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From R&D Brassboards to Navigation Grade FOG-Based INS: the Experience of Photonetics/Ixsea

Thierry Gaiffe
IXSEA
55, Avenue Auguste Renoir
78160 Marly-le-Roi
France
Tel: + 33 1 30 08 98 88
Fax: + 33 1 30 08 88 01
info@ixsea.com

1. Introduction

The year 2002 marks the 25th anniversary of the first experiment by Vali and Shortill [1] demonstrating that it is possible to use a fiber optic coil to quantify the rotation of solid bodies. The intervening quarter-century, from 1976 to 2002, a period of effort on R&D, industrialization and serial production of FOGs (Fiber Optic Gyroscopes), has resulted in the maturity and total mastery of this technology. FOGs are now *de rigueur* in a large number of applications, often those which until very recently were using older, and frequently less satisfactory, technologies (mechanical gyroscopes or laser gyros, for example).

Ixsea (formerly the Navigation Division of Photonetics, which became Ixsea in September 2000) took part, like other industrial companies in this domain, in the development of the FOG. The history of our company is therefore closely associated with that of the technology, a history of which this paper contains a summary.

In addition, since this technology has been mature since the mid-1990s (this can be pinned down precisely to the SPIE congress in Denver in 1996, held to celebrate the 20th anniversary [2]), the last five years have allowed the various manufacturing companies concerned to find ways of using FOGs. These firms, focused as they naturally have been on very diverse markets, have introduced this technology into a range of domains, which explains why FOGs are now used in both military and non-military applications, with a presence in all aspects of navigation: aeronautical, marine, space, terrestrial, robotic, and others.

It was during these same years that Ixsea/Photonetics shifted its FOG-based activity away from R&D into production and marketing. The development of navigation systems, the beginning of production of its navigation grade FOGs, and continued R&D focused on very high levels of performance, enabled Ixsea/Photonetics to address two domains of application: at sea and in space. These activities are described after the historical summary.

2. The history of the FOG at Ixsea/Photonetics (or the first twenty years from 1976 to 1996)

The FOG made its "official" debut at Photonetics towards the middle of the 1980s, but its history goes back further, beginning in fact at the University of Stanford in the late 1970s (a period which could be described as its "prehistory"). This is so because Hervé Lefèvre and Hervé Arditty, respectively the former R&D Director and the President of Photonetics, both did their post-doctoral work at Stanford as members of Professor Shaw's team. Both then continued their FOG research at the Central Research Laboratory of Thomson-CSF (France) in the early 1980s. During this early period, several dozen articles, often considered as landmarks in the literature, were published by the "two Hervés" (see for example the SPIE collection [3]).

Following these years of FOG "prehistory", in 1987 Hervé Lefèvre joined Photonetics, which had been founded by Hervé Arditty in 1979. FOG R&D was an essential activity in the dozen or so years that followed (and it remains very energetic at the present time with respect to very high performance devices for space applications). Describing this R&D very briefly, and highly schematically, we can say that everything began with the biggest breakthrough made by Photonetics in the late 1980s: the "all-digital" concept, involving the combination of digital demodulation and digital phase ramp [4]. This core concept is an absolute prerequisite if good performance is to be obtained. Later, at the beginning of the 1990s, development of coolerless, wavelength-stabilized erbium-doped fiber source [5] made it possible to enhance intrinsic performance levels even more (reduction of bias due to non-polarization, reduction of random walk noise, source sharing architecture, etc.). By the mid-1990s, fundamental work on improving integrity under environmental stress (notably resistance to thermal transients, i.e. the Shupe effect [6]) enabled a navigation grade (0.01 deg/hour) FOG to be produced for military applications [7]. FOG architecture as it is currently used by Ixsea dates from this period and remains virtually unchanged. Since that time, other improvements, essentially minor in nature, have been made in order to attain very high levels of performance [8].

Almost the entire history of the FOG at Photonetics until the mid-1990s can be summed up in one graphic, to be seen in figure 1: the improvement in performance levels over the years (bias stability is stability over the thermal range –40°C/+80°C).

Since 1995, developments have essentially involved using FOGs in systems that had to be designed: attitude detection units, inertial navigation systems, space-hardened IMUs and so on. Efforts, other than those involved in R&D for these systems, were concentrated mainly on ramping up production and marketing.

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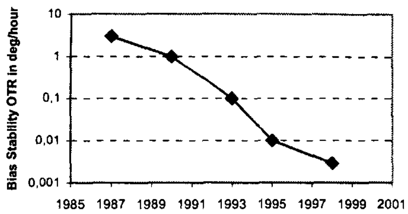

Figure 1: Performance improvements achieved over time by Photonetics FOGs

3. Development of FOG-based inertial navigation systems (or the last five years: 1996 to 2001)

1. The positioning of the FOG in relation to other technologies

By 1996, the situation at Photonetics was as follows: the technology was mature and capable of meeting the most exacting gyrometer requirements, but the commercial role of the FOG remained uncertain. This was because FOG technology is "just another method" among many existing technologies for the measurement of rotation, others being mechanical rate gyros (spinning mass), laser gyros (RLG) and resonating gyros (MEMs and HRGs).

Generally speaking, if a new technology is to be meaningful in manufacturing terms, it must bring with it "quantifiable" advantages compared with existing technologies already available on the market: this is, in other words, the classic "market penetration" problem. In actual fact, apart from its performance, FOG technology has two major advantages: ruggedness and price.

Where ruggedness is concerned, FOGs are the only rate gyros with no moving parts: everything is totally solid-state in a FOG. If you put an ear to a mechanical gyro, you will hear a steady hum which is the sound of the rotation of the spinning top on which the unit is based. The same is true of the laser gyro, which emits a very distinctive buzzing sound due to its mechanical activation (dither). In short, this feature of the FOG makes it very resistant to mechanical environments and gives it a very long use life. In the case of the laser gyro, life time is not dependent by the dither but is affected by oxidation of the mirrors, which makes its survival doubtful after seven years of use.

Where the cost of the FOG is concerned, this technology has seen its price constantly fall in recent years, a decline driven by two phenomena: first, economies of scale, which are standard when new products are put in production ("the more you make, the less it costs"), and second, the dramatic explosion in the fiber-optic telecoms market. Some industrial companies developing FOGs (like Photonetics) chose early in the 1990s to switch from 850nm to 1550nm as the operating wavelength, and did so for purely technical reasons: to obtain high performance (erbium-doped fiber source). One can only observe that this turned out to be a judicious choice where cost was concerned. This is because the fiber-optic telecoms market went through a period of phenomenal growth from 1995 onward, driven by the development of multicolored networks (D-WDM). This growth led to the manufacture of the base components in their hundreds of thousands (pump diodes, isolators, couplers, etc.). The economies of scale thus generated, which would never have been possible for the FOG market alone, made component prices infinitely more affordable. A side-effect of this was to enable a substantial improvement in component reliability (a 980nm pump diode is much [illegible] reliable that a 850nm DSL because 100,000 are manufactu[illegible]ery year for fiber amplifiers (EDFA) with a claimed use life of more than 20 years).

2. Development of attitude systems – the Octans range

However, despite the advantages of FOGs over competing technologies, penetrating a market that has been in place for decades was still no foregone conclusion, and this was so for various reasons. The first was that any rate gyro is in fact just one component in a more complex system, called an "inertial measurement unit", and from the point of view of the user, only the system as a whole is of any real interest. The second is that purchasers of inertial systems are still relatively conservative in outlook and a great deal of time is needed before their level of confidence in the new technology can be raised sufficiently.

It was therefore necessary to find new market niches in which the advantages of systems based around the new technology would be so substantial as to appear to users to constitute a genuine revolution. In 1997/98, Photonetics decided to develop a fiber optic gyrocompass called Octans [9]. Traditionally, gyrocompasses are systems that give the true heading of a ship, that is to say the angle between the ship and geographic North. Developed in the 1920s, they are classically based around a rapidly spinning mass which aligns its angular momentum with the Earth's rotational vector. They weigh several dozen kilos, are difficult to install, are still relatively fragile and sensitive to mechanical environments, and they take several hours to find North.

The Octans uses three 0.05 deg/hour class FOGs associated with three accelerometers to detect the heading in a few minutes, thanks to the original algorithm developed by Photonetics. The Octans is in fact a high-end attitude system which gives all angles and accelerations referenced to the terrestrial axes. This high-performance attitude detection unit (heading to 0.1 deg, pitch and roll to 0.01 deg) is ultra-compact (4 kg) and has very low consumption compared with existing products.

The marketing of the Octans began in earnest in 1998 and focused on industrial marine applications, largely in the area of oil prospecting and exploration. Ixsea has been IMO (International Maritime Organization) certified [10] since mid-2000 and has delivered nearly 200 Octans units to customers around the world. There is a surface version, and underwater versions capable of withstanding pressures of up to 900 bars.

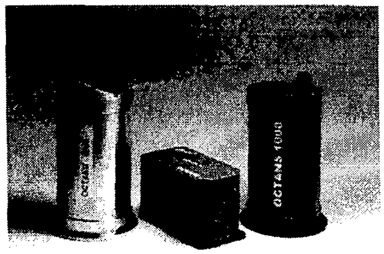

Figure 2: the Octans family

3. Development of inertial navigation systems – the PHINS range

One of the applications of the Octans is as a positioning tool for submarine robots called UUVs (Unmanned Underwater Vehicles). Non-military UUVs are mainly used for oil exploration and exploitation, since the oil fields in operation today are all at depths currently barred to human operators...

It will be readily understood that the positioning of a UUV is absolutely crucial, and the Octans is used for dead-reckoning navigation based on the precise heading supplied by the Octans, combined with speed data.

There is however a method for determining the position of any vehicle with greater accuracy and this is to use an inertial navigation system (INS), which can be considered as a black box based on high-performance rate gyros and capable of merging all the types of navigation data (Kalman filter). INS units are used essentially in aviation and for military applications, and are usually based at the present time around laser gyro technology. Maritime non-military surface applications are based at the present time overwhelmingly around GPS, which supplies peerless accuracy (no drift) at a ridiculously low cost.

If the vast majority of existing UUVs do not use INS units for their position determination, it is partly due to the very high cost of the systems used in aviation and their unsuitability for the very special characteristics of underwater environments.

However, Ixsea/Photonetics has had navigation grade rate gyros (bias stability better than 0.01 deg/hour) since 1995, these being the core component of inertial navigation systems.

Ixsea therefore decided in 2000 to develop a inertial navigation system specifically for positioning applications at sea and underwater, based around very high performance FOGs and a Kalman filter, in order to merge data supplied by conventional sensors (GPS) and other sensors specific to maritime uses: acoustic positioning systems (LBL, USBL), Doppler speed logs (DVL), pressure sensors, etc. This unit was called the PHINS (PHotonics Inertial Navigation System) [11].

In its underwater version (U-PHINS), it has been selected by a large number of manufacturers of military and non-military UUVs. Its surface version (M-PHINS) is ideal for solving the problem posed by ultra-accurate attitude control at sea.

Developments currently in progress involve the optimization of the parameters of the PHINS for applications in the terrestrial (L-PHINS) and aeronautical (A-PHINS) domains.

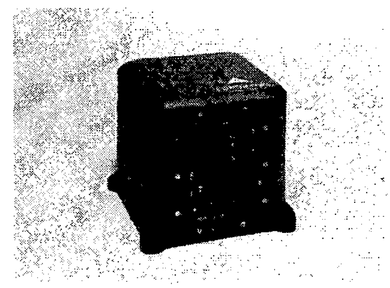

Figure 3: The PHINS

4. Tomorrow: space-dedicated attitude detection systems

1. Very high levels of performance

The FOGs used in the PHINS have a temperature bias stability better than 0.01 deg/hour (0.003 deg/hour at ambient) for a noise level of 0.001 deg/√hour. With FOG technology, it is feasible to further enhance this performance very considerably.

In 1997, Photonetics was selected as supplier of the core rate gyro for the Sofia project (Stratospheric Observatory For Infrared Astronomy) developed by NASA. The underlying concept of Sofia was to install a 3-meter telescope on a Boeing 747 in order to circumvent the constraints imposed by atmospheric fluctuations.

The four FOGs manufactured at that time, termed FOG 180 [8], offered much better performance than the best laser gyro on the open market (figure 4). Intrinsically, the resolution of a laser gyro is limited, whereas that of the FOG may be increased at will. This advantage, allied with the fact that the level of noise intrinsic to FOGs is much lower than that of laser gyros, make the FOG an ideal candidate for the precise aiming of telescopes, imaging systems and radiotelescope antennas (another advantage is that its lack of moving parts prevents any pollution of the observation system by mechanical interference).

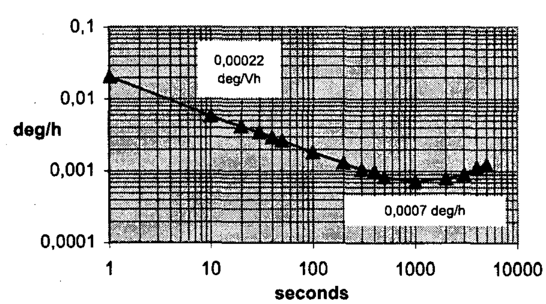

Figure 4: Allan variance analysis of a FOG 180 (1998)

2. *The FOG: ideal for space-dedicated applications*

Many of these device-aiming applications are located in space on telecommunications and observation satellites. The technical requirements for space-based applications are extremely demanding: resistance to ultra-high vacuum, high radiation levels, almost unbelievable impact and vibration parameters on lift-off, combined with peerless reliability and use life. It is easy to see that for certain of these specifications (integrity in extremely harsh mechanical environments, life time), the FOG is in principle a very good candidate.
Photonetics began its research on the use of FOGs in space in 1996, focusing largely on their capability to withstand high-radiation environments and ultra-hard vacuum in space. The studies were funded by the European Space Agency (ESA) and the French space agency (CNES) [12].
Qualification models and 0.01 deg/hour class flight models have since been produced, incorporating space-hardened electronics capable of withstanding levels of over 50krad in orbit (figure 5).

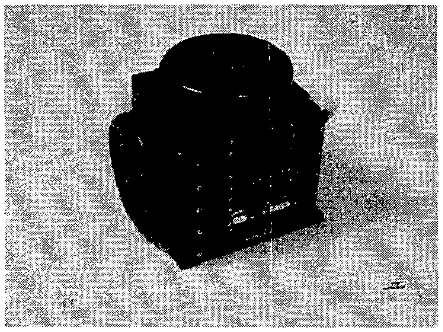

Figure 5: Three-axis, navigation grade FOG flight model for space applications

5. Conclusion

The FOG took 20 years of development to reach maturity; 20 years from the initial laboratory demonstration in 1976 to the SPIE congress in Denver in 1996. This can be seen as a constant factor in the development of new gyrometer technologies (it is also true of the laser gyro, between its first demonstration in 1962 and the first industrial uses in the early 1980s).

It is never easy for a new technology to penetrate an existing market, even when it has undoubted advantages (in the case of the FOG, one could cite, among other things, its low cost and absence of moving parts). A company therefore needs to find a rational and well thought-out way into the market; a real revolution is needed for this to occur rapidly, otherwise there will be a risk that marketing costs will become totally prohibitive.

It is for this reason that Ixsea has chosen to direct its efforts toward maritime and space applications, where the technologies in use are to some extent either unsuitable or obsolete.

Attitude detection and positioning systems (the Octans and PHINS ranges) intended for industrial maritime applications are now well rooted in the market and are increasingly seen as benchmark systems. They are also beginning to be used in other markets, such as those for terrestrial (land survey) and aeronautical applications (Unmanned Air Vehicle).

The commercial challenge of tomorrow will probably be the integrated, very high performance, space-dedicated attitude control unit.

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