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The Sagnac effect: 100 years later / L'effet Sagnac : 100 ans après

The fiber-optic gyroscope, a century after Sagnac's experiment: The ultimate rotation-sensing technology?



*Le gyromètre à fibre optique, cent ans après l'expérience de Sagnac :
la technologie ultime de mesure inertielle de rotation ?*

Hervé C. Lefèvre *

iXBlue SAS, 52, avenue de l'Europe, 78160 Marly-le-Roi, France

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ABSTRACT

Taking advantage of the development of optical-fiber communication technologies, the fiber-optic gyroscope (often abbreviated FOG) started to be investigated in the mid-1970s, opening the way for a fully solid-state rotation sensor. It was firstly seen as dedicated to medium-grade applications ($1^\circ/\text{h}$ range), but today, it reaches strategic-grade performance ($10^{-4^\circ}/\text{h}$ range) and surpasses its well-established competitor, the ring-laser gyroscope, in terms of bias noise and long-term stability. Further progresses remain possible, the challenge being the ultimate inertial navigation performance of one nautical mile per month corresponding to a long-term bias stability of $10^{-5^\circ}/\text{h}$. This paper is also the opportunity to recall the historical context of Sagnac's experiment, the origin of all optical gyros.

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R É S U M É

Profitant du développement des technologies de télécommunication à fibre optique, le gyromètre à fibre optique a commencé à être étudié au milieu des années 1970, ouvrant la voie à un gyromètre entièrement à état solide. Il a d'abord été considéré comme seulement adapté aux applications de moyenne performance (de l'ordre de $1^\circ/\text{h}$), mais atteint aujourd'hui des performances de classe stratégique (de l'ordre de $10^{-4^\circ}/\text{h}$) et surpasse, en termes de bruit et de dérive à long terme du biais, son concurrent établi, le gyromètre laser. Des progrès supplémentaires restent possibles, le défi étant la performance ultime de navigation inertielle au nautique par mois, qui correspond à une stabilité de dérive de $10^{-5^\circ}/\text{h}$. Cet article offre aussi l'opportunité de rappeler le contexte historique de l'expérience de Sagnac, qui est à l'origine de tous les gyros optiques.

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* Tel.: +33 1 30 08 88 88; fax: +33 1 30 08 88 00.

E-mail address: herve.lefevre@ixblue.com.

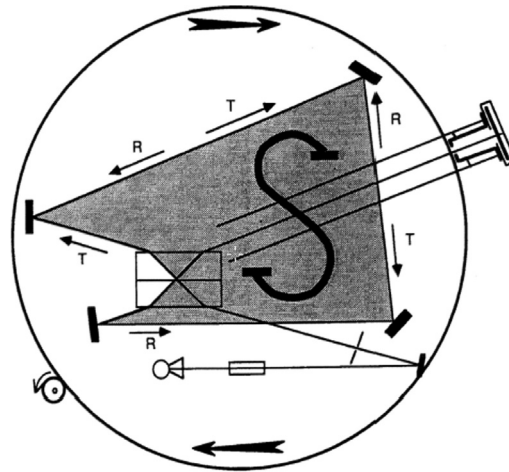


Fig. 1. Original Sagnac's setup [1] of a ring interferometer to demonstrate sensitivity to rotation rate (S stands for surface, which means "area" in French).

1. Introduction

Both optical gyroscopes, the ring-laser gyro (RLG) and the fiber-optic gyro (FOG), are based on the same Sagnac effect [1], which shows that light travelling along a closed-ring path in opposite directions allows one to detect rotation with respect to inertial space. Over one turn as in the original Sagnac's experiment, a century ago [2], the effect is extremely weak but it can be increased with recirculation in the resonant cavity of a ring laser or using the numerous loops of a fiber coil. The RLG was demonstrated only a few years after the invention of the laser in 1960, and it is based on helium–neon (He–Ne) technology. It became very successful in the 1980s and has since overcome classical spinning-wheel mechanical gyroscopes because of its improved lifetime and reliability. It also provided an excellent scale factor performance, making strap-down navigation systems possible. Earlier mechanical systems used a stabilized gimballed platform where the gyros work only around zero to stabilize the attitude of the platform; a strap-down system avoids the delicate mechanics of the gimballed approach but the gyros are attached directly to the vehicle, and then they have to follow precisely the whole dynamical range of the vehicle rotation, which requires a very good stability of the scale factor. It was clear progress over mechanical gyroscopes, but gas lasers still have several drawbacks such as high-voltage discharge electrodes that tend to wear out over the long term or the need for perfect sealing of the gas enclosure. The advent of low-attenuation optical fiber and efficient semiconductor light source developed for optical communications in the 1970s opened the way for a fully solid-state device. Then, however, the FOG was seen as an approach dedicated to medium performance, and unable to compete with the RLG for top-grade applications. As we shall see, this is not the case anymore. This paper is also the opportunity to recall the historical context of Sagnac's experiment and to outline the early theoretical contribution of Max von Laue [3].

2. Historical context of Sagnac's experiment

If Huygens proposed in the 17th century a wave theory of light, Newton imposed his views of a corpuscular theory in the early 18th century. It is only in the early 19th century that Young's double-slit experiment reopened the wave theory, knowing that it was not easily admitted: you did not contradict Newton! It required the exceptional quality of the theoretical and experimental work of Fresnel to convince the physicist community.

However, for the minds of that time, a wave needed some kind of propagation medium, as for acoustic waves. It was called "*luminiferous Aether*", and light was seen as propagating at a constant velocity c with respect to this fixed Aether.

Even when Maxwell showed in 1864 the electromagnetic nature of light wave, Aether was not questioned. It required the famous Michelson and Morley experiment in 1887 to have a clear demonstration that the concept of Aether should be revised, and this yielded, in 1905, the special theory of Relativity, when, based on earlier theoretical works of Lorentz, Poincaré, Planck and Minkowski, Einstein abandoned the concept of Aether and stated that light is propagating at the same velocity c in any inertial frame of reference in linear translation, despite its own velocity.

This revolutionary conceptual leap was very difficult to admit, and Sagnac's experiment [Fig. 1], the base of present optical gyroscopes, was actually performed to demonstrate that Aether did exist as clearly stated in the title of his publication [2]: "*The luminiferous Aether demonstrated by the effect of the relative wind of Aether in an interferometer in uniform rotation*".

Sagnac's experiment, which takes place in a vacuum (actually in air, but it can be considered as in a vacuum), can be either explained by special Relativity or classical Aether theory, and does not allow one to demonstrate which theory is right or wrong. It was explained clearly by von Laue in 1911 [3] [Fig. 2], two years before Sagnac's publication, and maybe the Sagnac effect should be renamed the Sagnac–Laue effect!

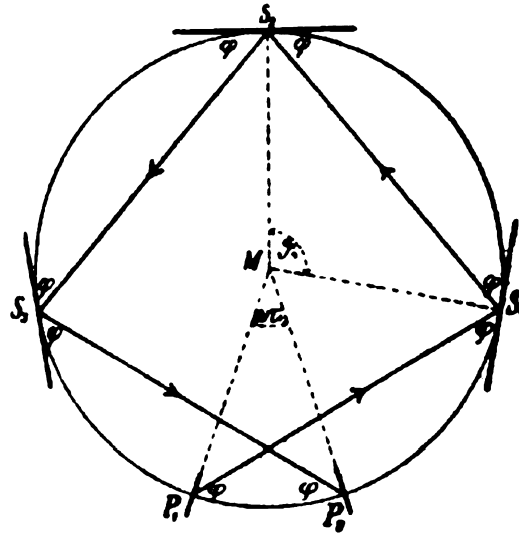


Fig. 2. Explanation of “Sagnac–Laue” effect in von Laue publication of 1911 [3].

Another important point of Aether theory was the hypothesis made by Fresnel in 1818 of the drag of Aether by matter, which was demonstrated experimentally by Fizeau in 1851 [4]. The velocity v of a wave that propagates in a medium of index n that moves at a speed v_m is not c/n anymore, but:

$$v = \frac{c}{n} + \left(1 - \frac{1}{n^2}\right)v_m \tag{2.1}$$

Note that in Fizeau’s experiment, one has to take into account the dispersion of the index, since the wave frequency seen by the medium is not the same in both directions because of the Doppler effect, but in a fiber gyro both opposite waves have the same frequency in the frame of the medium and there is no dispersion effect [5].

This Fresnel–Fizeau drag effect was explained by von Laue in 1907 [6] as resulting from the law of combination of speeds of Special Relativity:

$$v = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}} \tag{2.2}$$

where v_1 is the speed of a mobile in a frame moving at v_2 with respect to the “rest” frame, and v is the speed of this mobile in this “rest” frame. One sees that Eq. (2.2) yields Eq. (2.1) to first order in v_m , considering $v_1 = c/n$, $v_2 = v_m$ and $v_m \ll c$. The Fresnel–Fizeau drag effect is actually a relativistic effect!

The important point is that, because of the Fresnel–Fizeau drag effect, the Sagnac effect does not depend on the index of refraction of the corotating propagation medium as it was stated by von Laue [7] as early as in 1920, and as it is clearly experienced in a fiber-gyroscope [5]. If the Sagnac effect in a vacuum can be explained by Aether theory, the Sagnac effect in a medium is related to the Fresnel–Fizeau drag effect and is then also a relativistic effect.

3. What are we looking for? Single-mode reciprocity is key

Going back to present optical gyros, despite their difference of principle, RLGs and FOGs have similar theoretical noises for the same single-turn enclosed area and the same number of recirculations [8]. The typical RLG perimeter is 20 to 30 cm with on the order of 10^4 recirculations in the high-Q mirror cavity [Fig. 2]. An FOG coil of 10^4 loops of 10 cm in diameter (i.e. 3 km long and typically 3 dB of attenuation) has the same potential. Today, RLGs are in the so-called navigation-grade performance range needed for airliners, i.e. below $10^{-2^\circ}/h$ in term of long-term bias stability, while highest-performance FOGs are in the so-called strategic-grade performance range needed for very long-term marine and submarine navigation, i.e. at least ten times better, below $10^{-3^\circ}/h$. Translated in path length difference induced by the Sagnac effect, it means a relative change on the order of 10^{-18} for the RLG, and 10^{-19} to 10^{-20} for the FOG! These incredible numbers may look unrealistic, but there is the fundamental principle of reciprocity of light propagation which acts as a perfect common-mode rejection between both counter-rotating waves, when there is single-mode propagation. Because of single-mode reciprocity, the transit time of both counterpropagating waves can be perfectly balanced, leaving out only the Sagnac effect. The quality of the residual bias instability (zero instability) depends on the residual lack of reciprocity.

A detailed analysis of the principle of RLG can be found in a work by F. Aronowitz [9], one of the pioneers of this technology. The RLG has naturally “quasi-reciprocity” because it operates in a single transverse laser mode as well as a

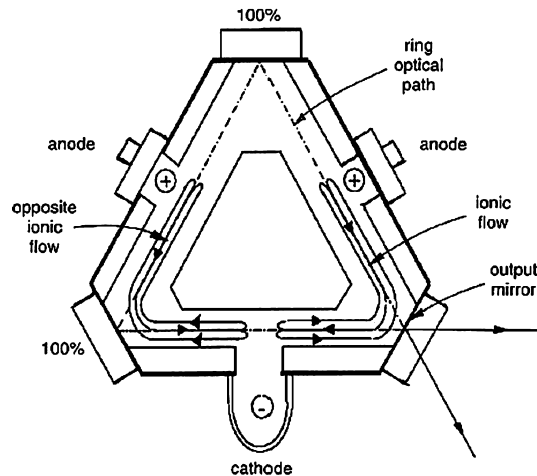


Fig. 3. Symmetrical discharge to balance. Fresnel–Fizeau drag effect due to the ionic flow in an RLG.

single longitudinal mode and the reflection birefringence of the mirrors due to the large angle of incidence ensures a single polarization in the cavity, but its reciprocity is not perfect. The electrical discharge creates an ionic flow, and because of the Fresnel–Fizeau drag effect, this matter flow yields a velocity difference between counterpropagating waves [9]. It is only on the order of 10^{-15} in terms of relative velocity, but it creates a spurious non-reciprocal effect equivalent to about $1^\circ/\text{h}$. It is counterbalanced by using a common cathode and two symmetrical anodes [Fig. 3], but this balancing cannot be perfect and there is a residual bias instability on the order of a few thousandths of degree per hour. One could think: why does not one use a solid-state laser to avoid this drag effect? After all, since the early 1960s, when the He–Ne laser gyro was invented, numerous kinds of lasers have been developed, but there is a key problem in laser behavior: mode competition! In principle, a CW ring laser should not work because both directions have the same lasing conditions and they “compete”, i.e. it is unstable. He–Ne ring lasers work because of a very subtle effect: with the flow, the moving amplifying ions see different frequencies for both opposite directions because of the Doppler effect, and the use of ^{20}Ne and ^{22}Ne isotopes with gain curves shifted in frequency allows one to get two “superimposed” lasers: one isotope amplifying one direction and the other one the opposite one, which avoids mode competition. “Magic”... but within the limit of the Fresnel–Fizeau drag-induced non-reciprocity!

In the case of FOG, reciprocity was much more difficult to get, mainly because of the residual birefringence of the fiber. As it is well known, a single-mode fiber has actually two orthogonal polarization modes that propagate with slightly different velocities because of fiber birefringence. One understands that if one direction uses one mode and the opposite one uses the crossed mode, there is a non-reciprocal phase difference. It was shown very early [10] that reciprocity does not require true single-mode propagation along the entire interferometer and that a single-spatial mode/single-polarization mode filter at the common input–output of the ring interferometer is sufficient. However, the requirement on polarizer rejection to fully suppress the problem can be very stringent. Because of coherence effects, the residual phase non-reciprocity in radian may be equal to the amplitude rejection of the polarizer [11], i.e. a very good rejection of -80 dB may yield a phase non-reciprocity as high as 10^{-4} rad, but today the problem is solved with the progress of the components and the use of decoherence [12,13]. Proton-exchanged lithium niobate (LiNbO_3) integrated-optics yields a single-polarization waveguide that provides excellent polarization rejection (as good as $-80/-90$ dB), and a polarization-maintaining (PM) fiber limits the amount of light in the crossed polarization mode, but it would not be sufficient by far. One has also to take advantage of decoherence/depolarization effects with the use of a broadband source which has a short coherence time. Because of the birefringence of PM fiber and LiNbO_3 crystal, the spurious crossed polarization propagates at a different speed from the main signal and loses its coherence with respect to this main signal, which drastically reduces the parasitic effect. To further reduce defects, one can also take advantage of the natural unpolarization of ASE (Amplified Spontaneous Emission) sources based on telecom diode-pumped EDFA (erbium-doped fiber amplifier) technology. The crossed component of the input unpolarized light (the component orthogonal to the polarizer axis) compensates for the residual nonreciprocity of the main component [12,13]. Because of the residual polarization dependent loss of the components, the actual input unpolarization is not perfect, but in practice the degree of polarization of the input ASE light is only few percent and this brings an additional 30-fold reduction of polarization non-reciprocities.

Now, light travelling in a dense medium and with high-power density because of the guidance, one could have faced nonlinear effect destroying reciprocity [14] which is based on the linearity of propagation equation, but the power fluctuation statistics of broadband source happens to balance this effect perfectly [12,13]. Today, the FOG appears as a unique sensor that could be just limited by its theoretical white photon shot noise without any source of long-term drift.

Note that the use of a low-temporal-coherence source brings excess relative intensity noise (excess RIN) because of the random intensity beating of all its spectral components. With an erbium fiber source, it can be as high as $10^{-6}/\sqrt{\text{Hz}}$, but

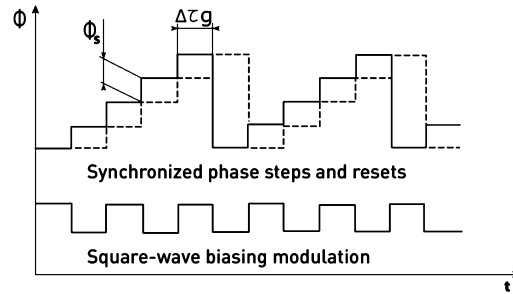


Fig. 4. Principle of digital phase ramp feedback, with $\Delta\tau_g$ being the transit time through the coil (5 $\mu\text{s}/\text{km}$), which depends on the group's velocity.

RIN can be reduced by compensation techniques [12], and it is possible to get very close to the theoretical photon shot noise, which is typically $10^{-7}/\sqrt{\text{Hz}}$ for a returning power of few tens of μW .

Finally, gyroscopes have to operate over a large dynamical range, and this requires signal processing techniques that will not degrade this intrinsic stability.

4. The other key issue: signal processing techniques

Among the advantages of RLG is its very simple read-out mechanism. As in any laser, there are an integral number of wavelengths along the cavity path. Path length difference created by the Sagnac effect induces a wavelength difference between both counterpropagating resonant beams, and therefore a frequency difference. Both output beams are recombined to interfere [Fig. 2] and yield a frequency beating that is proportional to the rotation rate. A simple counting electronics provides a linear read-out of the rate over a very large dynamical range.

Note however that at low rate, there is the so-called “lock-in” effect. Both laser beams have very close frequencies: about 1 Hz difference for $1^\circ/\text{h}$, when light frequency is 500 THz at a He-Ne operating wavelength of 633 nm. Despite impressive technological progress, there is still some residual mirror backscattering yielding coupling that locks them on the same frequency. This is eliminated by a mechanical dithering, but it increases the theoretical RLG measurement noise by an order of magnitude [9].

The FOG is not an active resonator anymore but a passive interferometer with an external light source. It is possible to get no lock-in, so no need for dithering that avoids its related noise degradation. In particular, the backscattering of a fiber is higher than the one of RLG mirrors, but the low temporal coherence of the broad-spectrum source of an FOG limit spurious interferences between this backscattered light and the primary waves. However, the raw response is the nonlinear raised cosine response of an interferometer. This has been overcome by a very efficient phase modulation technique associated with a drift-free digital demodulation and a phase feedback. This so-called all-digital phase ramp combines square-wave biasing modulation and synchronized phase steps generated and demodulated digitally [Fig. 4] [12,13,15].

This sophisticated processing approach is conceptually much more complicated than the simple frequency readout of an RLG, but it can be easily implemented with present digital electronics. It yields an excellent scale factor linearity of 1 ppm without any degradation of the basic noise or the reciprocity of the interferometer, and it works without quantization error despite a limited number of converter bits, because of averaging effects [12,15].

Bias noise and drift are calculated with Allan variance (or deviation, its square root) [12,16] and, in a temperature stabilized environment, a high-performance FOG does yield the theoretical $-1/2$ power reduction slope of a white noise over days of measurement without any visible bias stability limitation (no flicker, no rate random walk), down to the $10^{-5}^\circ/\text{h}$ range, corresponding to an interferometer phase difference close to 10^{-10} rad, and with a white noise below $10^{-2}(\circ/\text{h})/\sqrt{\text{Hz}}$, which corresponds to an angular random walk in the $10^{-4}^\circ/\sqrt{\text{h}}$ range, and a phase noise of few 10^{-7} rad/ $\sqrt{\text{Hz}}$. This is absolutely unique, compared to any other inertial sensors, as accelerometers or mechanical and laser gyros, which all face long term drift, even in a temperature-controlled environment.

There is a residual temperature dependence in FOG that is related to the so-called Shupe effect [12,17] due to temperature transient. However, symmetrical winding techniques [18] as well as careful modeling reduce very significantly the effect. Typical long-term bias stability specification for a high-performance FOG is in the range of a few $10^{-4}^\circ/\text{h}$ in an unstabilized temperature environment.

The scale factor varies also in temperature. It depends on the geometrical area of the gyro coil and on the wavelength. Temperature modeling allows one to get a reproducible stability of the coil size to an accuracy of 10 ppm, and wavelength stability may be improved to this same 10 ppm value with internal spectral filtering of an erbium-doped fiber source [12].

5. Configuration of an FOG

Based on solid-state technologies of optical-fiber communications, the FOG yields a high reliability and a very long life time in addition to its performance. It is composed of (Fig. 5; see for example [12,13]):

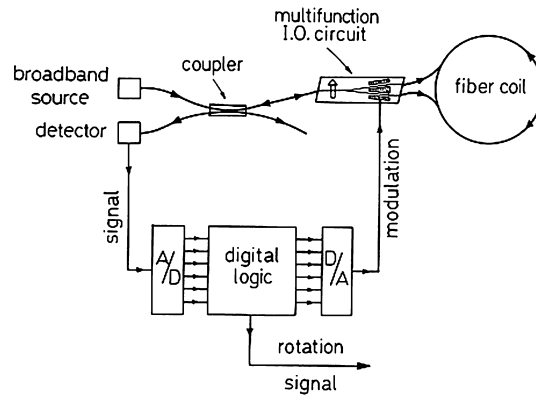


Fig. 5. Configuration of an FOG with a Y junction as the splitter and recombiner of the interferometer, a polarizer and a pair of electro-optic phase modulators on the multi-function LiNbO₃ integrated-optic circuit.



Fig. 6. (Color online.) iXBlue MARINS inertial navigation system ($400 \times 300 \times 280 \text{ mm}^3$) using gyro coils of 3 km over a mean diameter of 170 mm. The bias stability specification of the gyros over environment is $5 \times 10^{-4} \text{ }^\circ/\text{h}$, and the scale factor specification is 10 ppm.

- a broadband source based, for high grade, on EDFA technology at a wavelength of 1550 nm; wavelength stability may be obtained with internal spectral filtering with a fiber Bragg grating,
- a polarization-maintaining (PM) fiber coil (a few hundred meters for medium grade to several kilometers for very high grade),
- a LiNbO₃ integrated-optic circuit with electrodes to generate phase modulation with the electro-optic Pockels effect and that provides excellent polarization selectivity with proton-exchanged waveguide,
- a fiber coupler (or a circulator for higher returning power) to send to a detector light returning from the common input-output port of the interferometer;
- an analog–digital (A/D) converter to sample the detector signal;
- a digital logic electronics that generates the phase modulation and the phase feedback through a digital-to-analog (D/A) converter.

It is important to note that with the adequate design and components, the performance of an FOG is very reproducible in production, even for the high-performance end. It does not require trimming or selection.

Testament to the quality, accuracy and reliability of the fiber-optic gyro is its growing use for positioning and navigation instruments in navy [Fig. 6] and space [Fig. 7] applications.

As already discussed, the residual limit of FOG bias stability is the temperature transient, and Fig. 8 shows a promising laboratory result of longitude error of an iXBlue prototype of inertial navigation system that was performed “at rest” in a temperature-stabilized environment over more than one month (38 days). The longitude accuracy is in the range of one

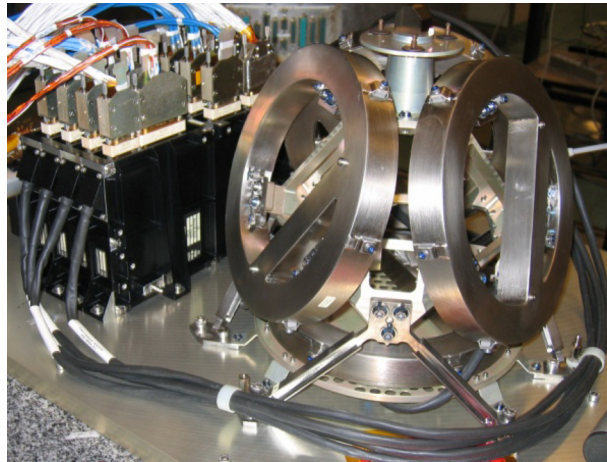


Fig. 7. (Color online.) Four-axis (for redundancy) FOG developed by iXSpace, an iXBlue company, in cooperation with Airbus Defence & Space (formerly EADS-Astrium) for space applications; the gyro coils are 5 km long over a mean diameter of 170 mm. Bias and scale factor specifications are similar to the ones of MARINS gyros.

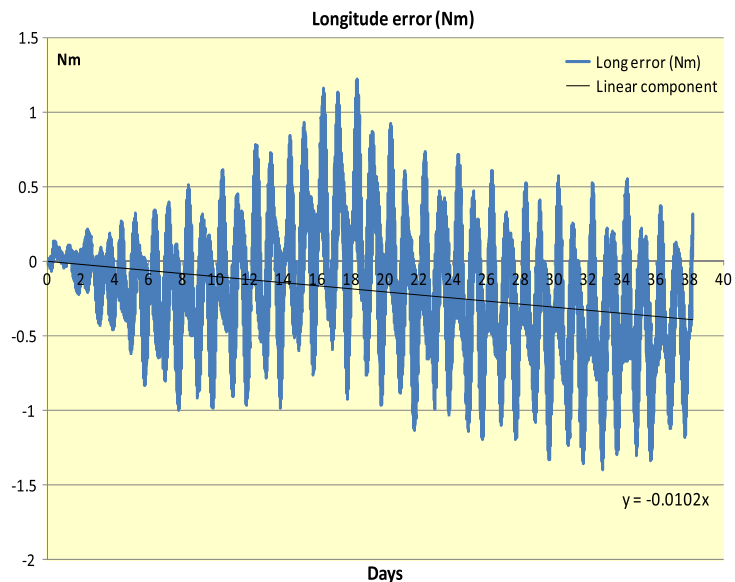


Fig. 8. Longitude error of iXBlue's inertial system prototype, in a temperature controlled environment, over 38 days: 1 nautical mile (Nm) per month.

nautical mile (Nm) over one month! It corresponds to a gyro bias stability of about $10^{-5} \text{ }^\circ/\text{h}$ and a gyro scale factor stability of about 1 ppm!

Understanding this result requires some explanations about inertial navigation. An inertial navigation system (INS) calculates the trajectory with respect to inertial space with the mathematical integration of the measurements of the rate of rotation by the gyros and of the acceleration by the accelerometers. Note that mathematical integration is similar to averaging and then it filters out short-term noise to keep only the effect of the long-term drift.

“At rest” with respect to the Earth means actually to follow the movement of rotation of the Earth, which is quite fast. At the latitude of 48° where the experiment was performed, the tangential velocity due to the Earth's rotation is 1100 km/h and it is measured by the gyros. Over the 38 days of the experiment, the system “at rest” travelled in fact over one million of kilometers, and its position in longitude is known by the integration of the tangential speed measured with the rotation rate. The linear component of the mean position drift being less than half a nautical mile (i.e. about one kilometer) over one million of kilometers, it means the measurement of the $15^\circ/\text{h}$ of Earth rotation rate is performed with a relative stability of one millionth, i.e. a $1.5 \times 10^{-5} \text{ }^\circ/\text{h}$ error combining bias and scale factor. The gyro fiber coils of this experiment being 3 km long over a diameter of 200 mm and the wavelength being 1550 nm, this $1.5 \times 10^{-5} \text{ }^\circ/\text{h}$ error correspond to a phase difference error of only 5×10^{-10} rad. Compared to the absolute phase of 2×10^{10} rad accumulated over 3 km of propagation in the fiber coil, it yields a relative stability of 2.5×10^{-20} !

There is also a 24 h oscillation in this experimental result: the modulus of the measurement of the Earth rotation rate vector by the gyro triad yields, as we just saw, the linear part of the drift, but there is also a residual error in the measured direction of the axis of this Earth rotation rate vector. At rest with respect to the Earth, the measured inertial movement should follow a circle with always the same latitude, but with an orientation defect, this measured circle will become slightly tilted yielding a 24-h oscillation of the position error in latitude and longitude. This error is bounded and then it is not as harmful as the linear component of the drift in longitude that grows continuously over time.

6. Conclusion

Entering production in the 1980s, the RLG has revolutionized inertial techniques, and it is clearly the technology of reference today. However, its limited lifetime and its need for dithering have motivated the development of FOG technology based on a fully solid-state approach. Theoretical performance is similar for both technologies, but it has been more difficult for FOG to obtain it. It started as a product for medium grade ($1^\circ/\text{h}$ range) applications in the 1990s [19]. However, with the development of fiber-optic communications components and digital signal processing techniques, it was shown that the FOG not only brings the expected improvement of lifetime, but does not face the performance limitation of the RLG in terms of noise and bias stability.

Today there is a clear change of mind, and the FOG is not seen any more as limited to medium grade, as presented during the last OFS (Optical Fiber Sensor) Conference [20] by Northrop Grumman, Honeywell and iXBlue. As shown in this paper, it even has the potential to become the “ultimate-performance” gyro that can surpass by at least one if not two orders of magnitude RLG technology. Results in a temperature-controlled environment are already impressive and the final challenge is to obtain this performance without this thermal control!

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