ROTATION SENSING WITH LARGE RING LASERS

Ring lasers are commonly used as gyroscopes for aircraft navigation and attitude control. The largest ring lasers are sensitive enough that they can be used for high resolution inertial rotation sensing of the Earth in order to detect tiny perturbations in the Earth's rotation caused by earthquakes or global mass transport. This book describes the latest advances in the development of large ring lasers for applications in geodesy and geophysics using the most sensitive and stable devices available. Chapters cover our current knowledge of the physics of the laser gyroscope, how to acquire and analyze data from ring lasers, and what the potential applications are in the geosciences. It is a valuable reference for those working with ring lasers or using the data for applications in geodesy and geophysics, as well as researchers in laser physics, photonics, and navigation.

K. ULRICH SCHREIBER is a professor at the Technical University of Munich. He has more than 30 years of research experience in the technology of space geodesy, in particular satellite and lunar laser ranging, ring laser development, and optical time transfer. He received the Huygens Medal for Instrumentation from the European Geosciences Union in 2016.

JON-PAUL R. WELLS is a professor of physics at the University of Canterbury in Christchurch, New Zealand. His research interests include large ring laser gyroscopes, optical interferometry, and laser spectroscopy of inorganic solids.

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Applications in Geophysics and Geodesy

K. ULRICH SCHREIBER
Technical University of Munich

JON-PAUL R. WELLS
University of Canterbury

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To the pioneers of our large ring laser adventure: Hans Bilger, Richard Falke, Morrie Poulton, Clive Rowe, Manfred Schneider and Geoffrey Stedman.

Contents

Preface

At the beginning there is always a dream: "Wouldn't it be nice to just go to the basement and read the instantaneous Earth rotation signal straight from a laser gyro, instead of waiting for several days for a computed result from a global network of GNSS receivers and VLBI telescopes?"[1] This dream, expressed by my supervisor Professor Manfred Schneider in 1991, was the short and challenging job description that I obtained when I inherited the *Ring Laser project* in my early postdoc years at the Technical University of Munich. Luckily, I was too young to understand the immense difficulties behind this request, and luckily again, I had the opportunity to find the ring laser group at the University of Canterbury, who already had a crudely working but promising prototype. When we teamed up, we *only* had eight more orders of magnitude of precision to go, and we had a lot of optimism too, which turned out to be an essential asset. Words like *accuracy* and *stability* did not even enter our minds in those early days, and that explains why we have continued on this thorny road of sensor development for so long. After three decades of struggle on this bumpy road, it is time to look back and to summarize our experience.

Large ring lasers are very suitable sensors for the precise monitoring of the rotation of the Earth. Their potential long-term stability, size, high sensitivity and rigid mechanical properties suggest themselves for terrestrial deployment. Ring lasers were developed through the 1970s, when the potential substitution of a complex mechanical rotating mass assembly against a simple laser cavity became a realistic expectation. Commonly, these gyros are single longitudinal mode helium–neon lasers operated at a wavelength of 632.8 nm in aircraft navigation applications. Laser gyroscopes used for inertial navigation usually have an area $<0.02\ \mathrm{m}^2$, corresponding to a perimeter of 30 cm or less. With a bandwidth of ≈ 1.8 GHz for the available laser transition in neon, this ensures single longitudinal mode operation. The typical sensitivity of such devices is around $5 \times 10^{-7}\mathrm{rad/s}/\sqrt{\mathrm{Hz}}$, and the drift is as low as

[1] GNSS: global navigation satellite system; VLBI: very long baseline interferometry.

0.0001°/h. This performance level is fully sufficient for navigational requirements but falls short by several orders of magnitude for most geophysical applications. Since the scale factor and hence the sensitivity increases with the area enclosed by the two counter-propagating laser beams, upscaling has been the logical route to sensor improvements. However, the value of large ring laser gyroscopes was initially met with a great deal of skepticism, mostly because it was regarded as doubtful that the operation of a single longitudinal laser mode could be obtained as the cavity free spectral range (FSR) decreased considerably. As it turned out, this was easily achieved.

Frequency pulling from two weakly coupled oscillators with neighboring frequencies can cause frequency synchronization. In ring lasers this effect, known as *locking*, can cause the beat note to disappear, even though the laser is physically rotating. The first large ring laser gyroscope to unlock on Earth rotation alone was the 0.748 m^2 Canterbury-I ring laser C-I, situated in Christchurch, New Zealand [207]. It was a planar, essentially square geometry defined entirely by dielectric *super* mirrors having a nominal reflectance of 99.9985%. In fact, it was the advances in dielectric mirror coating technology that made upscaled ring lasers a viable technology. The choice of a square ring was primarily made to optimize the signal-to-noise ratio but also because of the expectation of reduced backscattering for mirrors used at a 45° angle of incidence. 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. Tiny leaks in the viton vacuum seals caused the gas mix to degrade quickly. The initial location in a high rise building and the early generation super-mirrors employed caused further problems. Ultimately, C-1 was shifted to an old wartime 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 were essential for the state-of-the-art ring lasers in use today. In merely 15 years, ring lasers operating on a single longitudinal laser mode increased in size from ∼0.02 m^2 to an astounding 834 m^2. In fact, they could be made significantly larger; however, geometrical instabilities and increased losses at the mirror surfaces from larger beam spots do not make this an attractive option at the time of writing. Further, the mode competition processes that govern the start-up time of large ring lasers (i.e., the time the sensor takes to settle into mono-mode operation) may become prohibitively long.

Ring laser-based Sagnac interferometers measure any non-reciprocal effect, which gives rise to a difference in the respective optical path lengths of the counter-propagating laser beams within the cavity. However, the HeNe ring laser gyroscopes discussed here are best suited to the measurement of physical rotations, externally imposed on the monument of the device. Rotation sensing gyroscopes, which utilize the Sagnac effect in the optical domain, essentially fall into two categories: passive and active. Fiber optic gyroscopes are the most prominent passive optical Sagnac interferometers, while ring laser gyroscopes represent the group of active Sagnac devices. The latter group provides the most sensitive and most stable class of gyroscopic devices to date. Of course, alternatives, such as atom interferometry, have the often stated (intrinsic) advantage that atomic masses are much greater than the photon mass. As such they have very high potential as gyroscopes, although they do not (as yet) compete with advanced, large scale ring laser technology.

Highly sensitive rotation sensors have many applications. These range from robotic guidance and inertial navigation systems for a variety of vehicles, aerospace and military hardware; measurement of high order (non-reciprocal) optical effects in condensed phase systems, such as chiral liquids; through to very demanding high resolution measurements in seismology, geodesy and geophysics and even tests of fundamental physics. The vast array of applications necessitate a correspondingly wide range of different sensor types and specifications to satisfy these demands. For the required stable operation for applications in geodesy and geophysics specifically, the fundamental observable, the Sagnac frequency, δf, is strongly influenced by three factors:

- *Scale factor*: The variability of the sensor geometry and effects from laser functions (such as dispersion, laser gas aging and backscatter coupling) are reflected in the measurement quantity mostly as a slowly changing bias.
- *Sensor orientation*: The alignment of the normal vector of the sensor with the Earth's rotation vector as a function of time is critical. Pressure loading around the sensor site, varying wind loads, ground water variations, microseismic activity and solid Earth tides are readily visible.
- *Variations in the Earth's rotation*: This is our very small measurement quantity of prime interest, and it does not exceed a value of $\delta\omega \approx 6 \times 10^{-12}$ rad/s. For periodic diurnal and semidiurnal geophysical signals, these contributions can be well isolated, but aperiodic trends are hard to discriminate from (variable) orientational issues and scale factor instabilities.

Although δf is the only direct measurement quantity obtained from a Sagnac interferometer, one can treat these three contributors independently. The inclusion of auxiliary operational parameters helps in the identification of these signal sources. High resolution tiltmeters, together with an appropriate model for atmospheric attraction, based on gridded regional atmospheric pressure values from a meteorological service [118], for example, allow the estimation of variations in orientation but not the orientation itself. The measurement of perimeter variations through the self-referenced estimation of the FSR allow us to track scale factor variations. The scale factor itself is determined with the help of an optical frequency standard, such as an iodine referenced HeNe laser or an optical frequency comb. Sensor drift caused by changes in backscatter coupling can be determined from the continuous observation of the beam powers and the backscatter amplitudes of the two counter-propagating laser beams. Unfortunately, most of the available auxiliary measurements cannot be easily related to a single error mechanism, so that the correction of the interferometric measurements of a ring laser remains a very involved process.

This book summarizes approximately 30 years of laboratory experience on the development and operation of large HeNe ring lasers. In the beginning, C-I provided the rotation rate of the Earth with a stability of about 10%. Roughly one decade later, we successfully obtained ocean loading effects and the solid Earth tides for the first time, and shortly after that, the continuous detection of diurnal polar motion became a common observable, followed by the detection of very long period signals, like the Chandler wobble in 2012. Today our flagship gyro 'G' routinely operates at a resolution around and below 1 part in 10^8, and the most pressing questions are not primarily *sensitivity* as in the early days, but *stability* and *accuracy*. Large ring lasers are highly coherent optical interferometers, not unlike gravitational wave antennas. Despite some significant differences, they share a number of common problems. While gravitational wave antennas need to be well isolated from the body of the Earth, ring lasers need to be rigidly attached or, better put, *strapped down* to Earth.

On the other side, very subtle non-reciprocal effects between the two counter-propagating laser beams immediately cause a significant offset in the measured Earth rotation rate, which in most cases is slowly changing with time. As a consequence, we estimate, that the accuracy of G with respect to the estimated rotation rates is still only around a level of 1 ppm. The difficulty of giving an exact number here starts already with the problem of fixing the true orientation in terms of latitude of this single component gyro in its strapped down location in the underground ring laser facility of the Geodetic Observatory Wettzell (GOW) in Germany. The stability of G can finally be compared to the sensitivity once the laboratory is in thermal equilibrium, the pressure vessel closed and the optical frequency in the ring cavity actively stabilized. So one can see that this field of development is highly advanced but far from complete. However, we believe it is important to collect and document all our experience to date in this monograph, so that other groups with an interest in the application of large laser gyros have an easier start than we had. We have arranged the book as follows:

- There is a brief review of some important early experiments in rotation sensing by optical interferometry in Chapter 1,

- We take a short stop in Chapter 2 to look at some fundamentals of HeNe-based laser gyroscopes. This does not replace the recommendation to consult the classical work of [11, 40, 236] for the details of the laser theory involved.
- Chapter 3 constitutes the central part of this book. It discusses all the important aspects for the construction and operation of large ring laser gyros and provides a description of a number of very subtle error sources and not so obvious side effects.
- The successful operation of a large gyro does not stop at the design and the properties of the instrument alone. Aspects of data processing and the necessary auxiliary sensor components are also an essential part of gyro operation. Furthermore, we also need to take a look at the geophysical quantities of interest, their magnitude and their spectral range, in order to match the sensor performance to the application. All this is contained in Chapter 4.
- This is followed by a brief discussion of alternative rotation sensing concepts. Chapter 5 puts our work into perspective of the entire field of high resolution inertial rotation sensing, before
- Chapter 6 finally summarizes where large strapped down ring laser gyroscopes have contributed over the years and where we expect to be in the future.

As authors we have shared our effort. Jon-Paul Wells has written Chapters 1 and 2, while Ulrich Schreiber has written Chapters 3–6. Apart from a full account of our activities over the years, we hope that we have also managed to provide a profound overview of the existing large body of literature in this research field, both from an instrumental point of view and with respect to the application. Although the ring laser has come a long way already, there are still a number of challenges ahead. Absolute rotation sensing still requires several orders of magnitude of improvement in order to become a viable technique for tests in fundamental physics. A still more improved sensor stability is another item on this wish list. Due to the large inertia of the Earth, most geodetically relevant signals have signatures in the nHz regime, corresponding to periods of months and years. From that point of view, we are still lacking a consistent sensor fusion of large gyroscopes, the global navigation satellite system (GNSS), and the very long baseline interferometry (VLBI) technique. We hope that this book encourages more activities in that direction.

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