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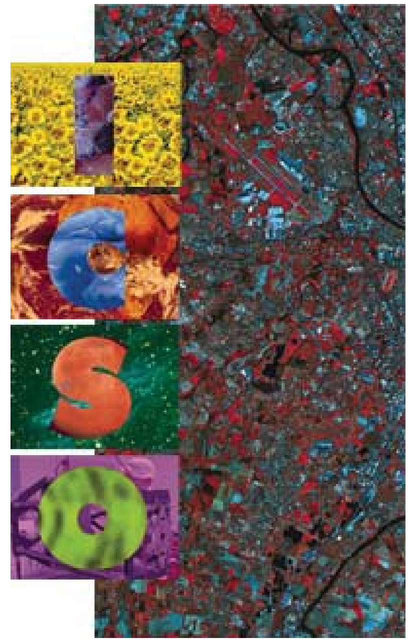

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FIBRE OPTIC GYROSCOPES FOR SPACE USE

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ABSTRACT – *Among the technologies available for gyroscopes usable in space, the Fibre Optic Gyroscope (FOG) technology appears to be the most suitable: no moving parts, very good lifetime, low power consumption, very low random walk, arbitrarily low angular resolution and very good behaviour in radiations and vacuum.*

Benefiting from more than ten years of experience with this technology, Ixsea (formerly the Navigation Division of Photonetics) is developing space FOG under both CNES and ESA contracts since many years.

In the 1996-1998 period, two space FOG demonstrators in the 0,01 °/h class were manufactured, including an optical head (optic and optoelectronic part) designed for space use and a standard ground electronics. Beyond the demonstration of the specified FOG performances, the behaviour of the optical head has been validated for use in typical space environment: vibrations, shocks, radiations (up to 50 krad) and thermal vacuum.

Since the beginning of 1999, Ixsea is developing a space electronics in order to manufacture two complete space FOG. The first one entered in qualification in October. The second one will be delivered beginning of next year, it will be used in a CNES attitude measurement experiment (MAGI) onboard the French-Brazilian Microsatellite (FBM) partly dedicated to technology evaluation.

1 - INTRODUCTION

The gyroscopes used in space for attitude measurement and for navigation, whatever the type of mission, are traditionally mechanical gyroscopes with spinning rotors. This technology has demonstrated since many years its advantages as well as its weaknesses: insufficient reliability and lifetime, sensitivity to the gravitational field and uncertain procurement continuity due to the gradual replacement of those gyroscopes by more recent technologies with better performances [1].

As a matter of fact, when one tries to draw a picture of the current situation, it appears that many space missions, most notably in telecommunication, broadcasting and some scientific missions, require gyroscopes with low mass and power consumption, long lifetime, medium performances and cost. Especially, devices with low mass and power consumption are further strong candidates for small satellite applications. On the other hand, Earth observation and astronomy missions often need high to very high performances and, additionally, some high level missions want to avoid any mechanical motion of the platform. Finally, there is a potential for life saving sensors in emergency and back-up modes of practically all missions if cost can be kept low enough, accepting possibly reduced performances.

Obviously, among the recent technologies, the Ring Laser Gyroscope (RLG), which began to be available as an industrial product at the very beginning of the eighties, is the most well-known. One can say that the RLG is now the main element of almost all medium and high performance inertial attitude and navigation systems used in the aeronautic field. It allowed the manufacturing of inertial strapdown systems as it combined for the first time an excellent ratio dynamic range over precision, a high bandwidth and a very good scale factor stability. Unfortunately, the RLG must be mechanically dithered around its sensitive axis in order to be able to measure low rotation rates. Additionally, the best random walk performance achieved at the present time, limited by an intrinsically poor angular quantification, seems to be insufficient for very demanding missions. The mechanical activation is not a problem with systems already experiencing high levels of vibrations, for instance due to engines, but it can prove to be a perturbation with satellites. On the other hand, the RLG seems to be a very good solution on launchers, Ariane being already equipped with two such systems.

However, another technology based on the same physical principle than the RLG appeared in laboratory when the RLG was itself reaching the industrial stage: the Fibre Optic Gyroscope (FOG). Over the last twenty four years, this technology has evolved from a pioneering physics experiment [2] to a practical device that has now reached the production stage since a few years.

Today, it is now accepted among inertial guidance and navigation specialists that the FOG technology is a strong contender for many civilian or military applications in the medium to very high range of performance. Among the recent technologies, it is especially competitive where the RLG is over dimensioned or intrinsically unsuitable and where vibrating gyroscopes do not present sufficient performances. It is already industrially used in a wide variety of applications, ranging from car navigation (e.g., Hitachi systems under Ixsea license) to ship or aircraft navigation (e.g., Honeywell redundant AHRS on the Boeing 777) [3].

More specifically, the FOG technology appears to be much suitable to replace the mechanical gyroscopes for space applications: low mass and power consumption, no moving parts, very good lifetime and high reliability, very low random walk and arbitrarily low angular resolution as well as a very good behaviour under space environment conditions. Moreover, its cost effectiveness is increased by the ability to scale easily the performance to fulfil a broad range of applications.

In this article, after an overview of the FOG technology, we will thus present the status of the activity at Ixsea before concentrating naturally on the development of the space FOG.

2 - FOG TECHNOLOGY OVERVIEW

We will first present the basic principle of the FOG, then the commonly recognized optimal architecture and signal processing technique and finally the erbium-doped-fibre source, which required a specific work to comply with the radiation constraint of the space environment.

2.1 - Basic principle

The FOG, like the RLG, is a rotation sensor based on the Sagnac effect [4]. Basically, this effect produces, in a ring interferometer, a phase difference $\Delta\Phi_R$ proportional to the dot product of the rotation rate vector $\mathbf{\Omega}$ by the area vector $\mathbf{A}$ enclosed by the closed optical path, usually written in the case of a fibre optic coil:

$$\Delta\Phi_R = \frac{2\delta LD}{\ddot{e}c}\Omega_{//}$$

where L is the total coil length, D the mean coil diameter, c the light velocity in a vacuum and $\Omega_{//}$ the rotation rate component parallel to the coil axis.

To understand simply Sagnac effect, it is possible to consider the case of an “ideal” circular path in a vacuum. Light entering the interferometer is divided into two counter-propagating waves which return perfectly in phase after having travelled along the same path in opposite directions. Now, when the interferometer is rotating, an observer at rest in the inertial frame of reference sees the light travelling with the same vacuum velocity c in opposite directions, but during the transit time through the loop, the beamsplitter has moved. Therefore our observer sees that the co-rotating wave has to propagate over more than one complete turn while the counter-rotating wave has to propagate over less than one complete turn. This difference of transit time may be measured by interferometric means.

Sagnac effect in matter is more delicate to explain, but it may be shown that it is a pure temporal delay, completely independent of the indices of refraction or of the guidance conditions and that it keeps the same value as in a vacuum. In a FOG, the light propagates in a fibre optic coil and the sensitivity is enhanced by the use of a multi-turn coil, just as the flux of the magnetic field is enhanced in a multi-turn inductance coil.

To give an order of magnitude, a phase difference of 10^{-7} to 10^{-8} radian should be measurable through time averaging, while the absolute phase accumulated by the wave along 100 m to 1 km is 10^9 to 10^{10} radians. Consequently, the sensitivity limit is 16 to 18 orders of magnitude below the total propagation path. Such a performance could look unrealistic when the temperature dependence is already on the order of 10^{-5}/K but the fundamental principle of reciprocity of light propagation in a linear medium is the key solution. The non-reciprocal Sagnac effect is a very small first order effect which should be buried in the changes of the zero order, the absolute phase accumulated in the propagation, but single-mode guided propagation and reciprocal configuration provide perfect "common-mode rejection" of this absolute phase.

2.2 - Optimal architecture and signal processing technique

After more than twenty years of research and development, the FOG technology has reached its maturity and the optimal configuration providing good performances is commonly recognized [5].

The optical architecture (Figure 1) requires:

- A source with a high spatial coherence and a low temporal coherence. The high spatial coherence ensures a good coupling efficiency of the light into the single mode fibre, the low temporal coherence reduces the effect of parasitic interferometers, backscattering and Kerr effect. This source also needs to be wavelength stabilized to ensure a good scale factor stability.
- A 3 dB coupler to extract the optical signal coming back from the ring interferometer.
- A single-mode filtering (spatially and in polarization) at the common input-output port of the interferometer. This spatial filtering is performed with a single mode fibre at the input of the Integrated-Optic Circuit (IOC) and the polarization filtering with the polarizing effect of the IOC.
- A multifunction IOC: very high polarization filtering, Y junction and high bandwidth phase modulators in a push-pull configuration (feedback modulation).
- A fibre optic coil with a polarization maintaining fibre.
- A quadrupolar coil winding to reduce the effect of thermal transients (Shupe effect).

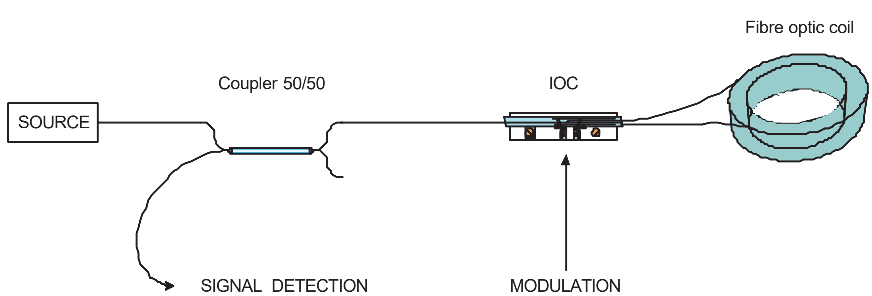

Figure 1: optimal architecture of a FOG

The signal processing technique used is as follows:

- A biasing modulation allowing the measurement of very low rotation rates as well as the sign of those rotations.
- A closed-loop signal processing to increase the dynamic range and remove the effect of fluctuations of the optical power and of the gain of the detection chain.
- An all-digital signal processing with a digital phase ramp allowing an easy autocalibration of the system and a good scale factor stability.

2.3 - Erbium-doped-fibre source

In order to be able to obtain both high performances and a correct behaviour under radiations, the source of a space FOG should have the following characteristics:

- A broadband spectrum (low temporal coherence).
- A high power and a good coupling efficiency into a single mode fibre (high spatial coherence).
- A good mean wavelength stability to ensure scale factor stability.
- Use of the 1550 nm wavelength window to ensure a correct behaviour under radiations of the fibre.

Deriving from the erbium-doped-fibre amplifier (EDFA) technology in the 1550 nm window, which is revolutionizing optical fibre communication, the erbium-doped-fibre source technology is perfectly suitable for this application. It is based on superluminescence, with a doped fibre excited by a pump laser diode. This superluminescence is also called ASE for Amplified (by stimulated emission) Spontaneous Emission. In addition to a broad spectrum and a high power which improves the signal over noise ratio, it brings an unpolarized emission which is useful to reduce polarization non-reciprocities and allows one to use ordinary (non-polarization maintaining) couplers.

We thus have developed such a source which we now use on all our medium to high performance FOG (Figure 2) [6]. Additionally, this source is wavelength and power stabilized and does not require any Peltier element, which improves the reliability and the overall power consumption.

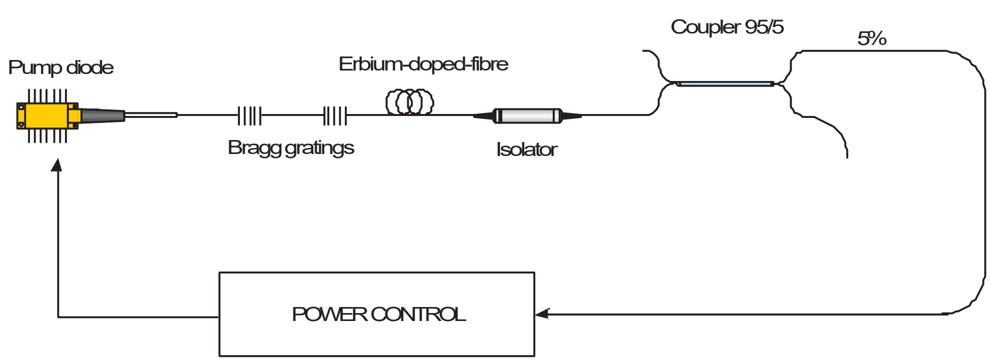

Figure 2: erbium-doped-fibre source

Under radiations, the main concerns are that first erbium is not an ideal dopant (problem of co-dopants) and second that the pumping wavelength being necessarily shorter than the emission one, its radiation induced attenuation (see for instance [7]) is higher, which decreases the conversion efficiency thus the emitted power. Hopefully, two effects counterbalance the radiation induced attenuation: the relaxation and the photobleaching [8]. Those effects are inverse chemical reactions to the one inducing attenuation, the photobleaching requiring additionally a photon, which implies it will occur only with incident light.

As a matter of fact, the development of our source lead to the choice of an erbium-doped-fibre using co-dopants allowing, for low dose rates typically observed in space, a real-time compensation of the induced attenuation by those two effects. The source has been tested up to 150 krad and we demonstrated its ability to function very correctly over its expected lifetime. Largely under-used at the beginning of its life, the source does not show any decrease in emitted power after a typical exposure to 50 krad.

Finally, it is interesting to note that even if in the past these sources might have been considered as a luxurious solution, today, with the very broad development of EDFA technology for communications, they are both cost effective and very reliable. This cost effectiveness is particularly advantageous with multi-axis operation since their high power may be used in a source sharing configuration with no penalty on noise.

3 - STATUS OF THE ACTIVITY AT IXSEA

In this paragraph, we will briefly present first the creation of the new Ixsea company and second the different standard products manufactured: FOG in the medium to very high performance range and attitude and navigation systems.

3.1 - Creation of Ixsea

Continuously increasing since 1987, the Photonetics activity dedicated to the development of the FOG technology went through many steps. From the first laboratory prototypes demonstrating the validity of the technology, it has reached full production of medium and high performance FOG as well as attitude and navigation systems, the demonstration of very high performance and the development of space FOG. In September, the whole activity was transferred from the Navigation Division of Photonetics to a new independent company created for this purpose: Ixsea. Completely dedicated to the FOG technology, Ixsea will continue to develop its activity in its different fields of interest as a major European supplier of demanding inertial systems.

3.2 - FOG products: medium to very high performance range

The proposed range of standard FOG products concerns the medium performance (0.05 °/h class) with the FOG 90 and the high performance (0.01 °/h class) with the FOG 120, both declined in single or three-axes configuration. The performances are presented below (Table 1).

	FOG 90	FOG 120
Random walk	0.0025 °/√h	0.001 °/√h
Bias stability (Allan variance analysis)	0.005 °/h	0.001 °/h
Bias stability vs temperature (-40/+80 °C)	± 0.05 °/h	± 0.01 °/h
Scale factor stability vs temperature (-40/+80 °C)	30 ppm	10 ppm
Scale factor linearity	5 ppm	3 ppm
Dynamic range (Ωπ)	± 250 °/s	± 130 °/s
Angular increment	0.2 arc sec	0.0012 arc sec

Table 1: FOG 90 and FOG 120 performances

They both benefit from the developments achieved since 1993 concerning the hardening against typical military environment (temperature, vibrations, shocks), the reduction of the residual Shupe effect and the erbium-doped-fibre source.

More recently, the SOFIA (Stratospheric Observatory For Infrared Astronomy) project allowed us to demonstrate very high performance. This project, driven by the NASA, aims at the direct use of a telescope aboard a Boeing 747 for stratospheric infrared astronomy. MAN Technologies (Germany), in charge of the telescope development, including pointing and stabilization, chose us to develop the necessary gyroscopes. The requirements were ones of a very high performance FOG, more particularly concerning the random walk. We thus first developed a FOG 180 prototype which fulfilled perfectly the different specifications [9], then three additional identical units to be integrated in the system developed by MAN Technologies. The performances are presented below (Table 2).

	FOG 180
Random walk	0.00022 °/√h
Bias stability (Allan variance analysis)	0.0007 °/h
Bias stability vs temperature (-20/+60 °C)	± 0.003 °/h
Scale factor stability vs temperature (-20/+60 °C)	15 ppm
Scale factor linearity	3 ppm
Dynamic range (Ωπ)	± 30 °/s
Angular increment	< 0.001 arc sec

Table 2: FOG 180 performances

The FOG technology presents an intrinsically good bias stability at relatively stabilized temperature (without high temperature transients). As an example, we present below the typical result of an Allan variance analysis performed over a FOG 180 bias measurement at ambient temperature (Figure 3).

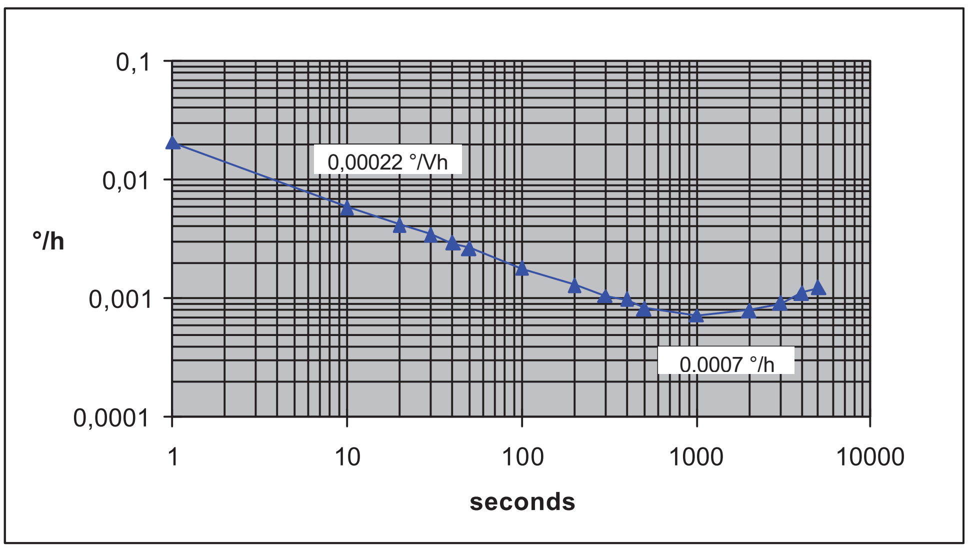

Figure 3: Allan variance analysis of a FOG 180

3.3 - Attitude and navigation systems

A step beyond the "standard" FOG products, we have developed Octans, a strapdown AHRS (Attitude and Heading Reference System) based on a FOG 90 triad. Dedicated to the industrial, scientific and military marine markets, it is available in different models depending on the application: surface (IP 65 or IP 67) or subsea (1000 m, 3000 m or 6000 m). Octans provides, without any external reference, heading with a dynamic accuracy of ± 0.2 ° secant latitude and attitude (roll and pitch) with an accuracy of 0.01 °. Some models are presented below (Picture 1).

Picture 1: Octans models

Much recently, we developed an evolution of Octans based on a FOG 120 triad, φ-INS, to propose a new strapdown Inertial Navigation System (INS) with a heading accuracy of 1 arc minute.

4 - DEVELOPMENT OF THE SPACE FOG

We will precise the different steps of the space FOG development that led to the current situation and present the most recent developments.

4.1 - Feasibility study

Beginning of 1996, a CNES contract allowed us to demonstrate in a paper study the feasibility of a FOG for space use. However, this study highlighted the different specific technical issues that would have to be solved: behaviour under radiations and vacuum, improvement of the gluing process reliability and development of a space electronics.

4.2 - Hardening of the optical head

End of 1995, an European invitation to tender from ESA/ESTEC was proposed for the development of a 0.01 °/h class FOG for space use and we were selected among major European manufacturers.

In the 1996-1998 period, we thus developed and manufactured two space FOG demonstrators deriving from the FOG 120 which were tested by the French LRBA. Those demonstrators were composed of an optical head (optic and optoelectronic part) designed for space use, including a purposely developed erbium-doped-fibre source (see § 2.3), and a standard ground electronics.

Beyond the successful demonstration of the specified FOG performances, the behaviour of the optical head was validated for use in typical space environment: vibrations, shocks and radiations (up to 50 krad).

The behaviour under thermal vacuum remained however to be verified.

4.3 - Improvement of the gluing process

In parallel, we benefited from a CNES contract in the 1997-1998 period to improve our gluing process. The results obtained, concerning essentially the behaviour against aging, temperature, humidity, vibrations and shocks, were considered very satisfactory and allowed us to reach a very good reliability level for this critical part of the FOG manufacturing process.

4.4 - Development of a complete one-axis qualification model

At the beginning of 1999, following the first ESA contract, CNES and ESA decided to join their efforts in two contracts running in parallel to continue the support of the space FOG development.

The CNES contract, which ended at the end of 1999, concentrated first on the yet to be verified behaviour under vacuum. It allowed us to successfully clarify this question with the verification of the very good behaviour of the optic and optoelectronic packaged components in vacuum, the study of the outgassing of organic materials used in the optical head and the test in thermal vacuum of one of the two ESA demonstrators. In a second part, we manufactured two new 0.01 °/h class optical heads deriving from the demonstrators ones and benefiting from the recent developments.

On the other hand, the ESA contract, still under progress, concerned first the development of a complete space electronics. This phase now completed, it was then originally planned to manufacture two complete one-axis FOG using the CNES optical heads: a qualification model and a flight model. The first unit, presented below (Picture 2), has been manufactured and entered in qualification in October.

Picture 2: 0.01 °/h class one-axis qualification model

4.5 - Development of a three-axis housing for the flight model

In the meantime, at the beginning of 2000, it was decided to go a step further with the flight model, which would benefit from the development of a three-axis housing under a new CNES contract.

This flight model will be delivered beginning of next year to be used in MAGI, equipped with the remaining real axis and two dummy axes due to a limitation on the available power supply. This CNES attitude measurement experiment should itself fly in 2002 onboard the French-Brazilian Microsatellite (FBM) [10] dedicated partly to technology evaluation. The purpose of the MAGI experiment is to evaluate the behaviour of a complete gyroscopic function during 13 months in orbit (circular LEO at 700 km) and MAGI will measure the angular movements of the satellite around one reference axis. The obtained results will then be compared with the attitude information provided by star sensors on several 90 minutes orbits, which will allow to check the short and medium term bias stability of the FOG in space.

The principal characteristics and specified performances of a complete 0.01 °/h class three-axis space FOG are presented below (respectively Table 3 and Table 4).

Weight	3.7 kg
Dimensions	171 x 180 x 174 mm (5.4 litres)

Power consumption	< 12 W

Table 3: 0.01 °/h class three-axis space FOG characteristics

Random walk	0.001 °/√h
Bias stability	0.005 °/h
Scale factor stability (OTR over 1 month)	< 100 ppm 3σ
Dynamic range	≥ 10 °/s
3dB bandwidth	≥ 100 Hz
Readout frequency	≥ 20 Hz
Angular increment	≤ 0.01 arc sec
Misalignments stability (OTR over 5 years)	≤ 10 arc sec

OTR: Over the Temperature Range (0/+50 °C full performance).

Table 4: 0.01 °/h class three-axis space FOG specified performances

A first three-axis qualification housing having been successfully qualified in vibrations and shocks in September, the manufacturing of the flight model housing began in mid October, for a planned integration in December.

5 - CONCLUSION

Low mass and power consumption, no moving parts, very good lifetime and high reliability, very low random walk and arbitrarily low angular resolution, very good behaviour under space environment conditions: it is commonly recognized that the FOG technology is much suitable to replace the conventional mechanical gyroscopes for a broad range of space applications.

Now, after five years of ESA and CNES supported specific development, benefiting from more than ten years of experience with the technology, we are ready to propose a complete 0.01 °/h class space FOG, both in one-axis and three-axis configuration.

Before the end of the year, the first one-axis model would have been fully qualified for space use.

Then, outcome of all the development performed, the three-axis flight model will be delivered beginning of next year for the first in orbit evaluation of the technology.

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