Quantum Electronics **42** (11) 1045 – 1050 (2012)

LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

PACS numbers: 42.60.Da; 42.62.Eh; 91.10.Nj; 91.10.P–
DOI: 10.1070/QE2012v042n11ABEH014616

Enhanced ring lasers: a new measurement tool for Earth sciences

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Abstract. **We report the progress in the technology of fabrication of large ring lasers that has resulted in an increase in instrumental rotation sensitivity by as much as a factor of 3, to $\delta\Omega = 1.2\times10^{-11}$ rad s^{-1} Hz$^{-1/2}$, which makes the domain of changes in the angular velocity of Earth's rotation, $\Delta\Omega/\Omega \approx 10^{-9}$, accessible to a local rotation sensor. New studies show that the largest contribution to the observed deviation in sensor performance with respect to the computed shot noise limit is caused by the micro-seismic background activity of the Earth. Our efforts have been concentrated on the improvement of sensor stability, including correction of drift effects, which are caused by the aging of the laser gas, fixing scale factor instabilities induced by atmospheric pressure variations, and minimising the temperature variations resulting from corresponding adiabatic expansion and compression of the local air around the instrument. To achieve this, we have recently introduced a pressure-stabilising vessel with dimensions slightly larger than the ring laser apparatus, such that it encloses the entire structure. By monitoring the optical frequency in the ring laser cavity continuously and stabilising the scale factor in a closed loop system with the pressure-stabilising vessel, it has become possible to extend the range of sensor stability from the short term (1 – 3 days) to well into the mid-term regime (>40 days), and possibly even well beyond that. Once a sufficiently long time-series of the ring laser data has been recorded, we will be able to define the range of temporal stability in more detail. The extension of the regime of stability gives access to geophysical signals at frequencies substantially lower than previously observable with ring lasers.**

Keywords: ring laser, optical frequency stabilisation, Earth's rotation, space geodesy.

1. Introduction

The rotation rate of the Earth and the orientation of the rotational axis of the Earth in space are the linking quantities between the terrestrial (ITRF) and the celestial (ICRF) reference frames. Until now, the only way of determining the Earth's rotational velocity as well as variations in the orientation of the Earth's rotational axis with sufficient accuracy has been to utilise a set of quasars, approximating them as forming an external set of markers to the respective reference frames. Today residuals of less than 10 μs for measurements of length of day and as low as 0.5 nrad (0.1 milli-arcseconds) for measurements of the pole position are routinely achieved by a network of VLBI radio telescopes and GPS observations [1, 2]. These efforts are carried out thanks to the services of the International Association of Geodesy (IAG). The operation of such a large network requires significant amounts of expensive equipment and a very substantial maintenance effort. Huge amounts of data are recorded in each measurement session, which require physical transport over large distances to enable the correlation process to take place in the analysis centres. Data latency, combined with the fact that there is no continuous measurement coverage, suggests that complementary methods for the precise estimation of Earth's rotation should be investigated. This idea is strongly supported by the fact that it is desirable to develop an independent measurement technique in order to identify intra-technique biases if they exist.

Ring lasers are potential candidates for such an alternative measurement technique. They are widely used in aircraft navigation and can measure rotations absolutely, i.e., independently of an external reference frame. However, the demands on such instruments are extremely high, and cannot be met by existing commercial devices. These demands can be summarised as follows:

(i) sensitivity to rotation of 0.1 prad s^{-1} over an integration of about 1 h;

(ii) sensor stability of 1 part in 10^9 over several months (required, for instance, to measure the Chandler Wobble);

(iii) resolution in sensor orientation of approximately 1 nrad, corresponding to a polar motion effect of around 1 cm at the pole.

This means that a substantial improvement in sensor technology over existing navigational instrumentation is required in order to make ring lasers a viable technique for applications in space geodesy. The design of the large ring laser gyro

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[*] Reported at the 'Laser Optics' Conference (Russia, St. Petersburg, June 2010).

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Received 25 February 2011
Kvantovaya Elektronika **42** (11) 1045 – 1050 (2012)
Submitted in English

G (Grossring) is one way of approaching these demands [3]. This gyro is a 16 meter perimeter ring laser which utilises helium and neon as a gain medium, similar in many ways to the systems used in aircraft navigation. However, the vastly increased scale of the G ring laser provides for a far superior sensitivity to rotational input signals compared to navigational ring lasers. A careful optimisation of the mechanical stability of the G ring laser body allows a level of performance which is very close to satisfying the demands which are summarised above. At present, we are only about half an order of magnitude short of achieving our goals with this ring laser. A particular difficulty is the proper coupling of the sensor to the Earth, since for such a sensitive instrument even tiny local geophysical effects are significant and cannot be ignored in the data analysis.

2. Large ring lasers

Bidirectional ring lasers measure the rate of rotation with respect to an inertial reference frame via the Sagnac effect. In a passive interferometer, this effect arises from the fact that two identical light beams travelling around a closed contour (enclosing a non-zero area) along exactly the same path but in opposite directions will experience a phase shift between them when the contour is rotating [4]. The exact phase shift depends on the size of the contour and is proportional to the rate of rotation. Consequently, provided that the beam path inside the contour is exactly known, a measurement of the phase shift gives an exact representation of the rotation rate the sensor is experiencing. This phase shift is translated into a frequency difference between the two counter-propagating light beams if the light path is part of an active ring cavity [5]. One can write that the frequency difference between the beams is

$$\Delta f = S\,|\boldsymbol{n}\times\boldsymbol{\Omega}| = \frac{4A}{\lambda L}\,|\boldsymbol{n}\times\boldsymbol{\Omega}|, \tag{1}$$

where $\boldsymbol{n}$ is the normal vector to the plane of the laser beams; $\boldsymbol{\Omega}$ denotes the vector of rotation; and S is the scale factor determined by the area A encircled by the laser beams, the cavity perimeter L and the optical wavelength λ. Since the observed beat frequency of the two laser beams is proportional to the rate of rotation, the factor S determines the resolution of the measurement quantity. If the scale factor is made substantially larger than the value for a typical aviation gyro, sufficient sensitivity will eventually be obtained to apply the technique of Sagnac interferometry to space geodesy. This is the fundamental concept behind our ring laser project. In practice, it is found that there is a critical trade-off between sensor size and the necessary mechanical stability of the entire apparatus.

The layout of the G ring laser cavity is in the form of a square with each side 4 m long. Four turning mirrors, which are optically contacted to the end of large Zerodur bars, define the optical cavity. The large Zerodur bars are situated on top of a mechanically and thermally stable massive Zerodur disc, measuring 4.2 m in diameter and 25 cm in thickness. The Zerodur bars are arranged in the shape of a cross in order to maximise the available enclosed cavity area atop the Zerodur base. The beam path between the four mirrors is enclosed by stainless steel tubes so that the ring laser cavity can be first evacuated and then filled with a mixture of helium and neon gas at the low pressures necessary to create lasing. A capillary 6 mm in diameter and two radio frequency driven electrodes generate a plasma, which allows for cw lasing at a wavelength of 632.8 nm. Because of the mechanically rigid construction, the use of low thermal expansion material and the optical contacting of the mirrors in the system, there are no elements of alignment available to adjust the laser cavity. The major advantage of this rigid construction is that it ensures that the G ring laser is not affected by mechanical instabilities, which are inherent to any mechanical adjustment feature on such a sensitive device. Figure 1 shows the semi-monolithic Zerodur construction of the G ring laser.

Figure 1. Construction of the G ring laser in the underground laboratory of the Geodetic Observatory in Wettzell (Germany).

Operation of the G ring laser near the lasing threshold forces the laser to run on a single longitudinal mode for each sense of propagation without the need of any intracavity mode selection devices. This allows single mode operation to occur despite the small free spectral range of only 18.75 MHz for the laser. The Q factor of the cavity has recently been improved and now stands at a value of $\sim 3\times10^{12}$, which has resulted in a reduction of the shot noise limit of the theoretical sensor resolution to a value of $\delta\Omega = 1.2\times10^{-11}$ rad s^{-1} Hz$^{-1/2}$. An important goal of the construction of the G ring laser was to create a new rotation sensor with as large a scale factor as feasible with the materials available. The limiting factor in the construction of the sensor proved to be the availability of large blocks of Zerodur, and thus the size of the G ring laser was entirely determined by the size of the Zerodur blocks that could be obtained at the time. The Zerodur blocks were produced by the SCHOTT Glasworks Mainz (Germany), while the G ring laser body along with the underground laboratory required to house the instrument were constructed by Carl Zeiss in Oberkochen (Germany). Other very important features of the G ring laser include the high degree of symmetry in the construction. All four arms were made as closely identical as possible, resulting in the fact that under the influence of atmospheric pressure variations, the ring laser structure shrinks or expands by almost exactly the same amount in each of the arms of the apparatus. The same high symmetry construction was utilised in the four steel tubes forming the sides of the square ring laser. Finally, all four mirrors installed at each of the corners of the G ring laser have precisely the same 4 meter radius of curvature (ROC). As a result, small scale homogeneous temperature variations and atmospheric pressure changes do not cause additional beam steering effects in the cavity.

The output signal from a typical ring laser is the beat frequency of the two counterpropagating He–Ne laser beams inside the cavity. An interferogram is generated by superimposing the two laser beams leaking through one of the low transmission mirrors in a 1:1 beam splitter and feeding this beat note created by the two light waves through a photodetector. In the case of the G ring laser in Wettzell, which is horizontally arranged at a latitude of approximately ~49.16°N, the beat frequency created by Earth's rotation amounts to roughly 348.518 Hz. The precise value is still unknown for several reasons. As one can see from equation (1), the Sagnac frequency depends both on the scale factor and the orientation of the ring laser normal vector with respect to Earth's instantaneous rotation axis. Currently the orientation of the instrument to the instantaneous rotation axis is not known to better than 10 nrad, and scale factor uncertainties caused by the active laser medium in the ring laser cavity are also not established to better than several parts per billion (ppb) of the measurement quantity.

3. Application of large ring lasers in Earth sciences

The G ring laser is operated at the heart of an enclosed and insulated underground laboratory which was constructed specifically to minimise the thermal flux around the instrument. There are no heat-dissipating devices present inside the ring laser chamber; as a result, the daily temperature variation around the laser cavity does not exceed 5 mK. All residual temperature changes come either from adiabatic expansion or compression due to atmospheric pressure variations, or from the annual heat cycle induced by the change of seasons. Scale factor changes caused by the varying atmospheric pressure and temperature are now actively controlled by a pressure-stabilising vessel enclosing the entire ring laser structure.

Figure 2 shows a comparison of the time deviations of a typical measurement series of data from the G ring laser, without (in 2006) and with (in 2010) pressure stabilisation. In the 2006 measurements one can see how fluctuations in the atmospheric pressure cause fluctuations in the measurements of Earth's rotation, caused by small modifications of the scale factor of the ring laser. Since the resulting changes in backscatter phase also affect the frequency pulling of the two optical beams in the cavity, the overall effect is quite pronounced in the frequency band of atmospheric pressure fluctuations (several hours to about 3 days in the time domain of Fig. 2). In the new configuration, the data taken in 2010 with the pressure-stabilising vessel in place does not show these pressure induced effects. The line on the lower left side of the diagram indicates the current shot noise limit of the G ring laser cavity. A significant factor in the difference between the 2006 and 2010 measurements comes from an improvement of cavity Q factor over the past four years, which has largely been a result of the installation of new ring laser mirrors with a considerably better super-polish in July of 2009.

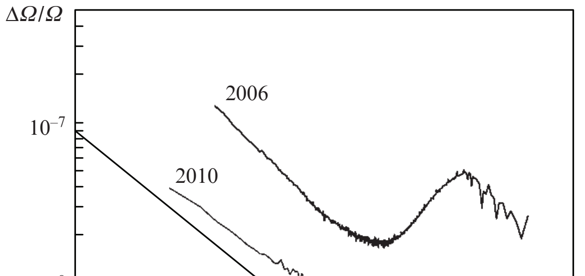

Figure 2. Theoretical shot noise limit of the G ring laser, and the experimentally obtained sensor resolution for two different sensor configurations (2006 and 2010).

Ring lasers rigidly mounted on the Earth show various contributions from geophysical signals, such as micro-seismic activity caused by pressure fluctuations on the sea floor which are generated by ocean waves, tilts from solid Earth tides caused by gravitational attraction from the moon which deforms the Earth's crust [6], as well as diurnal polar motion [7]. Once the latter two signals are removed from the measured time series of our ring laser, we obtain a sequence as outlined in Fig. 3. Much of the higher frequency noise contained in the measurement sequence can be attributed to micro-seismic background activity. The small variations at lower frequencies evident in Fig. 3 are believed to be caused by slowly changing backscatter, but up to the present time this has still not been unambiguously verified. These lower frequency signals are the reason for the flicker floor behaviour of the pressure-stabilised ring laser operation as shown in Fig. 2.

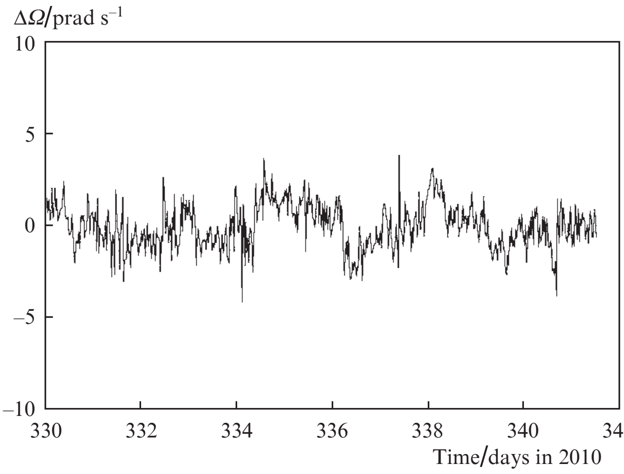

Figure 3. Sample of a time series of Earth's rotation measurements of the G ring laser in the configuration of 2010.

The fact that the noise levels created from various weather patterns limit the resolution of our instruments is also very evident in scatter plots of our ring laser measurements. Figure 4 shows an example of this, with the data corresponding to the same days of measurement as displayed in Fig. 3. There are two types of perturbations present in Fig. 4: relatively brief and intense spikes in the noise, and more slowly varying perturbations. The rather sharp and short increases in noise level are directly related to the activity of heavy vehicles which have been performing construction work at the Geodetic Observatory in Wettzell. The more slowly changing noise levels are caused by weather patterns, which over longer periods

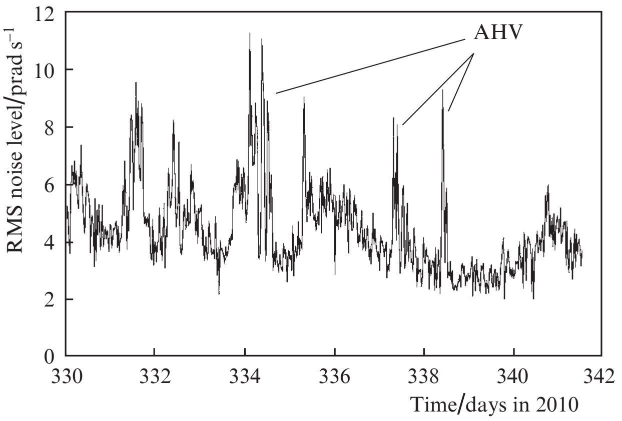

Figure 4. Background noise from the Earth during the ring laser measurements. Sharp spikes caused by the activity of heavy vehicles (AHV) involved in construction work.

show typical variations in the micro-seismic background noise.

Such a low noise level and extreme resolution of large ring lasers allows for the detection of rotational signals caused by distant earthquakes. The amplitudes of these seismic rotations are extremely small (down to 10^{-12} rad s^{-1} or 5.7×10^{-11} deg s^{-1}) and are impossible to measure directly with conventional techniques. Large ring lasers provide an accurate method of registering such rotational fluctuations in real time, which gives us access to a number of new seismological quantities. To measure and monitor these seismological quantities, a special measurement system named GEOsensor was designed and commissioned in 2005 [8]. The GEOsensor is a stand-alone measurement complex for seismic and geophysical studies, which consists of several major components. These components include a large perimeter one-axis ring laser gyroscope, a conventional three-axis broadband seismometer, a tilt-meter to monitor changes in the orientation of the ring laser sensor, and a GPS-station to provide time and reference frequencies for the data acquisition system. Figure 5 shows the structure of the ring laser component of the GEOsensor.

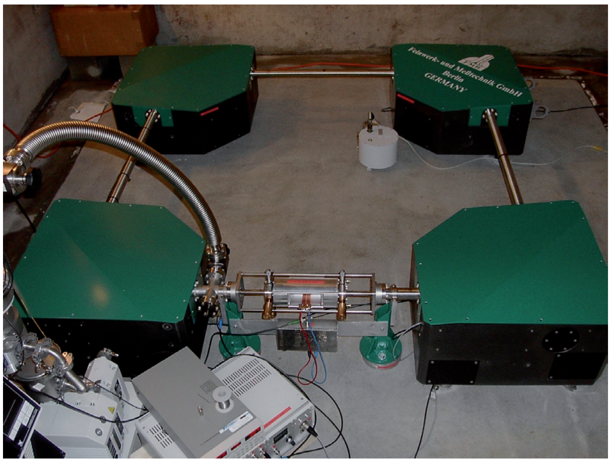

Figure 5. Construction of the ring laser component of the GEOsensor. The heterolithic structure is rigidly anchored on a 30-cm-thick concrete slab for stability.

The square ring laser cavity component of the GEOsensor consists of four 1.6-meter-long stainless steel tubes, all rigidly attached to corner boxes which contain mirror holders. As with the G ring laser, four high-reflectivity supermirrors create a closed square path which the laser beams traverse. The GEOsensor ring laser has a modular design, meaning for instance that it can be scaled up by using longer tubes while permitting other components of the laser to remain unchanged. This useful design concept allows one to adjust characteristics of the ring laser, such as its size and accuracy, at any given time according to the conditions and requirements at the particular location where the instrument is deployed [9].

While active ring lasers can successfully detect distant and medium-range seismic events, it is customary to adopt other kinds of optical interferometers for measurements of seismic rotations closer to the source. Close-range seismic events are characterised by very strong seismic waves appearing in the vicinity of the earthquake epicentre. In this case, the amplitudes of both linear and rotational motion are a lot larger than those that are seen in the case of teleseismic events. The linear velocity may vary from 0.1 up to 1 m s^{-1} for these close-range events, while the rotation rate variations can range from 0.0005 deg s^{-1} up to 15 deg s^{-1} [10, 11]. Due to the very complex structure of seismic signals in the near-field, one needs all three components of linear and rotational motion in order to properly estimate the seismic wave properties. Therefore, the application of fibre-optic gyroscopes (FOGs) for detection of strong rotational waves looks very promising, due in particular to the low production cost and small size of these sensors. Utilising these gyroscopes allows for building a three-axis measurement system which is capable of recording three components of rotational motion simultaneously with the three components of linear motion delivered by the standard seismometer. The FOG-based system can be easily relocated and installed without dedicated infrastructure, which makes it a perfect candidate for mobile seismic measurements.

In contrast to the beat frequency of a ring laser, the output signal of fibre-optic interferometer is a phase shift $\Delta\varphi$ between the two counterpropagating light beams, which is directly proportional to the rotation rate Ω. The explicit relationship is defined by the equation

$$\Delta\varphi = \frac{4\pi RL}{\lambda c}\Omega, \tag{2}$$

where R is the mean radius of the coil; L is the total length of the fibre; λ is the light source wavelength; and c is the speed of light. The advantage of the fibre technology is that one can enlarge the scale factor of the interferometer by increasing the number of fibre coils that form the light propagating cavity (consequently increasing the fibre length). In general, modern fibre-optic rotation sensors utilise two schemes of output signal processing: open-loop and closed-loop. The open-loop design allows for high linearity of the output signal at a near-zero rotation rate, while the closed-loop sensors achieve higher signal stability over a large input range. The latter scheme is rather complicated due to the presence of phase-nulling feedback, but may reach an accuracy level comparable with that of conventional ring lasers [12]. On the other hand, open-loop FOGs are well suited for seismology due to the high accuracy they have at low rotation rates, their more simple design and the availability of an analogue output.

The resolution of the open-loop fibre-optic gyro is limited by the random walk, which is a combination of various noises in the sensor. The major noise sources are the shot noise, relative intensity noise and detector noise. These can be minimised by using a better light source, as well as utilising noise suppression schemes and ensuring detector stabilisation. The usual accuracy margin of modern open-loop FOGs lies within $0.1-1$ deg h^{-1} of the drift rate (the output signal noise $0.0015-0.15$ deg $h^{-1/2}$) [13]. This performance is sufficient to cover the upper range of seismic rotation amplitudes introduced by near-field events.

In order to verify the abilities of FOGs to measure the seismic rotations, a number of experiments have been carried out by our research group. The first prototype of a large fibre interferometer (G-FORS) was built in the Wettzell Geodetic Observatory in Germany in 2006. It consists of 2.2 km of fibre wrapped around the 2.1 meter radius base plate of the G ring laser. The idea behind this simple design was to increase the scale factor of the fibre interferometer and to take advantage of the very stable environmental conditions inside the laboratory, which lead to stable operations of the FOG itself. The initial operation of the instrument showed that the large FOG possesses a reasonable accuracy level in comparison with the G ring laser (see Fig. 6). The noise level of the G-FORS is found to be approximately 30 nrad s^{-1}.

More recent tests of industry standard moderate accuracy fibre-optic gyroscopes also demonstrate their abilities to measure rotational signals equivalent to those produced by near-field earthquakes with good precision.

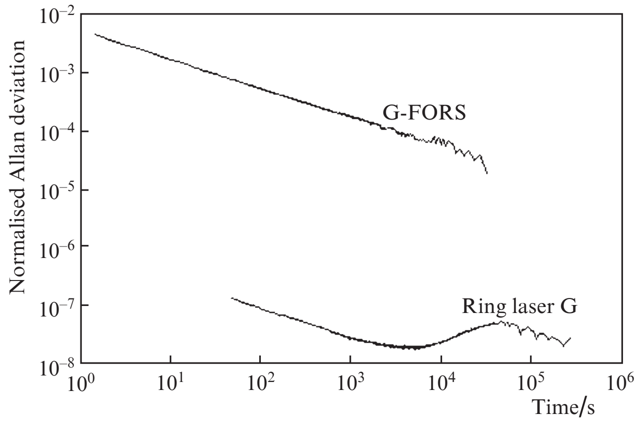

Figure 6. Comparison of G and G-FORS resolution levels.

4. Future outlook

The current state of development in large ring lasers allows various geophysical and seismological effects to be detected. It is important to note that these instruments are presently the only ones which can directly measure geophysical and seismological effects at a single surface point. Further improvement in these sensors will necessarily extend the stable operation time, which can be achieved by stabilising the operational conditions of the ring lasers as well as reducing the effects of backscatter. The latter can be realised through dedicated data processing techniques and recording additional operational parameters of the ring laser. The joint operation of VLBI with large ring lasers and the combination of these measurements will allow for nearly real-time precise estimation of the length of day and the orientation parameters of the Earth.

Seismic rotations can be detected by large ring lasers (particularly for teleseismic events) as well as fibre-optic gyro-based measurement systems dedicated to mobile near-field strong motion recordings. The current seismic network can be expanded by utilising base stations equipped with large ring lasers as well as FOG-based modules for field campaigns.

5. Conclusions

The ring laser project, a combined effort between the University of Canterbury (New Zealand), the Technische Universität München (Germany) and the Bundesamt für Kartographie und Geodäsie (Germany), has over the course of two decades successfully built and improved a series of eight different ring lasers of various sizes and quality. To date, the G ring laser in Germany has evolved to be the most stable and best performing gyroscope on the Earth. While it is about four orders of magnitude behind the Gravity Probe B gyroscope performance in the micro-gravity environment of a near Earth orbit after post processing ($\sim 8\times 10^{-16}$ deg s^{-1} [14]), it surely outperforms other technological efforts in the field of gyroscopy, such as the Josephson effect rotation sensors in superfluid ^{4}He interferometers with a total resolution of about $\sim 8\times 10^{-9}$ rad s^{-1} $Hz^{-1/2}$ [15]. Gustavson et al. reported a short term sensitivity (with 1 s of integration time) of $\sim 6\times 10^{-10}$ rad s^{-1} for their cold atom interferometer [16]. However, despite all the progress in rotation sensing techniques of the recent years, none of the alternative measurement concepts have reported the measurement of any slowly changing geophysical effects coming from actually strapping down such a device to the Earth. While helium–neon ring laser instruments are eventually technically limited by the Q factor of the cavity and hence super-polish quality of the mirrors, the ultimate limit of Sagnac interferometry as a novel technique of precisely measuring Earth's rotation eventually appears to be strongly linked to the question of how well an instrument can be attached to the ground to provide a global measurement quantity from a local sensor.

Acknowledgements. This work was supported by the Bundesamt für Kartographie und Geodäsie (Germany), the Deutsche Forschungsgemeinschaft (DFG) under contract FOR-584 and through the Marsden fund of the Royal Society of New Zealand, research contract UOC106. A. Velikoseltsev acknowledges support from the Federal targeted programme 'Scientists and Science Educators of Innovative Russia in 2009–2013'.

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