HIPERGA

Executive Summary Report

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1 INTRODUCTION

1.1 Purpose and Scope

The purpose of this document is to provide a concise summary of the HIPERGA project, and the findings accounted during its execution. In particular, it briefly summarizes the scope of the project, and the step followed for its completion.

1.2 List of abbreviations and acronyms

Acronym	Description
AI	Atom Interferometry
AOCS	Attitude and Orbit Control System
ARW	Angular Random Walk
AUV	Autonomous Underwater Vehicle
BM	Breadboard Model
CAIG	Cold Atom Interferometry Gyroscope
CDR	Critical Design Review
CLDB	Control Loop Demodulation Board
CVG	Coriolis Vibratory Gyroscope
DDVP	Design, Development and Verification Plan
DM	Development Model
DTG	Dynamically Tuned Gyroscope
EM	Engineering Model
EQM	Engineering Qualification Model
FOG	Fiber Optic Gyroscope
FPGA	Field Programmable Gate Array
FRR	Flight Readiness Review
FM	Flight Model
GNSS	Global Navigation Satellite System
HRG	Hemispherical Resonator Gyroscope
INS	Inertial Navigation System
ISS	International Space Station
KO	Kick Off
LAV	Light Armored Vehicle
MEMS	Microelectromechanical Systems
MHDG	Magneto Hydro Dynamic Gyro
PB	Proximity Board

PDR	Preliminary Design Review
PFM	Proto Flight Model
PSB	Power Supply Board
QM	Qualification Model
QR	Qualification Review
RLG	Ring Laser Gyroscope
ROV	Remotely Operated Vehicle
RR	Requirements Review
SAT	Satellite
SM	Structural Model
STM	Structural Thermal Model
TRL	Technology Readiness Level
TM	Thermal Model
UAV	Unmanned Aerial Vehicle
WBS	Work Breakdown Structure
WP	Work Package

Table 1-1: List of abbreviations and acronyms

2 APPLICABBLE AND REFERENCE DOCUMENTS

2.1 Applicable documents

The following documents are applicable to this document in Table 2-1:

AD#	Title	Project Code	SENER Code	Issue	Rev
[AD 01]	Gyro Specifications per Missions Scenarii	HIPE-TN-01	DOC00154627	1	2
[AD 02]	Technology Survey and Achievable Performances	HIPE-TN-02	DOC00201685	1	2
[AD 03]	Most Promising Technology Selection and Conceptual Design	HIPE-TN-03	DOC00204887	1	2
[AD 04]	Market Analysis and Roadmap	HIPE-TN-04	DOC00204888	1	2
[AD 05]	Final Report	HIPE-TN-05	DOC00268974	1	1

Table 2-1: Applicable Documents

3 PROJECT OVERVIEW

3.1 Study Scope

The HIPERGA project is a multidisciplinary activity with the aim of selecting the most promising gyroscope -i.e. angular rate sensing - technology, and to define a detailed roadmap for fulfilling future space mission needs.

Gyro technologies for space use have been developed in the last 30 years with significant results in widely used products. In Europe, the Fibre-Optic Gyroscope (FOG) technologies offer the highest performance for satellites applications and is currently fulfilling all immediate mission needs. The high-performance portion of the gyro landscape is dominated by *the hemispherical resonator gyroscope* (HRG) technology in the United States. In Europe, this technology also has – but more recently – achieved very high performance, for terrestrial applications. The field of new gyroscope technologies is a dynamic and strategic field of research, steered by numerous high-precision marine, terrestrial and aeronautical applications. One promising technology currently applied to angular and linear motion sensing is Atomic Interferometers (AI), which have not yet been converted in a product. Cold atom interferometric-based (CAI) gyroscopes has demonstrated performance metrics around 2 orders of magnitude better than FOG products. For other kind of use, Magneto-Hydro-Dynamic (MHD) technology enables very high bandwidth measurement, in a limited volume and mass, enabling active line of sight stabilization of mirrors.

Future space missions will require higher performance gyroscopes as enablers, either for high accuracy attitude pointing or line-of-sight stabilization (coronography, Earth Observation imaging missions...). The mass, volume and power consumption of such future solutions will be particularly important to enable the adequate positioning of inertial sensors.

The purpose of the HIPERGA project is to exhaustively assess the recent and disruptive inertial angular rate sensing technologies, available and under research, in order to provide assessment and detailed recommendation for space product developments. The activity encompasses the following tasks:

- Identification of needs per mission types, identifying the driving requirements
- Trade off gyroscope technologies, including functional characterization and technology survey
- Identification of most promising technology and main technical challenges with regards space application needs (incl. Robustness to space environment, volume, mass, performance)
- Conceptual design (incl. Electronics)
- Roadmap for future development (incl. Cost/schedule)

3.2 Consortium

The HIPERGA consortium is formed by two gyroscope manufactures (Civitanavi Systems and InnaLabs), supported by an external independent expert on CAIGs (Carlos Garrido-Alzar), one company acting as independent gyroscope surveyor (GeoNumerics) and one company with relevant experience in AOCS development (SENER Aeroespacial).

SENER Aeroespacial (SAe) is a company specialised in providing high accuracy AOCS and optical payload solutions, GeoNumerics (GN) is a company specialized in the processing of inertial measurements for trajectory determination in various high-accuracy applications and Civitanavi Systems (CNS) and Innalabs (IL) are European gyroscope manufacturers aiming to become the supplier of the future very high accuracy gyroscopes for ESA missions. The consortium altogether offers an unprejudiced and unbiased experienced team in all required engineering disciplines

- SENER Aeroespacial: as AOCS designer and gyroscope user, as well as leader of the consortium, will also supervise the final selection.
- GeoNumerics: is a geomatics and navigation company with a wide and long experience with different gyroscope types (DTG, FOG, HRG, MEMS and RLG) and an independent position in front of technology selection
- Civitanavi Systems: is a FOG designer and manufacturer with world-class optical gyroscope experts.
- InnaLabs: is a Coriolis vibratory gyroscope (CVG) designer and manufacturer with world-class VG/HRG experts.
- External independent expert on CAIGs (Carlos Garrido-Alzar)

With this consortium, a wide range of promising technologies are covered, while assuring the independency of the gyroscope selection. If any of these technologies is selected, a detailed preliminary sizing of the equipment could be provided. In all cases, SENER Aeroespacial will support the preliminary sizing of the unit(s) with its wide experience in space electronic products.

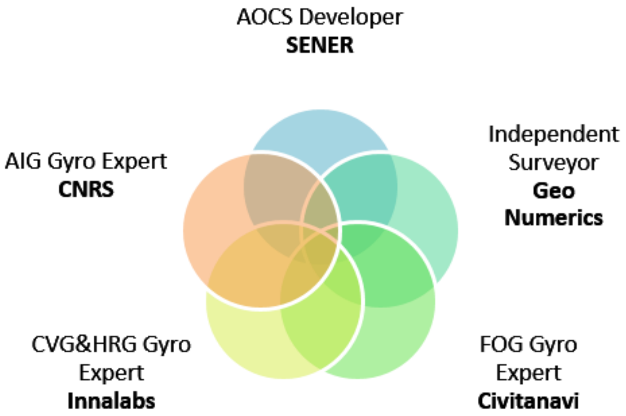

Figure 3-1. HIPERGA industrial Consortium

3.3 Work Logic

The HIPERGA work is organised in 3 WPs covering the 3 tasks indicated in the proposal [AD 01]. In particular:

- Future Gyro Specifications (WP1000) covers Task 1
- Gyro Technology Survey (WP2000) covers Task 2
- Future Gyro trade-off, Design, Market Analysis & Roadmap (WP3000) covers Task 3

The following diagram describes the proposed Work Logic for the project:

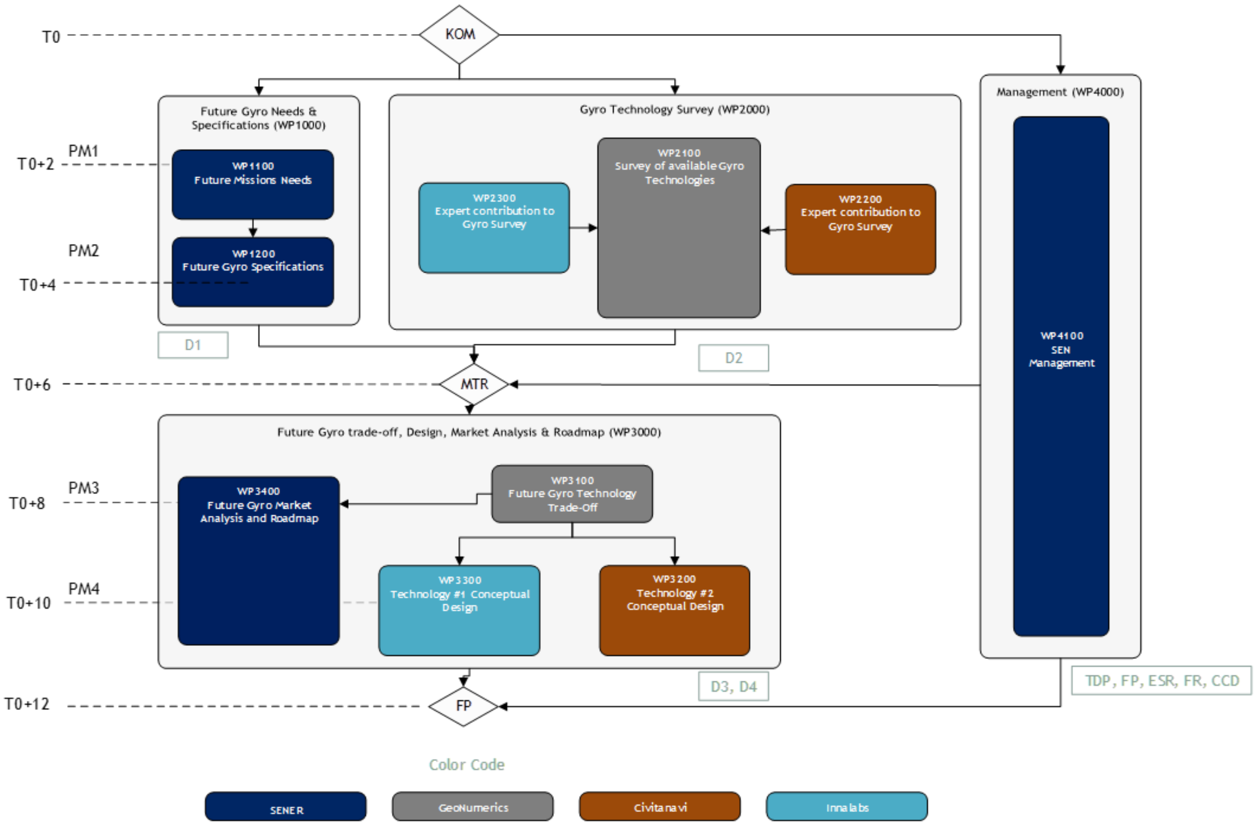

Figure 3-2. HIPERGA study logic

4 MOST PROMISING TECHNOLOGY SELECTION

4.1 Reference Missions and Specification

Figure 4-1 presents the list of reference missions selected for the HIPERGA project. The selection of reference missions for this study has been performed considering the following as main drivers:

- The level of accuracy required in the mission
- The launch date, giving priority to future missions
- The owner/originator of the mission, giving priority to ESA missions instead of NASA or commercial ones (e.g. Pleiades). This facilitates the gathering of the mission information
- SENER’s previous experience in the missions or similar which facilitates the derivation of specification. This includes Lisa, Euclid and Proba-3
- The coverage of the required missions needs

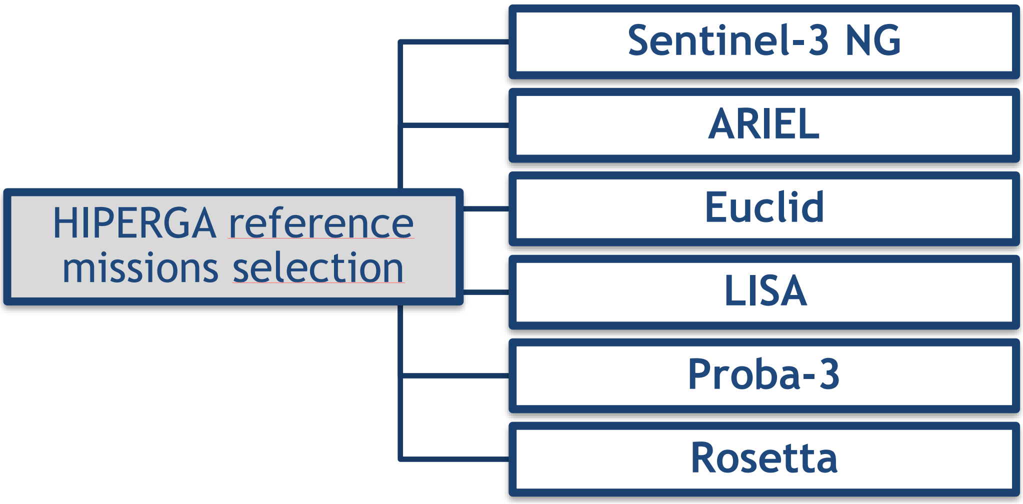

Figure 4-1. HIPERGA reference missions

Note that in a first step, the Lagrange or Space Weather (SWE) was also selected, since it is the first-ever mission to L5, and its inclusion in the HIPERGA project was considered interesting for the study and for the mission itself. However, the lack of available information led to take the decision of discarding its selection.

In [AD 01], the reader can find a detailed analysis of the mission needs and gyro requirements for each specific mission. These requirements are later use during the gyro trade-off, described below.

4.2 Gyro Technology Survey

The analysis of the state of the art conducted in [AD 02] made clear that the FG, DTG and MHDG technologies shall be disregarded as promising technologies for high-performance applications in the current decade. On the one side, despite being used in some applications —as legacy devices/designs meeting specifications are unnecessarily expensive to replace— FG and DTG technologies are not subject to research and development efforts. Even under the assumption that MHDGs may be the technology of choice for some very specific applications, its narrow application scope combined with an unavoidable steep mastering curve makes us not to recommend it and not to further consider it as a promising technology within the coming years.

The rest of angular rate sensing technologies passed the preliminary filter. FOGs, RLGs and HRGs are high-performance realities already being used in space and so they will continue to be. In the optical family of sensors, FOGs have the potential to improve in various technological directions as opposed to RLGs that are not subject to significant research and development efforts.

In the family of resonating sensors, current HRGs scored better than the rest apparently having less room for improvement than FOGs. CVG technology is the young brother of the family. Their precision and accuracy are currently not the highest, however they have a big potential (confer to the CVG design for self-calibration and reduced angular random walk) and, given its moderate SWaP-C, can be used for hybridisation with CAIGs playing the measurement interpolation role due to their higher bandwidth.

Cold-atom interferometry and the attendant CAIGs deserve a special comment. There is no doubt that they are, by far, the most “promising” angular rate sensing technology. They are, literally, bias free sensors with an extraordinary low-level angular random walk (see details in [AD 02]). However, their low TRL compromise their practical application in space within the present decade. In any case, they pass the preliminary selection filter.

Type	In short	Reasons in Favour	Reasons to Avoid	Space Heritage
FOG	Mature and improving fast	Coping with most of reqs	Few	Yes
RLG	Mature but stagnant	Coping with many reqs	FOG can do better, swap	Yes
CVG	HRG’s promising young brother	Many when they meet specs, swap	Few if they deliver	Yes
HRG	Mature and improving	Coping with most of reqs	Few	Yes
CAIG	Promising young brother	The hope when “impossible” reqs	Risk (current low trl)	No
DTG	Mature and stagnant (legacy t.)	Still recommended, e.g. Safran	MTBF < 15 y	Yes
MHDG	An American relative	In few cases, “me too” [like DARPA]	Far from European expertise	Yes

Table 4-1: Summary of gyroscopic technologies

4.3 Gyro Trade-off

For providing the final technology selection, a two-step trade-off process has been performed using the inputs the gyro specifications from [AD 01] and gyro technology survey from [AD 02]:

1. A qualitative trade-off has been performed to sort the different technology based on how feasible they are for each mission. This process is based on providing weights to each gyro technology, and to each requirement for each mission, and see which is the technology that obtains the higher score. Table 4-2 summarises the results of the qualitative trade-off in two rankings, from “best” to “worst” for the current state of the art and for the predicted one in ten years time.
2. A quantitative trade-off has been performed to see how each gyro technology comply with the requirements for each mission (see details in [AD 01]). Table 4-3 summarises the results of the quantitative trade-off, its scores being computed as the number of “compliances” divided by the number of requirements, also for current and predicted performances respectively.

The considerations bring us to include the CVG technology in the list recommended technologies together with FOGs, in the first place.

		1	2	3	4	5	6	7
2020	technology	HRG	FOG	CVG	MHDG	DTG	CAIG	RLG
	score	3337	3072	2790	1732	1716	1425	891
2030	technology	FOG	HRG	CVG	CAIG	MHDG	DTG	RLG
	score	3760	3376	2869	2638	1732	1716	1138

Table 4-2: Classification of gyroscopic technologies (qualitative trade-offs)

		1	2	3	4	5
2020	technology	FOG	RLG	HRG	CVG	CAIG
	score	0.829	0.826	0.821	0.735	0.704
2030	technology	FOG	CAIG	RLG	HRG	CVG
	score	0.928	0.843	0.826	0.823	0.759

Table 4-3: Classification of gyroscopic technologies (quantitative trade-offs)

5 GYRO CONCEPTUAL DESIGNS AND MARKET ANALYSIS

5.1 CVG Conceptual Design

ARIETIS-HP (High Performance) is a conceptual design derived from ARIETIS, InnaLabs Space 3-axis Rate Measurement Unit initially developed as part of an ESA CTP activity and currently selected for PLATO, LSTM, and ARIEL missions.

It is an enhanced Rad-Hard, high performance, high-reliability, ITAR-free 3-axis CVG Gyro featuring improved noise performance and Angular Random Walk, but also excellent bias and scale factor stability resulting from novel self-calibration mechanizations. An ultra-fine mode in a reduced measurement range is also proposed to reduce the output noise and improve the ARW parameter during precision pointing operations.

The concept of redundancy is out of scope here but might be proposed in future proposals based on some ideas generated in the paragraphs below.

The development of ARIETIS-HP is based on ARIETIS Hi-Rel rad-Hard gyro but draws also on the experience of ARIETIS-NS rad tolerant gyro. ARIETIS (see Figure 5 1, left) and ARIETIS-NS (see Figure 5 1, right) share the same high level architecture, performance and gyro sensor (CVG2), but whereas the former uses Hi-Rel class 1 EEE parts, the latter uses mostly automotive EEE parts that are upscreened by means of radiation tests.

Figure 5-1. (left) ARIETIS Rad-Hard gyro and (right) ARIETIS-NS rad-tolerant gyro

The following Table 5-1 is a comparison table between ARIETIS and ARIETIS-HP. It provides an overview of the mechanical and communication interfaces, mass and power budgets, operating environments, and performances.

Parameter	ARIETIS	ARIETIS-HP
INTERFACE		
TM/TC user interface	RS422 redundant. TM output rate 8 to 32Hz (nominal). Optional 10kHz for high precision pointing. Provision for RS485 (optional) or CAN bus (optional). TC (mode select) for Bias and SF self-calibration.	
Ground test interface	RS422 receiver only - not redundant.	
Sync Input	Provision for redundant RS422 receiver (optional).	
Power Input	28V regulated and unregulated (nominal). Power on and power off command.	
ENVIRONMENT		
Operating Temperature Range	[-30°C; +60°C] (qualification levels).	
Random vibration	26.9g rms (// to mounting plane).	
Shock (SRS)	2000g in 2kHz to 10kHz.	
Sine (pk)	25g up to 100Hz	
Radiation	Hi-Rel EEE qualified to 50krad TID / 60MeV SEE.	
PERFORMANCES		
Measurement range	• Fine: ±3°/s • Coarse: ±48°/s	•Ultra-Fine: ±1°/s •Fine: ±3°/s •Coarse: ±48°/s
ARW	≤0.005 °/√h	≤0.0008 °/√h (typical 0.0003)
Bias - at constant temperature (ACT)	<0.1°/h	<0.01°/h
Bias - thermal sensitivity residual (OTR)	<3°/h (3σ)	≤0.1°/h (3σ) (self-calibrating mode)
Bias repeatability	<1 °/h	≤0.1°/h
SF stability EOL	3000 ppm (3σ)	≤50 ppm (3σ) (self-calibrating mode)
Magnetic sensitivity	≤1°/h/Gauss (up to 15 Gauss)	
Reliability	1000 FIT	
Life	16 years in flight	
BUDGETS		
Mass	3 kg	3.3 kg
Envelop	186 mm x 186 mm x 81 mm	215 mm x 186 mm x 85 mm
Max Power consumption	8 W (nominal)	12 W (nominal)

Table 5-1: ARIETIS and ARIETIS-HP, budget, and performances.

The proposed development is the ARIETIS-HP project, which is summarized in Table 5-2.

Internal Development	• FPGA • CLDB • PB • Cluster and mechanical design updates to fit four sensors • CVG2 Sensing Element
External Development	None
Developed Models	• FPGA-CLDB Breadboard Model • Mechanical Breadboard Model • ARIETIS-HP Engineering Model • ARIETIS-HP Engineering Qualification Model • ARIETIS-HP Proto Flight Model

Table 5-2: Main features of the ARIETIS-HP Project for the future CVG space technology

5.2 FOG Conceptual Design

The proposed architecture for the future FOG conceptual design consists in three possible configurations, all based on four FOG in a skewed tetrahedral configuration. The principal difference from these configurations is the coil diameter, length of the wound optical fiber and the level of integration/hybridization of the optoelectronic and electronical components. The proposed three conceptual designs will be identified as “first”, “second” and “third” configuration and detailed in the next paragraphs.

Compared to other sensors, a gyroscope needs a much better accuracy over a much wider dynamic range: the important measurement is the integrated rotation angle, and any past error degrades future information. It is important to have low noise and low drift to measure a very low rate, but it is also important to have an accurate measurement of high rates (i.e., an accurate scale factor). The scale factor depends on the time, the temperature, the input rate; the bias depends on the time, the temperature, the magnetic field, the mechanical acceleration. Some of these sensitivities are modelled, others could be only measured.

Starting from the mission requirements, the relative constraints on performance but also on weight, mass and consumption were identified. Based on this analysis, three conceptual designs are identified, with different evolutions including considering the scalability of the FOG technology.

The three conceptual designs proposed shall be identified as “first”, “second” and “third” configuration.

The “first configuration” is defined with fiber optic coils with very high length. The gyroscopic axes are in a skewed redundant tetrahedral configuration, with a total of 4 axes. In this configuration each axis contains a Photonic Integrated Chip as evolution of the opto-electronic circuit and an ASIC as evolution of FOG Management functional block. The weight and volume indicated are evaluated without the evolution related to the “lighter materials” for the housing components. The µ-shields that enclose the coils have a geometrical optimization to reduce the total weight, identifying and covering only the devices sensitive to Faraday effect.

- The “second configuration” has the fiber optic coils in a skewed redundant tetrahedral configuration, with a total of 4 axes, each axis contains a fiber optic coil with a medium length. One Photonic Integrated Chip and one ASIC complete this very compact conceptual design proposed.

- The “third configuration” does not contain the evolution for the opto-electronic circuit and the evolution of FOG Management functional block, but there’s an optimized classical configuration which includes an ASE source (Amplified Spontaneous Emission) based on discrete fiber optic components. The improvement of the performance for such configuration are obtained by the inclusion of an optical scheme able to reduce excess RIN (Relative intensity noise) that limits the ARW (angular random walk).

In Table 5-3, the principal characteristics of the proposed three configurations are summarized. Note that in the configurations it is not included the power board (optional functional block), but they include axis redundancy.

Parameters	1st Config	2nd Config	3rd Config	Note
Number of axes	4	4	4	
Mechanical Envelope				
Mass [Kg]	~7	5-6	~8	
Volume [m3]	~0.007 m^3	~0.005	<0,017	
Performance				
ARW [°/√h]*	0.000063	6*10^-3	~3*10^-5	*(1σ)
Scale Factor error ACT [ppm]*	10	10	<5	*(1σ)
Scale Factor error OTR [ppm]*	<30	30	20	*(1σ)
Bias Instability [°/h]*	~8*10^-5	6*10^-3	<8*10^-5	*(3σ)
Bias on/off repeatability (ACT) [°/h]*	1*10^-4	0.01	1*10^-4	*(1σ)
Bias thermal sensitivity residual (OTR) [°/h]	1.2*10^-4	0.012	1.2*10^-4	*(1σ)
Misalignment [10urd/°C]*	10	25	10	*(1σ)
Full performance measurement [°/s]	±5	±150	±5	
Measurement range [°/s]	±15	±200	±15	
Bandwidth (-3dB) [kHz]	>2	>2	>2	
Latency (s)	0.001	0.0001	0.001	
Output frequency (Hz)	>2K	>2K	>2K	
Consumption				
Power [W]	<24W	<24W	<20W	
Power input [V]	±5V, +5V	±5V, +5V	±5V, +5V	
Environment				
Operative thermal range [°C]	-30 +60	-30 +60	-30 +60	
Random Vibration	20g rms	20g rms	20g rms	

<table>
<tr><th>Parameters</th><th>1st Config</th><th>2nd Config</th><th>3rd Config</th><th>Note</th></tr>
<tr><td>Shock [g]</td><td>>40g</td><td>>40g</td><td>>40g</td><td><table><tr><td colspan="2">SRS profile</td></tr><tr><td>f [Hz]</td><td>A [g]</td></tr><tr><td>100,0</td><td>100,0</td></tr><tr><td>1000,0</td><td>2000,0</td></tr><tr><td>10000,0</td><td>2000,0</td></tr></table></td></tr>
<tr><td colspan="5">Radiation</td></tr>
<tr><td>TID [Krad]</td><td>50</td><td>50</td><td>50</td><td></td></tr>
<tr><td colspan="5">Reliability</td></tr>
<tr><td>FIT</td><td>Lower*</td><td>Lower*</td><td>Higher*</td><td>*Numerical evaluation of the FIT is not possible without the complete and final definition of each component of the BOM</td></tr>
<tr><td>Lifetime [years]</td><td>>13</td><td>>13</td><td>>13</td><td></td></tr>
<tr><td colspan="4">Interface</td><td></td></tr>
<tr><td>TM/TC</td><td>RS422*</td><td>RS422*</td><td>RS422*</td><td>*Other serial interfaces are possible</td></tr>
</table>

Table 5-3: Parameters estimation for the first, second and third configuration

The start of the developments of the third configuration is based on the VNE IMU project, inertial measurement unit for NAVIGA equipment in the frame of VEGA-C launcher. The start of the developments of the first and second configurations are based on the FOG-PIC for terrestrial applications (CNS patent on 13/04/2022, issue number: 1020200005710).

Two projects are proposed for the FOG technology, which are summarized in the following table. Note that in this table, the price allocated from QR to FRR already includes the price for the Proto Flight Units respectively.

- The Configurations 1 and 2 are developed as joint project since they only differ in coil dimensions. This is a long-term project to develop high accuracy units with the best performances.
- The Configuration 3 separately, which is a short-term project which presents a direct improvement of the ARW with the current FOG architecture.

	Configuration 1 & 2	Configuration 3
Internal Development	• ASIC • Photonic Integrated Chip • Octuple winding	• ARW Optimization • Octuple winding
External Development	None	None
Developed Models	• Engineering Model #1 • Engineering Model #2 • Engineering Qualification Model • Proto Flight Model	• Engineering Model #1 • Engineering Model #2 • Engineering Qualification Model • Proto Flight Model

Table 5-4: Main features of the development for the future FOG space technology

5.3 Market Analysis

A detailed market analysis has been performed focusing on the European Space Market for the high-performance gyros, mainly composed by satellites and launchers (for now neglecting reusable vehicles). Following figure provides the expected increase of satellites and launches in the following years.

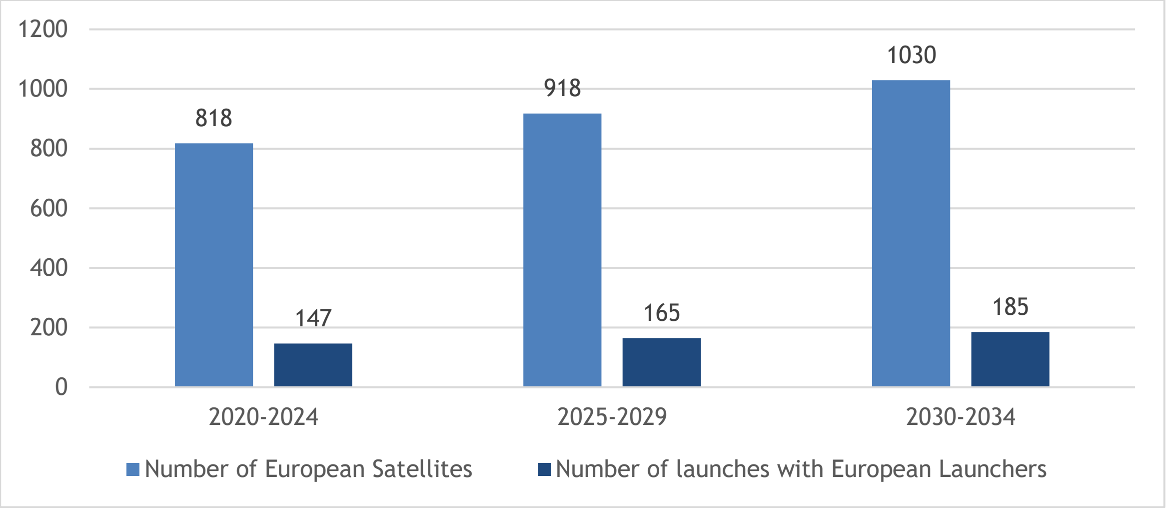

Figure 5-2: European space market forecast

After the general market analysis, and second step has been performed to address the number of targets for each selected technology. The main characteristics of the selected units has been analysed, and also their competitors for each type of market. Then, a specific percentage of the market has been addressed to each gyro technology, obtaining the final number of expected units, which is included in Table 5-5.

Gyro Technology	Expected number of units to be sold between 2030-2034
FOG	83
CVG	163

Table 5-5: Expected market for the FOG and CVG gyro technologies, within the European Space Sector, 2030-2034

The conclusions retrieved from the market analysis were the following:

- The target number to be sold of units for, both FOG and CVG, are included in Table 5-5, which addresses only the Space European Market.
- These number of units supposes a 20% of increment with respect to the period between 2020-2025.
- Further units could be sold for sure within the European Military Market, while for the non-European Market, fewer units are expected to be sold, since the US presents the main competitors for both technologies.

6 CONCLUSIONS

The HIPERGA project has provided a detailed analysis of the status of the current gyro technologies and market, and also, the analysis of the needs of the future high-performance missions. Based on these surveys, the two gyro technologies deemed as more promising have been the CVG and FOG technologies.

For both CVG and FOG technologies, a preliminary conceptual design of the future high-performance units has been presented, together with the roadmap to achieve the final units, including the necessary developments and their associated effort.

END OF DOCUMENT