near Infra-Red
O_	Optical (test requirement type in test setup requirements)
PDE	Performance Drift Error
PID	Proportional Integral Derivative
PSF	Point Spread Function
PZT	Piezoelectric Translator
RPE	Relative Performance Error
RWA	Reaction Wheels Assembly
SAD	Sum of Absolute Differences
SADM	Solar Array Drive Mechanism
SCA	Scanning mechanism Assembly
SFTS	Static Fourier Transform Spectrometer
SNR	Signal to Noise Ratio
SOW	Statement Of Work
SSA	Spectral Separation Assembly
SSD	Sum of Squares of intensity Distance
TDI	Time Delay Integration
VAE	Video Acquisition Electronics
WFE	Wave Front Error

1 INTRODUCTION

1.1 SCOPE OF THE DOCUMENT

This document is the executive summary of the High Accuracy Image Stabilization Breadboarding, under ESA contract 4000126060/18/NL/FE.

1.2 APPLICABLE DOCUMENTATION

DR	Reference	Issue	Title
AD01	4000126060/18/NL/FE	1	High accuracy Image stabilization bread-boarding contract
AD02	ESA-TECSAA-SOW-01396	0rev0	Statement of work
AD03	TAS/DOS/PRP/FR/660-18-EQ-555	1	Negotiation meeting MoM
AD04	0005-0009987386	1	ThalesAlenia Space ISABELA Proposal
AD05	ESSB-HB-E-003	1	ESA pointing error engineering handbook

1.3 REFERENCE DOCUMENTATION

DR	Reference	Issue	Title
DR01	MTG-TAF-CI-TN-524	2	MTG FCI instrument technical description
DR02	MCR_HAI_18_11_2016	1	Hosted Arctic Imager MCR slides

1.4 ORGANIZATION OF THE ACTIVITY

The main objective of the study is to design, develop, manufacture a breadboard, and test a line of sight stabilization system. Such line of sight stabilization system must be suitable for hosted payload cases. The breadboard tests results extrapolation must allow determining the achievable performances of a payload mounted on a medium to low pointing stability performance platform, and the interest for Earth observation or Science missions. A specific task is included to define a preliminary concept of a high frequency angular rate sensor that would be used to measure high frequency inertial rates on the payload or a sensitive part of the optical path (e.g. M1 mirror).

The work is organized as follows:

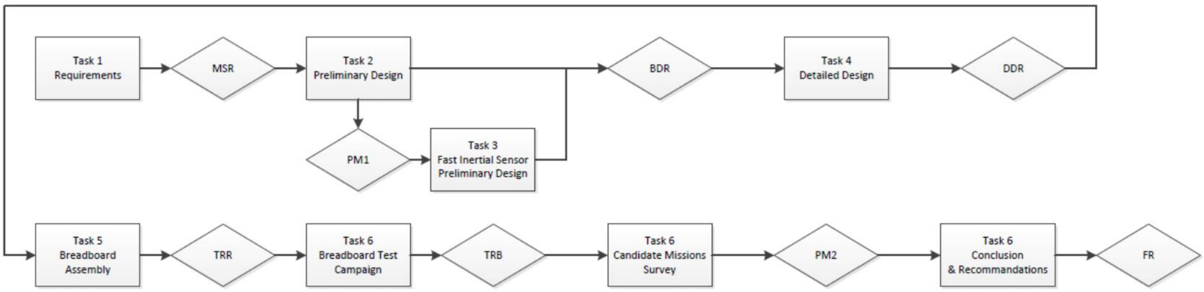


Figure 1-1: Work logic (ESA SoW)

- Task 1 : Hosted payload application case definition and requirements analysis with the objective to select one or two hosted payload candidates missions and to define the line of sight stabilization system requirements when considering low performance bus, and medium to high mission performances

- Task 2 : Line of sight stabilization system preliminary design with the objective to design the line of sight stabilization system and the breadboard, defining the relevant payload structural mechanical and optical elements. Note that, at least, the following components should be considered: use of a fast steering mirror, of an optical sensor and of a high frequency inertial sensor
- Task 3 : High frequency Inertial Sensor preliminary design with two open options for industry: either perform the preliminary design of an equipment similar to the US Angular Rate sensor (e.g. ARS-14), or identify the modifications to be performed to an existing gyroscope, to meet the requirements defined in task 2
- Task 4 : Line of sight stabilization system detailed design and simulations with the objective to design and tune the line of sight stabilization system controller, to perform the detailed design of the breadboard with its list of components, to develop a closed loop simulator, and to perform the simulator test campaign
- Task 5 : Breadboard assembly with the objective to procure the breadboard components, to manufacture, assemble and perform the functional validation of the breadboard
- Task 6 : Breadboard test campaign with the objective to perform tests on the breadboard
- Task 7 : Candidate missions survey with the objectives to use the experimental test results to consolidate the selected hosted payload mission pointing performances, and to identify hosted payload candidate missions that could benefit from the line of sight stabilization system, addressing any useful adaptation
- Task 8 : Conclusion and recommendations with the objectives to synthesise the hosted payload achievable performances at payload and at mission level when implementing a line of sight stabilization system, and to define the development roadmap of key components such as, but not limited to, the High frequency Inertial sensor, the optical sensor and the fast steering mirror

The following figure presents the work breakdown structure.

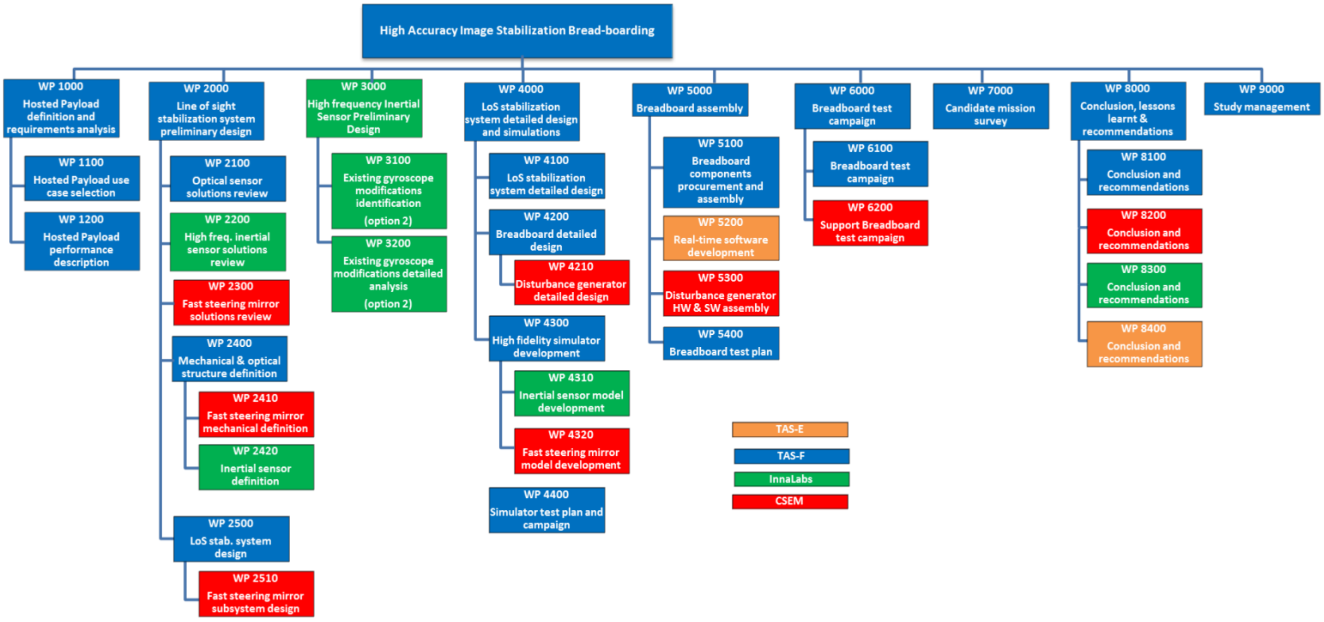


Figure 1-2: work breakdown structure

2 HOSTED PAYLOAD MISSION SURVEY AND REQUIREMENT ANALYSIS

The first task consisted in a survey of the Hosted Payload, defined as Payloads integrated in a platform that is not designed especially for it, which can be:

- A platform with another primary payload performing a different missions
- A standardized with low pointing performance not compliant alone to the payload requirements.

In addition, a literature review of the line of sight stabilization system implemented inside hosted payload.

The mission that have been identified as possible candidates are:

- Hosted multispectral Imager on a GEO Telecommunication Platform
- Small hyperspectral imager on a LEO Telecommunication platform
- Hosted multispectral Imager on a LEO Telecommunication Platform
- Hosted multispectral Imager on a HEO Telecommunication Platform

The following figure shows an overview of the different platform considered for the assessment.

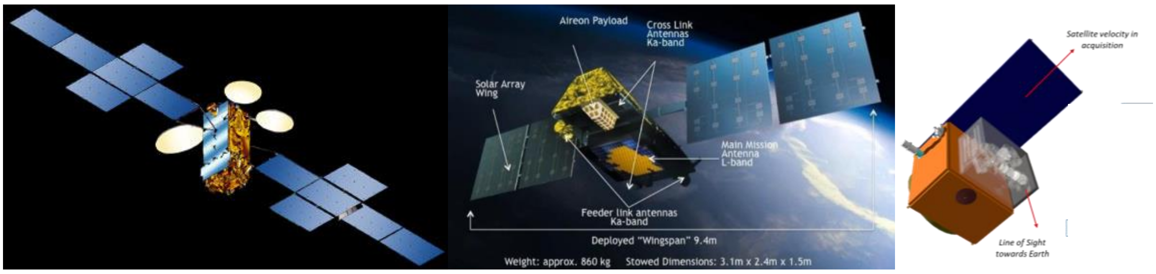
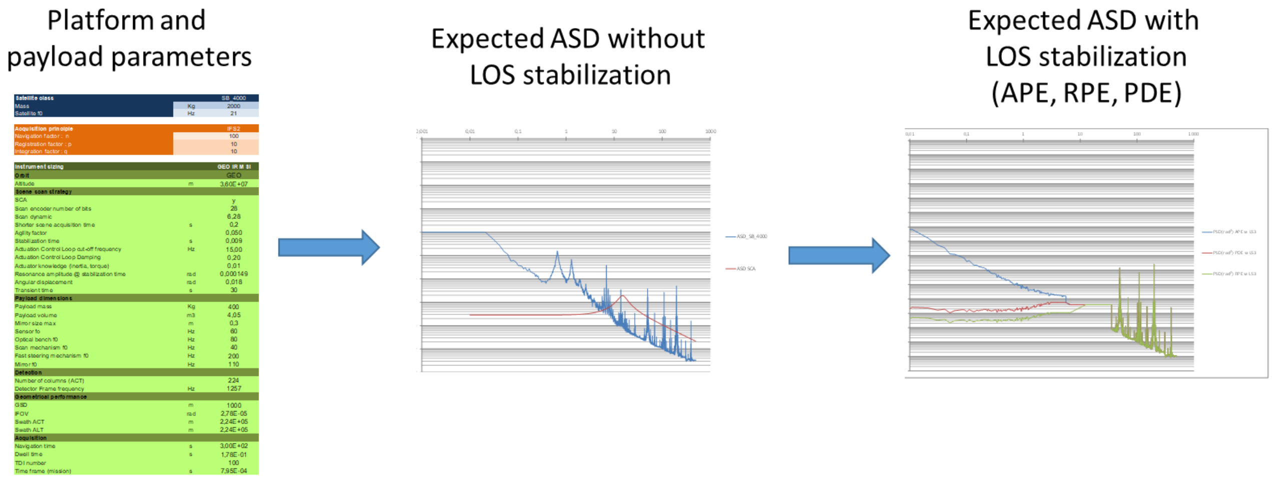


Figure 2-1: SB4000 and Elite platform overview

The missions have been assessed with a tool available internally and upgraded in the frame of the study. The tool compares the pointing stability requirement APE, RPE and PDE defined for the payload with the stability of the platform and of any scan mirror if present, integrating or not the line of sight stabilization system based on inertial sensor, on image optical sensor or both.



Satellite class		SB_4000
Mass	Kg	2000
Satellite f0	Hz	21
Acquisition principle		IFS2
Navigation factor : n		100
Registration factor : p		10
Integration factor : q		10
Instrument sizing		GEO IR M SI
Orbit		GEO
Altitude	m	3,60E+07
Scene scan strategy		
SCA		y
Scan encoder number of bits		28
Scan dynamic		6,28
Shorter scene acquisition time	s	0,2
Agility factor		0,050
Stabilization time	s	0,009
Actuation Control Loop cut-off frequency	Hz	15,00
Actuation Control Loop Damping		0,20
Actuator knowledge (inertia, torque)		0,01
Resonance amplitude @ stabilization time	rad	0,000149
Angular displacement	rad	0,018
Transient time	s	30
Payload dimensions		
Payload mass	Kg	400
Payload volume	m3	4,05
Mirror size max	m	0,3
Sensor fo	Hz	60
Optical bench f0	Hz	80
Scan mechanism f0	Hz	40
Fast steering mechanism f0	Hz	200
Mirror f0	Hz	110
Detection		
Number of columns (ACT)		224
Detector Frame frequency	Hz	1257
Geometrical performance		
GSD	m	1000
IFOV	rad	2,78E-05
Swath ACT	m	2,24E+05
Swath ALT	m	2,24E+05
Acquisition		
Navigation time	s	3,00E+02
Dwell time	s	1,78E-01
TDI number		100
Time frame (mission)	s	7,95E-04

Figure 2-2: Overview of the procedure for ALS preliminary assessment on potential missions

Two missions have been proposed for detailed analyses: the hosted Multi Spectral Imager in GEO, and the Static Interferometer.

3 LINE OF SIGHT STABILIZATION SYSTEM DESIGN

Once identified the interesting application cases the next part of the work consisted in designing the LOS stabilization system for both missions. The system consist in:

- Line of sight motion sensors and estimation algorithms
- Actuators and control algorithm
- Processing unit
- Accommodation in the current instrument

3.1 RETAINED ARCHITECTURE

The following figure shows the architecture of the LOS stabilization system selected for the hosted multi spectral instrument and the Static Interferometer mission.

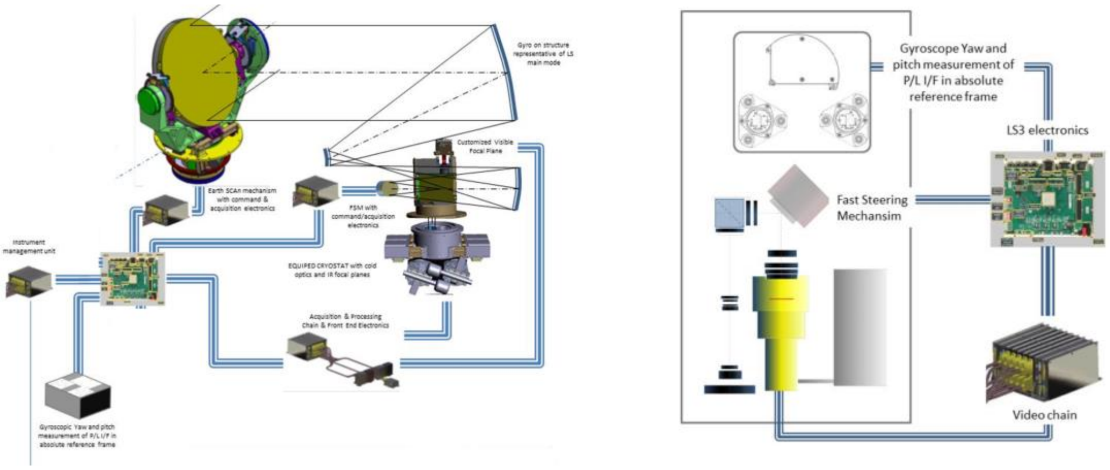


Figure 3-1: Hosted MSI LOS stabilization architecture (left) and Static Interferometer (right)

The main principle of the system is to control a synthetic line of sight reconstructed in real-time from the available sensors, calibrated using on-ground image processing.

The hosted MSI mission stabilization consists in a two axis gyroscope, located in the main payload structure, a scan mirror for Earth scanning, and a fast steering mirror for the stabilization. The L3S electronics computes the line of sight of the instrument taking into account the scan and fast steering mirror measurements and the gyroscope measurement.

The Hosted Static Interferometer stabilization system uses a two axis gyroscope, located in the main payload structure, with a fast steering mirror and a dedicated electronics unit.

The image processing is performed using a dedicated visible detector for the hosted FCI scenario and the mission detector for the Static Interferometer scenario. Since there is no interest to perform the processing on-board, except for data compression purposes, the line of sight verification will be performed on ground by extracting small windows from the image detector at high frequency.

3.1.1 Fast steering mirror

The following figure presents the concept of the Fast steering mirror designed by CSEM for the two application cases. The two mission differs in terms of stroke and size, but the configuration of the FSM are very similar.

Figure 3-2: ISABELA FSM concept baseline, with elliptical mirror, isometric view (left), upper view (right)

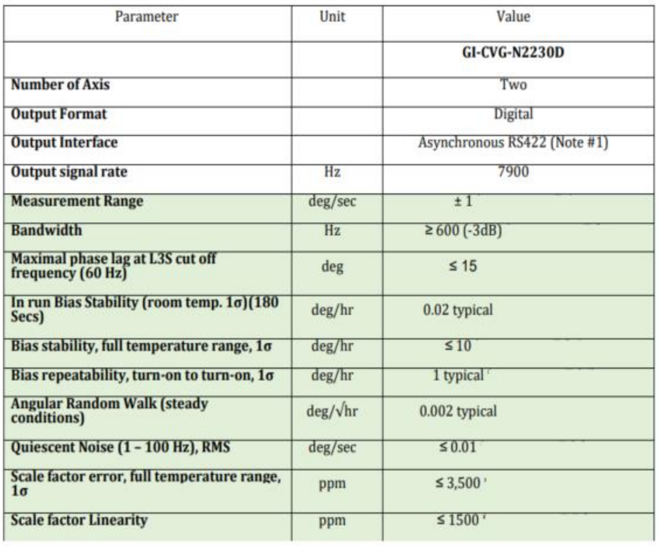
Considering costs and procurement, glass and Zerodur are the favoured solutions. The Zerodur solution is the middle ground choice for good performances and controlled costs. The actuation of the mirror is done with the use of three voice coils arranged at 120°. The sensor used for FSM positioning control are Eddy current sensors.

3.1.2 Actuators and sensor accommodation

For the selected application cases, the mechanism has to been designed to be accommodated in very constrained volume. In the case of GEO MSI Hosted FCI the mechanism is placed in place of the M4 mirror. For the LEO Static Interferometer application the mechanism volume is also constrained by the small size of the sensor. The implementation of a dedicated detector like the CMOSIS CMV 12000 is envisaged for the Hosted FCI while the mission detector is considered for the Static Interferometer application.

3.1.3 Gyroscope

The gyroscope retained is the Innalabs CVG gyroscope that have been prototyped expressely for ISABELA.



Parameter	Unit	Value
		GI-CVG-N2230D
Number of Axis		Two
Output Format		Digital
Output Interface		Asynchronous RS422 (Note #1)
Output signal rate	Hz	7900
Measurement Range	deg/sec	± 1
Bandwidth	Hz	≥ 600 (-3dB)
Maximal phase lag at L3S cut off frequency (60 Hz)	deg	≤ 15
In run Bias Stability (room temp. 1σ)(180 Secs)	deg/hr	0.02 typical
Bias stability, full temperature range, 1σ	deg/hr	≤ 10
Bias repeatability, turn-on to turn-on, 1σ	deg/hr	1 typical
Angular Random Walk (steady conditions)	deg/√hr	0.002 typical
Quiescent Noise (1 – 100 Hz), RMS	deg/sec	≤ 0.01
Scale factor error, full temperature range, 1σ	ppm	≤ 3,500
Scale factor Linearity	ppm	≤ 1500

Figure 3-3: ISABELA Gyroscope prototype

3.1.4 Detector and image processing algorithm

The image detector is used for the verification of the line of sight using COTS sensors and image processing algorithms. The performance of the LoS measurement can be optimized with respect to the following detector characteristics, such as the size of the detector, the Pixel pitch, the used of a windowing mode, the acquisition frequency, and the sensor SNR performance. The trade-off led to the choice of the CMV12k dedicated detector (which is also the mission detector for the Static Interferometer).

Finally, the Lucas-Kanade algorithm is considered as the baseline algorithm for the performance analysis, keeping in mind the following considerations:

- In case of displacement higher than 1 pixel, a pyramidal approach must be added, with moderate additional complexity.
- In case of higher precision required, an iterative resolution could be made, with higher complexity.

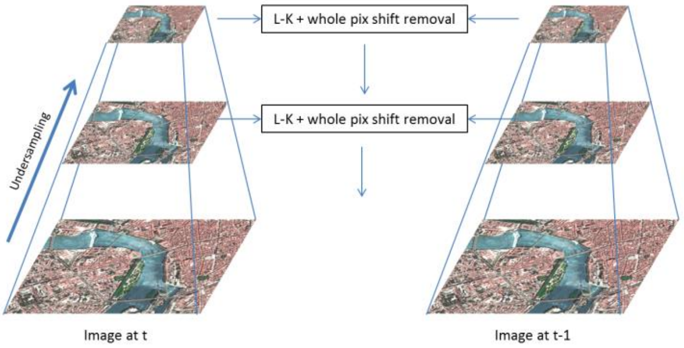


Figure 3-4 : Pyramidal under sampling

4 THE ISABELA LOS STABILIZATION BREADBOARD

The second part of the study allowed the development of a dedicated inertial stabilization breadboard, which is described hereafter.

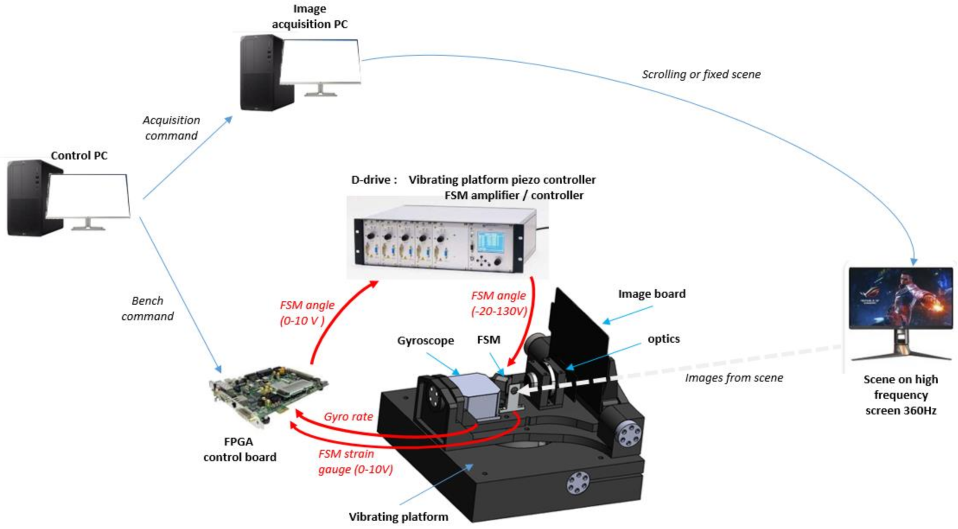


Figure 4-1 : Breadboard architecture

One can find the different components:

1. Vibrating platform: it generates the disturbances for the gyroscope and the camera in order to reproduce the Line of Sight residual error of a typical AOCS. It uses two piezoelectric actuators in order to control the breadboard, controlled by the D-drive controller, to control the pitch and yaw axes.
2. Innalabs gyroscope: Coriolis vibratory gyroscope used to sense the vibrating platform motion in order to stabilize the line of sight.
3. Control board
    a. Xilinx Kintex UltraScale FPGA KCU105 Acquisition kit: FPGA with the implementation of the controller
    b. Digital Analogic Converter: electronics that receive the digital command from the controller and send the voltage 0-10V to the Fast Steering Mirror amplifier.
    c. Analog Digital Converter: electronics that receives the strain gauge analog signal [0-10V] and send the digital measurement to the controller.
    d. RS422 board that perform the acquisition of the gyroscope digital angular rate signal.
4. D-Drive: piezoelectric digital controller and amplifiers, consisting of two amplifiers for the vibrating bench and two amplifiers for the fast steering mirror
5. Fast Steering Mirror: Piezoelectric fast steering mirror used for the image stabilization
6. Optics: optics used to focus the scene on the detector
7. Screen: PC screen used for the generation of typical space scenes used for calibration and verification of the ALS loop.
8. Image acquisition board: electronics used for the image acquisition and the verification of the image stability
9. DC power supply 28V to power the gyroscope.

The following figures presents the results in open loop and in closed loop.in terms of APE and RPE8.4s

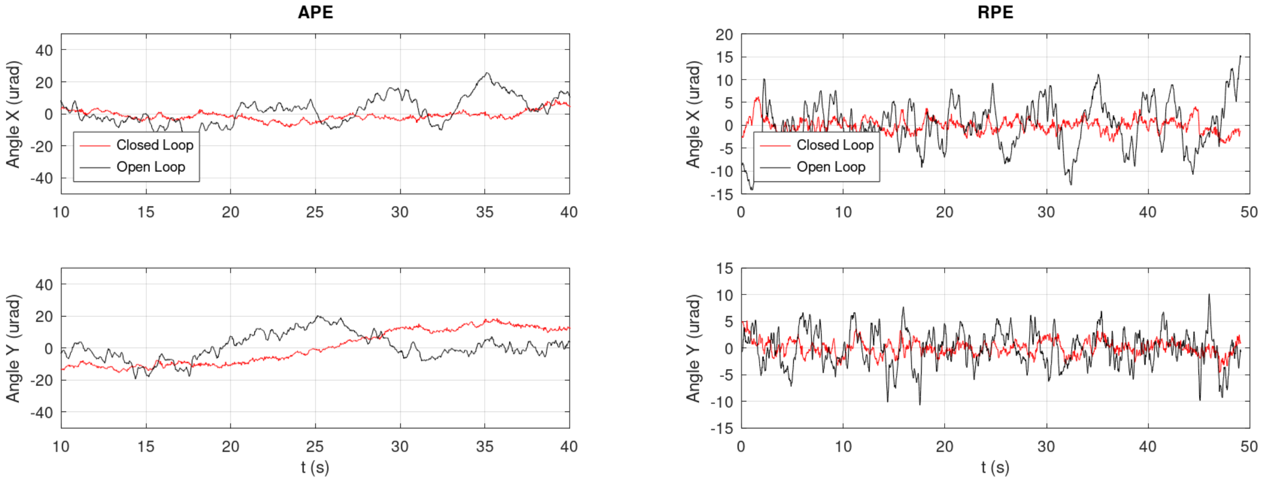


Figure 4-2: APE (left) RPE (right) SC and LOS with degraded AOCS

5 MISSION SURVEY

The last task of the study consisted in the assessment of the potential hosted payload applications, with the expected results extrapolated from the breadboard. The following table summarizes the possible combination of the payloads and platforms identified above, with the most critical requirement for the Line of Sight stability and the expected performance using the ISABELA system. The stability of the platform has been obtained from heritage and simulations, and the expected performance with ISABELA is obtained using the breadboard results.

Instrument	Platform	Driving Pointing stability Requirements	Comments
LEO Static Interferometer	**NanoAvionics M16P**	7µrad (1sigma) over 8.4s (Goal) 0.7µrad 1-sigma over 8.4s	The pointing accuracy presented is similar to the Static application case studied in the breadboard
	Microsat		Baseline Static Interferometer application, the interest is confirmed by simulations.
	Elite		A gain in performance is possible as for the Microsat mission
LEO Time Delay Integration Imager (w/o Agility)	**Gomspace 6U**	1µrad over 1ms	The gain for this type of mission is limited due to the very short time window of the RPE requirement, mainly driven by high frequency micro-vibrations
	Microsat		
	Elite		
LEO Hyper-spectral Imager	**NanoAvionics M16P**	6 µrad over 17s	The platform is not compliant to the payload requirement. ISABELA allow a large reduction of the error and enables the implementation of the payload.
	Microsat		The platform is almost compliant to the requirement, and ISABELA can provide the additional stability required.
	Elite		The platform is not compliant to the payload requirement. ISABELA allows a large reduction of the error and enables the implementation of the payload.
GEO Multi spectral Imager (FCI)	**Telecom**	2.8 µrad over 180ms	As presented in the simulations, the performance is compliant with the requirement only with the ISABELA system.
GEO Sounder	**Telecom**	5 µrad over 10s	The ISABELA system allows reaching a better stability, that is close to the requirement and slightly worse. In any case there is too little margin and a better gyroscope is required.

Table 5-1: Summary of potential applications of the ISABELA stabilization system

6 CONCLUSION

The study allowed to assess the LOS stabilization for several potential hosted payload mission using inertial approaches.

The first part of the work focused on the main application, selecting eventually a multispectral instrument in GEO as a simulation study, and a Static Interferometer as a breadboarding scenario. The design of the LOS stabilization converged toward an architecture using only an inertial sensor, but using the optical part as a verification means done on ground using typical LOS estimation algorithms.

The simulation campaign on the GEO multispectral imager led to the conclusion that the stability performance can be improved for longer performance index (>100ms), and also in presence of payload vibrations, but they requires previous in-orbit calibration phases. With the ISABELA system in fact, any additional vibration identified on-board can be characterized and stabilized.

In the last phases of the study a breadboard has been designed and assembled using COTS elements representative of the ISABELA LOS stabilization system. The breadboard allowed to adjust the control algorithm increasing their TRL, to cope with the additional error sources discovered on the hardware. The stabilization results eventually confirmed the results obtained by analysis with representative spacecraft pointing disturbances.

In conclusion a mission survey has been assessed in order to identify the future missions that will need the ISABELA system. The most interesting ones are those involving long image acquisitions, such as hyperspectral imagers and interferometers, that need a good stability not always provided by hosting platform. Other interesting applications are multispectral or visible imagers with long integration times in low illumination conditions. ISABELA is a key enabler for all these missions**.**