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

The centennial of the Sagnac experiment in the optical regime: From a tabletop experiment to the variation of the Earth's rotation

Le centenaire de l'expérience de Sagnac en régime optique : d'une expérience de laboratoire à la variation de la rotation de la Terre

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ABSTRACT

The investigation of non-reciprocal behavior of optical beams in a rotating reference frame was the main motivation of the historic tabletop experiment of George Sagnac. His ground-breaking experiment was extended to a very large installation more than a decade later, which was sensitive enough to allow Michelson, Pearson and Gale to resolve the rotation rate of the Earth by an optical interferometer. With the advent of lasers in the early sixties of the last century, rotating laser cavities with a ring structure demonstrated superior performance and very soon matured to a point where mechanical gyroscopes were quickly superseded by laser gyroscopes in aircraft navigation. When vastly upscaled ring lasers were taken back to the laboratory at the end of the 20th century, the goal of applying the Sagnac effect to geodesy for the monitoring of tiny variations of Earth's rotation was the main motivation. The large-ring laser G, which is the most stable instrument out of a series of instruments built by the New Zealand–German collaboration, routinely resolves the rotation rate of the Earth to better than eight orders of magnitude. Since G is directly referenced to the Earth rotation axis, the effect of diurnal polar motion, the Chandler and the Annual wobbles as well as tilts from the solid Earth tides can be found in the interferogram obtained from the ring laser. G has also demonstrated high sensitivity to rotations associated with seismic events. The toroidal eigenmodes of the Earth when they are excited by large earthquakes have been resolved. A surprisingly large amplitude has been measured for Love wave signals contained in the microseismic background signal. This paper summarizes the recent development of highly sensitive large Sagnac gyroscopes, and presents unique results from the measurements of rotations of the earth.

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RÉSUMÉ

La recherche sur le comportement non réciproque des faisceaux optiques dans un référentiel tournant était la motivation principale de l'expérience historique de George Sagnac. Son expérience révolutionnaire à été étendue à une installation beaucoup plus grande plus d'une décade plus tard, avec une sensibilité suffisante pour permettre à Michelson, Pearson et Gale de déterminer la vitesse de rotation de la Terre à l'aide d'un interféromètre optique. Avec l'arrivée des lasers au début des années 1960, des cavités laser en anneau tournantes ont montré des performances supérieures et ont très vite atteint un niveau de maturité permettant à des gyro-lasers de surpasser les gyroscopes mécaniques dans le domaine de la navigation aérienne. Les lasers en anneau de très grandes dimensions ont repris le chemin des laboratoires à la fin du vingtième siècle, avec comme motivation principale l'utilisation de l'effet Sagnac pour la géodésie, afin d'accèder à de minuscules variations de la rotation de la Terre. Le laser à large anneau G, qui est l'instrument le plus stable parmi toute une série d'instruments construits dans le contexte d'une coopération germano-néo-zélandaise, résout régulièrement la vitesse de rotation de la Terre jusqu'à mieux que huit ordres de grandeur. Puisque G se réfère directement à l'axe de rotation de la Terre, l'effet du mouvement polaire diurne, le mouvement de Chandler et l'oscillation annuelle comme les inclinaisons des marées solides à la surface terrestre apparaissent dans l'interferogramme obtenu à partir du laser en anneau. G s'est aussi révélé avoir une grande sensibilité aux rotations associées aux événements sismiques. Les modes propres toroïdaux de la Terre, lorsqu'ils sont excités par des tremblements de terre de grande ampleur, ont été résolus. Une amplitude étonnamment grande a été mesurée pour des signaux d'ondes de Love contenus dans le bruit de fond micro-sismique. Cet article résume le développement récent de grands gyroscopes de grande sensibilité, et présente des résultats uniques pour ce qui est de la mesure des rotations de la Terre.

1. Introduction

Highly sensitive rotation sensing has a wide range of applications. These reach from very basic controls in robotics up to complex aircraft maneuvers based on high performance inertial navigation in real time. The available sensors for this purpose also cover a wide range. In the simplest case, they comprise two mechanical parts that move at some angular velocity with respect to each other, such as a lever in a gearbox. In robotics and telescope control, where this concept is applied, one usually finds encoders that count increments of angles. The great advantage of such encoder systems is their long-term stability for the measurement of angles. This stability results from the rigid link for the relative rotation of two mechanical parts with respect to each other. On the other hand, the movement of a pendulum in an inertial space that senses Coriolis forces, such as the trajectory of a Foucault pendulum on a rotating Earth, does not have such a rigid link and the measurement is subject to perturbations caused by friction and other small experimental imperfections. The very large optical Sagnac interferometer, set up by Michelson, Pearson and Gale [1], pointed into a new direction. It demonstrated the capability of a strapped-down optical system to observe rotation rates as low as 15° per hour to an accuracy of about 2%. The high-end regime of modern rotation sensing finally is marked by highly sensitive optical Sagnac interferometers, such as the fiber optic gyroscopes (FOG) or the ring lasers (RLG). These devices outperform a mechanical pendulum by many orders of magnitude. Although superior to a pendulum, a FOG or RLG only measures rotation rates and their most significant limitation is their long-term stability. While a navigation gyro in an airplane integrates rates of angular motion over short periods of time only, much more demanding applications, such as the precise estimation of the orientation of the instantaneous Earth rotation axis in space, are required in space geodesy.

A network of radio telescopes routinely measures the relative orientation of these telescopes with respect to distant quasars interferometrically two times per week. This generates a precise estimate of the rate of rotation of the Earth and the orientation of the rotational axis. It would be very desirable to support this measurement effort with a number of autonomously operated strap-down gyroscopes, rigidly attached to the Earth's crust. While the telescopes of the International VLBI Service (IVS) [2] can resolve about 100 µs out of a total of 86400 s in length of day and the long-term stability of the measurement is given by the rigidity of the quasar constellation, large ring lasers have the sensitivity to perform to the same level of resolution, but not yet to the necessary long-term stability. However, they are much easier to operate and they do not require elaborate handling of large data volumes, including physical transport of storage media. In addition, unlike the other geodetic space techniques, such as Satellite and Lunar Laser Ranging (SLR/LLR), VLBI and the Global Navigational Satellite Systems (GNSS), ring lasers are referenced to the instantaneous axis of rotation of the Earth. Combining the inertial rotation measurement approach with the state-of-the-art measurements of the VLBI technique may eventually provide a ground-based assessment of the Lense–Thirring frame dragging process [3,4].

2. Active Sagnac interferometers

With the development of the laser in 1960 came the opportunity to move Sagnac interferometry from phase to frequency measurement, with a vast concomitant improvement in sensitivity. The first ring laser that operated as an inertial rotation sensor (albeit on a laboratory turntable) was reported by Macek and Davis [5] in 1963, exploiting the 1.15 μm line of the helium–neon (He–Ne) gain medium. The ring laser equation is given by [6,7]:

$$\delta f = \frac{4A}{\lambda P}\mathbf{n} \cdot \boldsymbol{\Omega} \tag{1}$$

with δf the beat note obtained from the two counter-propagating laser beams in the cavity after superposition in a beam-splitter behind one of the turning mirrors. A is the area enclosed by the optical signal, P the corresponding perimeter, λ the wavelength of the optical beam, $\mathbf{n}$ the normal vector to the plane of the laser and $\boldsymbol{\Omega}$ the rate at which the entire apparatus is rotating. This beat frequency is usually referred to as the '*Sagnac frequency*'. Laser gyroscopes are highly attractive navigational tools, as unlike mechanical gyros they have no moving parts. Modern aircraft navigational gyroscopes are commonly He–Ne lasers operated at a wavelength of 632.8 nm and usually have an area $< 0.02\ \text{m}^2$ corresponding to a perimeter of 30 cm or less, ensuring single longitudinal mode operation. The typical sensitivity of such devices is around $5 \times 10^{-7}\ \text{rad/s}/\sqrt{\text{Hz}}$.

Small laser gyros have a tendency at very low rotation rates for the two beams to frequency-lock (known as lock-in), and this is usually overcome by mechanical angular dithering. By contrast, the first large ring laser gyroscope to unlock solely on Earth rotation was the 0.748-m^2 Canterbury-I ring laser (C-I) situated in Christchurch, New Zealand [8]. It was a planar, essentially square geometry, filled with cold He–Ne gas and defined entirely by dielectric 'super' mirrors having a nominal reflectance of 99.9985%. A square ring configuration was chosen to optimize the signal-to-noise ratio, but also because of an expectation of reduced backscattering for mirrors used at 45° angle of incidence. Excitation occurred within a small glass capillary having no Brewster windows, thereby minimizing optical losses. In this early design, the required thermo-mechanical stability was achieved by placing the mirrors on super-invar holders, themselves attached to a 1-m^2 Zerodur plate. Yielding a Sagnac frequency of 76 Hz, this device only rotation sensed for short periods due to its initial location in a high-rise building and the early-generation super-mirrors employed. Ultimately, it was shifted to an old war-time bunker in the Christchurch suburb of Cashmere, the Cashmere Caverns facility. Its operation was a tremendous step forward and the technical advances employed in this early prototype underpin the state-of-the-art ring lasers in use today. In particular, the gain starvation approach within an over-pressured (2–8 Torr) cavity ensured operation on a single longitudinal laser mode. This technique utilizes the pressure induced homogeneous line broadening to reduce the curvature of the gain profile at its most strongly saturated point, which in turn allows weak saturation to persist to higher powers than it otherwise would [9].

The ring lasers developed after C-I used progressively larger perimeters. The first to have a monolithic construction was the C-II device [10], which was constructed entirely from Zerodur (by Carl-Zeiss) and rigidly attached to the local bedrock in the Cashmere Caverns in 1997. The optical beam path is drilled into the neutral plane of the Zerodur slab, so that an area of 1 m^2 is circumscribed by the counter-propagating laser beams. All four corners are beveled and polished so that ULE disks with optically contacted super mirrors can be wrung onto the laser body in order to generate a pre-aligned closed light path. Utilizing improved supermirror technology yielded a cavity Q of 8×10^{10} with a vast improvement in stability afforded by its monolithic design. Once enclosed in an ambient pressure stabilizing vessel, this ring laser structure detected already signals from solid Earth tides, exacerbated by ocean loading on the Banks Peninsula [11]. In the same year, when C-II was commissioned, the 12.25-m^2 G-0 ring laser was set up as a proof of concept for the already designed, but not at that stage constructed, German 'Gross-ring'. G-0 was only intended to demonstrate operation on a single longitudinal laser mode for an upscaled device with a significantly smaller FSR. However, it contained many design features that were be reused in later heterolithic rings, including a folded lever system which allowed for optical alignment of each cavity mirror to within ±10 seconds of arc [12]. Ultimately, the success of G-0 as an operational laser gyroscope removed the last hurdle for a more ambitious project.

The Gross-Ring (or G) is a 16-m^2 monolithic ring laser constructed from the largest available piece of Zerodur. G is housed in a purpose-built underground laboratory at the Geodetic Observatory Wettzell near the Bavarian–Czech border in southern Germany [13]. As with the C-II laser the supermirrors are optically contacted, in this case to four Zerodur bars that form an X-shape, which defines the four-by-four meter perimeter of the ring. Having temperature and ambient pressure control, coupled with state-of-the-art supermirrors (the Q is 3.5×10^{12}) and unparalleled stability, G yields the best overall rotation sensing performance of any ring laser developed in our group, as demonstrated by the recent observation of the Chandler and annual wobbles of the rotating Earth [14].

The success of the G-ring led to the development of ever larger lasers including the 834-m^2 Ultra-Gross-Ring-2 (denoted by UG-2) located at Cashmere, which was necessarily heterolithic [15]. Built under a premise that bigger would be better, these lasers ultimately failed to deliver on their potential due to unexpectedly high losses on the intra-cavity mirrors and a susceptibility to geometric variation [16]. Perhaps more importantly, the lesson was learned that there is an optimum size for a ring laser gyroscope rigidly attached to the Earth, at least when there is no active interferometric scale-factor stabilization involved. Ironically, that value falls remarkably close to the dimensions of the G-ring.

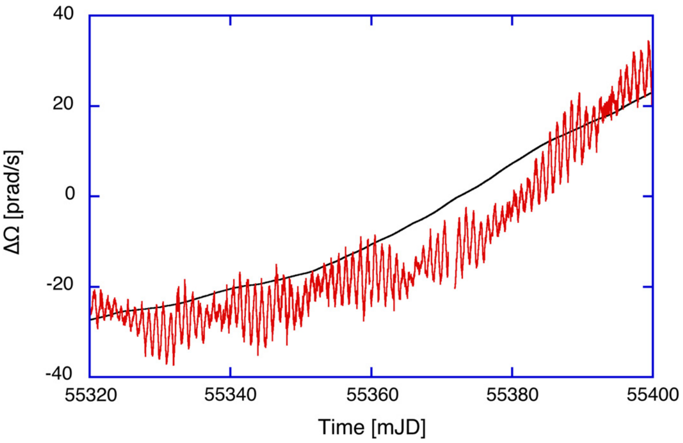

Fig. 1. (Color online.) Time series of rotations derived from the large-ring laser G at the Geodetic Observatory Wettzell. Solid Earth tides, diurnal polar motion and the long-period Chandler and the Annual wobble are clearly visible in the data. VLBI measurements carried out twice per week are shown for comparison.

3. Ring lasers in geodesy

Applications in space geodesy typically require a superior relative sensor resolution of 1 part in 10^9 with respect to the measurement quantity and a similar stability over several months [2]. This is in particular true for the precise measurement of a global measurement quantity, such as Earth's rotation based on a single local sensor [17]. The rotation rate in the Sagnac equation for an active ring cavity (Eq. (1)) then changes from $\boldsymbol{\Omega}$ to $\boldsymbol{\Omega_E}$, to denote the Earth's rotation vector with a typical value of 72.7 µrad/s. Since errors in the estimation of day length accumulate with every turn of the Earth, the desired sensor resolution is as high as 0.07 prad/s at integration times of about two hours in order to also resolve sub-daily effects on the rotation rate of the Earth. In order to achieve this, it is important to have even better control over the scale factor $4A/\lambda P$, as well as all the variations of the inner product between $\boldsymbol{\Omega_E}$ and $\mathbf{n}$, which finally relates the normal vector of the gyroscope to the instantaneous axis of rotation of the Earth. This property of an inertial sensor is unique among all the measurement techniques of space geodesy. It means that small variations in the orientation of the Earth rotation vector relative to the orientation of the ring laser structure are also contained in the observation of the beat note of the interferometer. Changes in orientation can have several causes. It is either possible to observe a variation of the normal vector with respect to the local vertical or to experience a change of attitude of the Earth rotation vector with respect to the body of the Earth. While the corresponding tilt of the solid Earth tides and ocean loading are important examples of the former, diurnal polar motion, nutation and Eulerian wobble of the rotating Earth, known as the Chandler wobble, are typical candidates for the latter. Fig. 1 illustrates the combined observation of these signals in a long-term measurement of Earth's rotation. The G ring laser in Wettzell is a single component gyroscope, orientated nearly horizontally in the laboratory at the latitude $\varphi = 49.1444°$ north. It is only sensitive to the projection $\sin(\varphi)$ of the normal vector to the Earth rotation vector $\boldsymbol{\Omega_E}$. North–south tilts induced by geophysical signals together with a small offset in the horizontal alignment are changing the projection by a small amount denoted as $\delta\phi$. Eq. (1) then changes to:

$$\delta f = \frac{4A}{\lambda P} n \cdot \Omega_{\mathrm{E}} \sin(\varphi + \delta\phi) \tag{2}$$

In addition to the above-mentioned rather periodic geophysical signals, the initial sensor orientation and local variations of the ring laser monument are causing an offset. Variations in the atmospheric pressure loading as well as changes in the local ground water table can alter the instantaneous gyroscope orientation significantly. In order to keep track of these irregular non-periodic changes, we are operating several high-resolution tiltmeters with a sensitivity of about 0.5 nrad on top of the ring laser body. While a tiltmeter is referenced to the local plumb line, it is sensitive to both the displacement caused by the solid Earth tides and the variation of the plumb line. A ring laser gyroscope, on the other hand, is only sensitive to the change of projection as a result of local displacement and corresponding latitude variation [18]. It is

$$\delta\phi_{\mathrm{tilt}} = -\frac{(1+k-h)}{gR}\frac{\partial v}{\partial\varphi} \tag{3}$$

and

$$\delta\phi_{\mathrm{RLG}} = \frac{(h-l)}{gR}\frac{\partial v}{\partial\varphi} \tag{4}$$

where h, l, k are the respective Love numbers and g the mean equatorial gravity and R the Earth's equatorial radius. Here v is the tidal potential and φ the latitude. The differences between the ring-laser-derived orientation changes and the tiltmeter measurements are small, but can not be neglected. Up to now, it was not possible to establish the exact optical scale factor of the active ring laser cavity along with the true orientation of the gyroscope. The hot cavity path-length of the laser beams inside the cavity can be established from the optical frequency of the lasing mode, but this is insufficient to establish the corresponding gyroscope area. Therefore we are only obtaining relative changes of the ring laser beat note.

Fig. 1 compares two measurements, namely the VLBI-derived CO4 series of the north–south component of polar motion with respect to the longitude of 12.878° east of the ring laser on the Geodetic Observatory Wettzell. Comparing the change of the rate of rotation as a result of the motion of the instantaneous rotational pole with respect to the ring laser location, one can see small deviations between the VLBI inferred and the ring laser derived measurement. This is caused by the variation of the backscatter coupling between the two counter-propagating laser modes in the ring laser cavity, limiting the ring laser measurements to about $\Delta\Omega/\Omega_{\mathrm{E}} = 8 \times 10^{-9}$, within half an order of magnitude of the VLBI measurements from a global network.

A data set, recorded in 2007 during the storm event “Kyrill”, indicated a significant amount of correlation between the measured local rotational signal, regional barometric pressure loading and the corresponding wind activity. The observed phase shift between the signatures of the storm in the meteorological parameters and the ring laser response suggested an elastic local response to the wind load. With the improved data quality and sensor stability based on the newly introduced sensor stabilization methods [19], most of the earlier observations were identified as instrumentally induced effects. However, locally acting wind loads are causing rotational dither within the sensitivity regime of the gyroscope. A finite element analysis approach was used to identify the transfer mechanisms and to reconstruct the amplitude and frequency regime of these perturbations. It was found that local wind, although creating small oscillations of the gyroscope with frequencies around 1 Hz, is not a limiting factor for the measurements of variations in length of day, because they average out over the longer integration times used in the geodetic application [20]. The finite-element model was chosen to be 10 km by 10 km wide and about 3 km high. It was shaped according to a digital terrain model (DTM) around the observatory with a spatial resolution of 25 m for the model surface. Since the rheology is assumed to be elastic, the results can be scaled linearly for the Young’s modulus of the soil. At the side and the bottom boundaries, the nodes were allowed to move along the plane, but not out of the plane. The wind load was applied to the nodes of the model surface from different directions. The force field is a sum of the pressure loading derived from the topography of the DTM and friction at the surface estimated from the corresponding land-use model (DLM). Forests have a much larger contribution than grass land. Every scenario generated a deformation and a rotation matrix for the ring laser site, which could be compared to the gyroscope measurements. The effect of friction is about two orders of magnitude higher than the loading effects and the modeled amplitudes are comparable to the observations. Since the wind typically has a rather turbulent spatial structure, the resultant rotational field quickly drops off, since the individual contributions become incoherent about 300 m away from the ring laser.

4. Ring lasers in seismology

Currently there are two types of measurements that are routinely used to monitor global and regional seismic wave fields. Standard inertial seismometers measure three components of translational ground displacement (velocity, acceleration) and form the basis for monitoring seismic activity and ground motion. The second type aims at measuring the deformation of the Earth (strains). It has been noted for decades ([21] and previous 1980 edition) that there is a third type of measurement that is needed in seismology and geodesy in order to fully describe the motion at a given point, namely the measurement of ground rotation. The three components of seismically induced rotation have been extremely difficult to measure, primarily because previous devices did not provide the required sensitivity to observe rotations in a wide frequency band and distance range (the two horizontal components, equal to tilt at the free surface, are generally recorded at low frequencies, but are contaminated by horizontal accelerations). Single-component ring laser measurements of rotational ground motions—in particular the G-ring located in Wettzell (station WET)—have basically provided so far the first and only high-resolution broadband observations for seismology. The observations had a strong impact in the community and contributed substantially to the emergence of a new field, now termed “rotational seismology” (already two special issues published on the topic). In the following, we will briefly review the current state of the art and illustrate current research activities.

The collocated observations using the G-ring laser sensor at WET measuring the local vertical component of the rotation vector and a classical seismic broadband station have allowed seismologists to collect a data base with several hundred earthquakes covering magnitudes from M3 to M9 [22,23]. In seismology, a fundamental property of elastic wave fields can be exploited over a wide range of applications: assuming plane wave propagation (well justified in global seismology) the amplitude ratio of transverse acceleration (seismometer) and rotation rate (ring laser) is proportional to phase velocity (e.g., [22,24]). This has tremendous implications: the collocated point measurement contains direct information on the subsurface seismic velocity structure and propagation direction that both single observations do not have. These facts inspired the development of an entirely new approach to solving the seismic inverse problem using amplitude information: seismic tomography without using travel times [25,26]. The new method allows the tomographic reconstruction of seismic velocity models around the receivers. The locality of this approach is powerful for applications where sensors cannot be deployed in small-scale arrays (e.g., ocean floor, remote regions, boreholes, planetary missions).

A substantial quality improvement of the G-ring laser in Wettzell in summer 2009 led to the first ever made observation of the Earth’s free oscillations on a vertical rotation component [27]. In the long-period range, seismometer records are

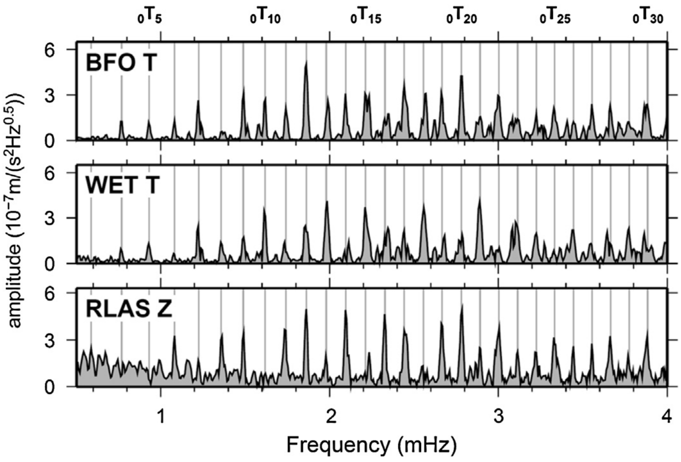

Fig. 2. Amplitude spectra of ground motion observations following the M8.8 Maule earthquake in Chile 27 February 2010. The spectra are based on 36 hr seismograms. The vertical gray lines are theoretical predictions of toroidal $_nT_m$ free oscillations based upon a spherically symmetric Earth model. The spectral lines indicate the excitation of individual modes (overtones of the fundamental modes). Top: For comparison the transverse component of ground motion at the Black Forest Observatory, Germany (BFO). Middle: Transverse component of ground motion at Wettzell, collocated with the ring laser. Bottom: Vertical component of rotational motions (ring laser observations).

severely contaminated by tilt motions [28]. Following several of the recent giant earthquakes time series with Love waves traveling around the Earth, more than four times could be observed on the ring laser. The spectrum of the observations revealed the theoretically expected spectral lines for toroidal modes (Fig. 2). The relative amplitudes of the individual modes are different from those observed in the translational components as a consequence of the differential relation between both motion types illustrating their complementary nature. It is important to note that, in particular, toroidal modes are extremely difficult to measure and ring lasers have started to fill this gap. Our pilot study opens many questions on further constraints from such observations on the Earth”s deep structure and seismic sources. In particular, the coupling between toroidal and spheroidal modes observed in some of the past earthquakes is currently being investigated [29,30].

A further quite sensational observation in the ring laser record could recently be made. Our planet is constantly vibrating—even in the absence of earthquakes—as a consequence of atmospheric pressure variations as well as interfering ocean waves. The use of this ocean-generated ambient seismic noise band (approx. 5–20-s period) in connection with cross-correlation techniques is currently revolutionizing seismology, as it allows earthquake-free tomography. Taking the noise source distribution into account would substantially improve the results. So far the studies of noise almost exclusively focused on the use of vertical component seismograms (Rayleigh-type surface waves, polarized in the plane through source and receiver). It is important to note that the ambient noise also contains a substantial amount of energy in Love waves (horizontal polarization), as recently discovered by Japanese scientists. The analysis of this motion type with a vertical-component ring laser is extremely attractive as the instrument records only this type of motion. After improvements of the ring laser signal-to-noise ratio the ocean generated ambient noise signal recently appeared in the observations [31]. These observations are remarkable and offer new ways in analyzing the origin of the ocean-generated noise wave field with a different perspective: the ring laser delivers pure Love-waves (something seismometers cannot do), and their origin and nature are not understood. The classic theory of Longuet–Higgins for the generation of ocean-generated ground motions predicts Rayleigh waves but not Love waves. Analysis of the ring laser recorded ambient noise field revealed clear evidence that Love waves are generated in the same area as the Rayleigh waves (mostly in the Northern Atlantic for European observatories). This implies that we are now ready to systematically investigate the Love wave part in the Earth's noise field without the use of seismic arrays and the difficulties that Love and Rayleigh waves are mixed in translational records.

5. Conclusion

When Georges Sagnac reported his famous experiment in 1913, he has managed to resolve rotation rates of approximately 1.8 rad/s with his optical interferometer. By means of significant upscaling Michelson, Pearson and Gale eventually achieved a resolution limit of their Sagnac interferometer of $\Omega \approx 1.6$ μrad/s. Their instrument covered an area of about 0.2 km^2. With the availability of ring lasers and low-loss mirrors, inertial rotation sensing for navigation and attitude control, based on rather compact devices, became feasible and widespread. Starting at the end of the last century, the concept of ring laser gyroscopes was revisited again with the goal of obtaining sufficient sensitivity and stability to apply Sagnac interferometry to geodesy and geophysics. Today, one hundred years after the original experiment by Georges Sagnac, we have reached a point where we can resolve $\Delta\Omega/\Omega_{\mathrm{E}} < 10^{-8}$ routinely. Under conditions where the instrumentation can be stabilized to a constant value for the backscatter coupling over several months, long-term variations of polar motion can be observed. Improving the sensor stability rather than improving the sensitivity has become the main objective of our research collaboration. If successful, a Sagnac interferometer has the potential to allow the detection of the Lense–Thirring frame-dragging in a ground-based experiment.

For the short term, the ring laser technology has provided seismology with a new quality of ground motion observations that is far from being fully explored. In particular, most observations so far are based on the vertical component G-ring observations. It is fair to say that the horizontal components of ground motion have never accurately been observed in the broadband seismic frequency band (tiltmeters are also sensitive to horizontal accelerations, which is why they are not able to provide pure tilt observations). This is one of the remaining research frontiers in ring laser applications to seismology and efforts are on the way to develop multi-component ring laser systems that are capable of measuring the complete vector of ground motion.

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References

[1] A.A. Michelson, F. Pearson, H.G. Gale, The effect of the Earth's rotation on the velocity of light, Astrophys. J. 61 (1925) 140–145.
[2] H.-P. Plag, M. Pearlman (Eds.), Global Geodetic Observing System, Springer, ISBN 978-3-642-02686-7, 2009.
[3] A. Di Virgilio, K.U. Schreiber, A. Gebauer, J.-P.R. Wells, A. Tartaglia, J. Belfi, N. Beverini, A. Ortolan, A laser gyroscope system to detect the gravito-magnetic effect on Earth, Int. J. Mod. Phys. D 19 (2010) 2331.
[4] F. Bosi, G. Cella, A. Di Virgilio, A. Ortolan, A. Porzio, S. Solimeno, M. Cerdonio, J.P. Zendri, M. Allegrini, J. Belfi, N. Beverini, B. Bouhadef, G. Carelli, I. Ferrante, E. Maccioni, R. Passaquieti, F. Stefani, M.L. Ruggiero, A. Tartaglia, K.U. Schreiber, A. Gebauer, J.-P.R. Wells, Measuring gravitomagnetic effects by a multi-ring-laser gyroscope, Phys. Rev. D 84 (2011) 122002.
[5] W.M. Macek, D.T.M. Davies Jr., Rotation rate sensing with travelling-wave ring lasers, Appl. Phys. Lett. 2 (3) (1963) 67.
[6] F. Aronowitz, The laser gyro, in: Laser Applications, vol. 1, 1971, pp. 133–200.
[7] G.E. Stedman, Ring laser tests of fundamental physics and geophysics, Rep. Prog. Phys. 60 (1997) 615.
[8] G.E. Stedman, H.R. Bilger, Li Ziyuan, M.P. Poulton, C.H. Rowe, I. Vetharaniam, P.V. Wells, Canterbury ring laser and tests for nonreciprocal phenomena, Aust. J. Phys. 46 (1993) 87.
[9] R.B. Hurst, R.W. Dunn, K.U. Schreiber, R.J. Thirkettle, G.K. MacDonald, Mode behaviour in ultralarge ring lasers, Appl. Opt. 43 (2004) 2337.
[10] K.U. Schreiber, C.H. Rowe, D.N. Wright, S.J. Cooper, G.E. Stedman, Precision stabilization of the optical frequency in a large ring laser gyroscope, Appl. Opt. 37 (1998) 8371.
[11] K.U. Schreiber, T. Klügel, G. Stedman, Earth tide and tilt detection by a ring laser gyroscope, J. Geophys. Res., Solid Earth 108 (B) (Feb. 2003) 2132, http://dx.doi.org/10.1029/2001JB000569.
[12] C.H. Rowe, K.U. Schreiber, S.J. Cooper, B.T. King, M. Poulton, G.E. Stedman, Design and operation of a very large ring laser gyroscope, Appl. Opt. 38 (12) (1999) 2516.
[13] K.U. Schreiber, T. Klügel, A. Velikoseltsev, W. Schlüter, G.E. Stedman, J.-P.R. Wells, The large ring laser G for continuous earth rotation monitoring, Pure Appl. Geophys. 166 (2009) 1485.
[14] K.U. Schreiber, T. Klügel, J.-P.R. Wells, R.B. Hurst, A. Gebauer, How to detect the Chandler and the annual wobble of the Earth with a large ring laser gyroscope, Phys. Rev. Lett. 107 (2011) 173904.
[15] R.B. Hurst, G.E. Stedman, K.U. Schreiber, R.J. Thirkettle, R.D. Graham, N. Rabeendran, J.-P.R. Wells, Experiments with an 834 m^2 ring laser interferometer, J. Appl. Phys. 105 (2009) 113115.
[16] B. Pritsch, K.U. Schreiber, A. Velikoseltsev, J.-P.R. Wells, Scale-factor corrections in large ring lasers, Appl. Phys. Lett. 91 (6) (2007) 061115.
[17] K.U. Schreiber, J.-P.R. Wells, Invited review: large ring lasers for rotation sensing, Rev. Sci. Instrum. 84 (2013) 041101.
[18] W. Tian, On tidal tilt corrections to large ring laser gyroscope observations, Geophys. J. Int. 169 (1) (2014) 189–193.
[19] K.U. Schreiber, A. Gebauer, J.-P.R. Wells, Long term frequency stabilization of a 16 m^2 ring laser gyroscope, Opt. Lett. 37 (11) (2012) 1925.
[20] A. Gebauer, K.U. Schreiber, T. Klügel, N. Schön, U. Ulbrich, High-frequency noise caused by wind in large ring laser gyroscope data, J. Seismol. 16 (4) (2012) 777–786, http://dx.doi.org/10.1007/s10950-012-9283-x.
[21] K. Aki, P. Richards, Theoretical Seismology, Freeman and Company, 1980, Second edition: 2002.
[22] H. Igel, K.U. Schreiber, B. Schuberth, A. Flaws, A. Velikoseltsev, A. Cochard, Observation and modelling of rotational motions induced by distant large earthquakes: the M8.1 Tokachi-Oki earthquake September 25, 2003, Geophys. Res. Lett. 32 (2005) L08309, http://dx.doi.org/10.1029/2004GL022336.
[23] H. Igel, A. Cochard, J. Wassermann, A. Flaws, U. Schreiber, A. Velikoseltsev, N.D. Pham, Broad-band observations of earthquake-induced rotational ground motions, Geophys. J. Int. 168 (1) (2007) 182, http://dx.doi.org/10.1111/j.1365-246X.2006.03146.x.
[24] A. Cochard, H. Igel, B. Schuberth, W. Suryanto, A. Velikoseltsev, K.U. Schreiber, J. Wassermann, F. Scherbaum, D. Vollmer, Earthquake Source Asymmetry, Structural Media and Rotational Effects, Chapter 30, Rotational Motions in Seismology: Theory, Observation, Simulation, Springer, 2006.
[25] A. Fichtner, H. Igel, Sensitivity densities for rotational ground motion measurements, Bull. Seismol. Soc. Am. 99 (2009) 1302–1314.
[26] M. Bernauer, A. Fichtner, H. Igel, Inferring Earth structure from combined measurements of rotational and translational ground motions, Geophysics 74 (6) (2009) WCD41–WCD47.
[27] H. Igel, M.-F. Nader, D. Kurrle, A.-M.G. Ferreira, J. Wassermann, K.U. Schreiber, Observations of Earth's toroidal free oscillations with a rotation sensor: the 2011 magnitude 9.0 Tohoku-Oki earthquake, Geophys. Res. Lett. 38 (2011) L21303, http://dx.doi.org/10.1029/2011GL049045.
[28] R. Widmer-Schnidrig, W. Zürn, Perspectives for ring laser gyroscopes in low-frequency seismology, Bull. Seismol. Soc. Am. 99 (2B) (2009) 1199, http://dx.doi.org/10.1785/0120080267.
[29] M.F. Nader, H. Igel, A.M.G. Ferreira, D. Kurrle, J. Wassermann, K.U. Schreiber, Toroidal free oscillations of the Earth observed by a ring laser system: a comparative study, J. Seismol. 16 (4) (2012) 745–755, http://dx.doi.org/10.1007/s10950-012-9304-9.
[30] M.F. Nader, H. Igel, A.M.G. Ferreira, D. Al-Attar, J. Wassermann, K.U. Schreiber, Normal mode coupling observations with a rotation sensor, Geophys. J. Int. (2014), submitted for publication.
[31] C. Hadziioannou, P. Gaebler, K.U. Schreiber, J. Wassermann, H. Igel, Examining ambient noise using co-located measurements of rotational and translational motion, J. Seismol. (2012), http://dx.doi.org/10.1007/s10950-012-9288-5.