The Sagnac Effect

The story of an experiment that might have kept Einstein awake at night—but that paved the way for the dawn of optical gyroscopes and that could enable future gravitational-wave detectors.
A team led by the Technological University Munich recently used the Sagnac-effect-enabled ring-laser interferometer G at the Geodetic Observatory Wettzell to measure Earth’s rotation with unprecedented precision.

A. Eckert / TUM
More than a century ago, George Sagnac—an ardent advocate of the concept of “absolute space”—challenged Einstein’s theory of special relativity, employing data from his meticulously crafted loop interferometer to scrutinize and question Einstein’s ideas. Einstein remained silent in response, andironically, as subsequent events unfolded, Sagnac’s interferometer itself eventually proved a testament to the validity of Einstein’s theories.

Yet this early rivalry between Sagnac and Einstein bore unexpected fruit. It gave rise to modern optical gyroscopes—presenting, in turn, a multitude of applications in technology and fundamental sciences ranging from precision navigation to geophysics to the potential for next-generation gravitational-wave detectors. This feature looks at how the early controversy surrounding the “Sagnac effect” reverberates in science and applications today.

Of transformations and relativity
At the turn of the century, two fundamental laws of physics ruled supreme: Newton’s laws, governing mechanics, and Maxwell’s equations, which described the principles of electromagnetism. Newton’s laws treated space as absolute, with time considered an additional parameter and so-called Galilean transformations defining the transformation of space and time between two inertial frames. In contrast, Maxwell’s equations treated time and space as intertwined, with Lorentz transformations elucidating how different observers perceive electromagnetic phenomena.

Einstein’s profound insight was driven by the conviction that there must be a unified set of transformation laws encompassing both mechanical particles and electromagnetic phenomena. In 1905, he introduced the theory of special relativity, elevating space and time to equal standing. Central to Einstein’s concept was the assertion that all moving observers measure the same speed of light, a value intrinsically linked to nature’s fundamental constant found in Lorentz transformations.

This unifying theory had the notable advantage of explaining the null results of the 1887 Michelson–Morley experiment. Instead of replicating that experiment, he chose to construct a different interferometer to test the concept of absolute space.

In Sagnac’s loop interferometer, a light source was split through a beam splitter, and the light traveled both clockwise and counterclockwise through the loop. The two beams were then recombined at the beam splitter, creating an interference fringe. Sagnac contended that light in a rotating loop interferometer should experience speeds of \( c_0 + R \Omega \) and \( c_0 - R \Omega \), where \( R \) is the loop radius and \( \Omega \) is the rotation rate. This challenged Einstein’s special-relativity rule of velocity addition. Sagnac calculated that the difference...
in travel time for a single trip around the loop would be \( \Delta t_{\text{Sagnac}} = \frac{4A}{c_0^2} \Omega \), resulting in a fringe shift \( \Delta \phi_{\text{Sagnac}} = \frac{8\pi A}{c_0 \lambda_0} \Omega \), where \( A \) is the area of the loop and \( \lambda_0 \) is the wavelength of light in vacuum. In 1913, Sagnac successfully demonstrated the fringe shift in his constructed interferometer, in accordance with his formula—thereby challenging the principles of special relativity.

The Sagnac experiment sparked a significant debate within the scientific community. Aligning as it did more with the concept of absolute space, it stood in opposition to the results of the renowned Michelson–Morley experiment, which had lent support to Einstein’s special relativity and to the rejection of the ether and absolute space. Proponents of absolute space, who of course largely found vindication in Sagnac’s results, outnumbered those supporting Einstein. Sagnac, resolute in his position, authored additional papers championing the ether theory and, in a surprising turn of events, was awarded a prize in 1919 for challenging Einstein’s prevailing theory.

### Explaining the Sagnac effect

The controversy persisted until 1920. Then, Max von Laue demonstrated that applying Einstein’s formula for the addition of velocities under special relativity actually resulted in Sagnac’s formula, effectively reconciling the Michelson–Morley and Sagnac experiments—a triumphant moment for Einstein.

Typically, relativistic effects are associated with the motions of objects traveling at high velocities, such as particles in accelerators, satellite/GPS systems or the movement of inner electrons in heavy elements. However, von Laue’s analysis unveiled the Sagnac effect as a unique instance in which relativistic effects become observable even at low speeds. This revelation broadened physicists’ understanding of the application and manifestation of relativistic phenomena, challenging conventional expectations and contributing to the evolving landscape of scientific knowledge.

In 1921, Paul Langevin demonstrated that the Sagnac effect was compatible not only with Einstein’s special relativity, but also within the theoretical framework of his general relativity—thereby bolstering the case for the latter theory as well. The comprehensive analysis of Langevin and von Laue not only provided substantial support for Einstein’s ideas but also brought forth a crucial revelation. Langevin’s work illuminated the fact that the derived Sagnac time-delay formula between counterrotating waves remained unaffected by the nature of the propagating medium, be it air or glass. Importantly, this consistency in time delay persisted as long as the enclosing area remained the same.

Despite the profound significance of von Laue’s and Langevin’s analyses, their findings have not garnered universal appreciation, even among a few contemporary researchers. Some erroneously suggest that employing slow-light media in a Sagnac interferometer (such as a gyroscope) could significantly enhance its sensitivity. A crucial point, however, is that the \( c_0 \) in Sagnac’s expression does not signify the speed of a wave around an interferometer; rather, it represents nature’s fundamental constant—an unalterable quantity, independent of the medium through which the wave propagates. This clarification underscores the intrinsic nature of \( c_0 \) as a constant, unaffected by the medium’s properties. And that, in turn, debunks the misconception surrounding the potential enhancement of sensitivity through alterations in wave speed within the interferometer.

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Rediscovering Sagnac: The optical gyroscope

The early-20th-century activities involving Sagnac interferometers remained a scientific curiosity for nearly four decades. But a resurgence of interest then began with the invention of the helium–neon (HeNe) continuous-beam gas laser at Bell Laboratories by Ali Javan in December 1960. Shortly thereafter, in 1963, W.M. Macek and D.T.M. Davis introduced a gain medium (HeNe tube) into a ring cavity, marking the first operational laboratory demonstration of a ring-laser gyroscope (RLG) based on the Sagnac effect.

The RLG rests on the fact that, in a rotating ring-laser-cavity platform, the Sagnac time delay between clockwise (cw) and counterclockwise (ccw) directions leads to distinct oscillation frequencies. The disparity in frequencies is directly proportional to the rotation rate: \( f = \frac{4A}{\lambda P} \Omega \), where \( A \) is the ring area and \( P \) is the ring perimeter.

Although the RLG demonstrated by Macek and Davis functioned effectively at high rotation rates, the cw and ccw frequencies were locked (zero frequency difference) at low rates—a phenomenon known as the dead zone. It took another three decades, spanning the 1990s, to address and resolve the dead-zone issue and other associated challenges, transforming the RLG into a commercially viable product. RLGs boast the advantage of having no moving parts; that, coupled with their compact size, helped them emerge as a compelling alternative to mechanical gyroscopes for navigation applications. Today, commercial navigation-grade RLGs are available, albeit at a relatively high cost.

The development of optical fibers, lasers, modulators and detectors for optical communications during the 1970s inadvertently paved the way for the emergence of fiber optic gyroscopes. In 1977, V. Vali and R. Short-hill demonstrated a Sagnac fringe shift between cw and ccw rotations in a 950-m fiber loop, marking the onset of a new era for these gyroscopes. In the United States, H.J. Shaw at Stanford University and S. Ezekiel at the Massachusetts Institute of Technology (MIT) spearheaded research on fiber optic gyroscopes. Two distinct designs emerged: the interferometric fiber optic gyroscope (IFOG) and the resonating fiber optic gyroscope (RFOG).

In IFOGs, light traverses the sensing optical loop across a long distance (for example, 1 km) in both directions only once, and the platform’s rotation rate is deduced from interferometer fringe shifts. Due to the small path differences between cw and ccw beams, broadband light sources like EDFA-amplified spontaneous emission or light-emitting diodes can be used in IFOGs. In contrast, RFOGs resemble a fiber resonator; they feature a much shorter fiber length (for example, 10 m), but light circulates around the loop perhaps 100 or more times. Consequently, RFOGs necessitate a narrow, single-frequency laser source with a long coherence length to probe cw and ccw resonances, measuring the difference in resonance frequencies proportional to the rotation rate in a manner similar to RLGs.

In the early days, when fiber was expensive, RFOGs held a potential cost advantage over IFOGs. During my tenure at the Charles Stark Draper Laboratory in Cambridge, MA, USA, I was involved in projects related to both platforms. I learned that IFOGs exhibit far less sensitivity to fiber imperfections, such as inhomogeneity, backscatter, anisotropy, polarization cross-coupling and nonlinearity (Kerr effect), than RFOGs. IFOGs thus outperform RFOGs by orders of magnitude and, not surprisingly, have become work-horses among modern gyroscope instruments. IFOGs have even surpassed RLGs in precision, reliability and cost for precision navigation, emerging as the dominant choice in high-performance commercial applications today.
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From drone navigation to general relativity
The detection of rotational motions, such as that performed by optical gyroscopes, encompasses a wide range of applications. These include navigation for self-driving vehicles, flying platforms and space operations; platform stabilization for cameras and drones; pointing and tracking, especially in laser optical communications; control of robotic movements; monitoring rotational ground movements triggered by earthquakes; assessing vibrations in buildings; forensic seismology to detect nuclear detonations; precise measurement of Earth’s rotation rate and wobble, enabling ultra-precise navigation; scientific experiments to study general relativity; and other uses.

Given these widespread applications, there has been a push toward integrating IFOG optical components to enhance performance, reduce costs and facilitate mass production. Modern high-performance IFOGs have successfully incorporated the beam splitter, polarizer and phase modulator into a single lithium niobate chip. Progress in IFOG integration is still ongoing, however, with some companies actively exploring silicon technology to imprint all IFOG components (except the light source), including the coil—equivalent to tens of meters of waveguides—onto a single chip.

Notwithstanding this drive for integration and miniaturization, very precise, sensitive and consistent, large-area optical gyroscopes play an essential role in fundamental science and seismology projects. Several notable large-area optical-gyroscope projects exist worldwide. These include GINGER (Gyroscope IN General Relativity), situated in the underground Gran Sasso laboratory in Italy; the Technological University of Munich (TUM) 4x4-m G gyroscope at the Geodetic Observatory Wettzell in Germany; the

IFOGs: The “minimum configuration”
An example from navigation gives a flavor of the minuteness of the Sagnac effect—and the design considerations required for an interferometric fiber optic gyroscope (IFOG).

Suppose a rotation-rate resolution of 0.01 deg/hr is sought for aircraft navigation. Using a 100-meter fiber wound on a 10-cm sense coil, with an effective area of \(N(\pi R^2) = 2.5 \text{ m}^2\), the calculated Sagnac delay time would be \(\Delta t_{\text{Sagnac}} = 5.4 \times 10^{-24} \text{ s}\). This corresponds to a path difference \((c_0 \times \Delta t_{\text{Sagnac}})\) of \(1.6 \times 10^{-15} \text{ m}\)—a scale comparable to the diameter of a proton (~\(1 \times 10^{-15} \text{ m}\)).

Hence, it is crucial in an IFOG that the clockwise- and counterclockwise-rotating beams encounter the same environment. This so-called reciprocity condition is indispensable for extracting the subtle Sagnac time delay; ideally, the Sagnac shift should be the sole nonreciprocal effect in the IFOG, offering a direct indication of the platform’s rotation rate. The navigation accuracy of an IFOG correlates with the degree to which reciprocity is maintained—a factor that has led to an IFOG design known as the “minimum configuration.”

Illustration by Phil Saunders
9×9-m ROMY (Rotational Motion in SeismologY) at the Geophysical Observatory of Bavaria; the 2.5×2.5-m ERI (Ernest Rutherford I) at the University of Canterbury in New Zealand; and the Huazhong University of Science and Technology’s HUST-1 gyroscope in Wuhan, China, a passive 3×3-m interferometer that is part of the TianQin spaceborne gravitational-wave observatory.

While all of these large-area optical gyroscope projects demonstrate a spirit of collaboration, each project is tailored to a specific mission. For instance, ROMY focuses on global seismology, the dynamics of volcano interiors and the origin of Earth’s ocean-generated noise field, among other objectives, while the TUM G gyroscope recently measured Earth’s rotation and wobble with unprecedented precision. GINGER’s primary mission, meanwhile, is to act as a ground-based laboratory to test general relativity.

According to Einstein’s predictions, the presence of a massive object produces two distinct effects: a gravito-electric effect that warps space, resulting in precession of a gyroscope as it orbits the massive object (also known as the geodetic effect or de Sitter effect); and a gravito-magnetic effect that depends on the angular momentum of a spinning mass. In the realm of general relativity, the gravito-magnetic effect (referred to as the Lense-Thirring effect or frame dragging) predicts that spinning massive objects drag spacetime along with them, in a manner analogous to a blender’s drag on the surrounding fluid. This dragging phenomenon induces precession in a gyroscope within the reference frame of distant stars.

Both the gravito-electric and the gravito-magnetic effects have been experimentally validated through the Gravity Probe B program conducted by NASA, a five-decade, US$750 million experiment that employed a satellite equipped with multiple spinning mass mechanical gyroscopes. Notably, Gravity Probe B was strategically placed in a polar orbit, ensuring that the precession resulting from the gravito-electric and gravito-magnetic effects occurred at right angles to each other—and, in turn, allowing for independent measurement of each effect. Gravity Probe B measured a geodetic effect of $2.09 \times 10^{-7}$ deg/hr (6602 milliarcsec/year) and a frame-dragging effect of $1.18 \times 10^{-9}$ deg/hr (37.2 milliarcsec/year), in close agreement with general relativity. In the 2023 progress report, the GINGER team claimed to have achieved better than $1 \times 10^{-8}$ deg/hr sensitivity in its RLG, bringing it to the brink of Earth-based testing of general-relativity effects.

Next-generation GW detection

Perhaps the crown jewel of new applications for the Sagnac interferometer could lie in gravitational-wave (GW) detection—the drive to capture ripples in spacetime. Facilities such as the Laser Interferometer Gravitational-wave Detector (LIGO) in the United States and Virgo in Europe have already brought about a revolution in astronomy, offering unprecedented insights into the universe and gathering data previously unattainable in terrestrial settings. These detectors, employed in “multimessenger astronomy,” have revealed that heavy elements such as gold and platinum are formed in neutron star collisions. Moreover,
The matching propagation speeds of gravitational and electromagnetic waves, with a precision of one part in $10^{15}$, have allowed for independent measurements of the Hubble cosmological constant.

GW detectors have also facilitated tests of general relativity, observations of compact binary coalescences (for example, of black holes and neutron stars) and the study of nuclear matter in extreme environments governed by quantum chromodynamics—all areas otherwise inaccessible in terrestrial laboratories. Furthermore, GW detection provides a unique avenue for exploring the Big Bang, which remains beyond the reach of sensors in the electromagnetic domain. And there is the potential for the discovery of exotic stars, leading to encounters with previously unknown physics and natural phenomena.

Currently, Michelson interferometers—exemplified by LIGO (with 4-km interferometer arms) and Virgo (with 3-km arms)—are central to GW detection. Next-generation GW detector projects now underway include Cosmic Explorer (CE), a US project for an L-shaped Michelson interferometer with 40-km arms; and Europe's Einstein Telescope (ET) project, whose plan envisions three detectors arranged in a triangular configuration. Each of the ET's three detectors would comprise two 10-km-arm Michelson interferometers, strategically positioned underground—one designed for low-frequency and the other for high-frequency GWs.

Proposals have also been made, however, to bring a zero-area free-space Sagnac interferometer into the GW-detector mix. Such an interferometer would be intentionally designed to be insensitive to rotation while retaining the ability to detect GWs. As early as 1996, researchers at Stanford University, USA, including Ke-Xun Sun and colleagues, argued that Sagnac interferometers would offer advantages over Michelson interferometers for GW detection, including insensitivity to laser frequency instability, mirror displacement, parasitic birefringence, power disparity in interferometer arms and optical quantum back action (quantum radiation pressure noise). Moreover, Sagnac interferometers would exhibit higher sensitivity in frequencies of interest compared with their Michelson counterparts.

At present, given the availability of the relevant optical components, the Michelson configuration offers cost advantages relative to Sagnac interferometers. However, in view of the other advantages of Sagnac interferometers, they could well replace Michelson interferometers for future generations of GW detectors, if the ongoing development of new optical components can make the Sagnac variety more cost-competitive.

Such a development would add yet another touch of irony. Sagnac’s effort to disprove Einstein’s theory of special relativity ended up playing a pivotal role in affirming the validity of that very theory. Now, Sagnac interferometers are on the brink of contributing to better detection of gravitational waves, thereby further confirming general relativity. Einstein’s contributions to physics thus endure as a beacon, casting light on our understanding of the universe in unexpected and profound ways. And the echoes and legacies of past debates and intellectual battles continue to shape the landscape of modern physics and technology.

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References and Resources