Advances in high resolution inertial rotation sensing

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Large ring lasers have improved significantly in recent years, such that we are now in the position to separate and mitigate error sources that are not directly related to the rotation sensing process from the Sagnac interferogram. As a result, we are now able to reduce the measurement error of the 16 m^2 G ring laser of the Geodetic Observatory Wettzell by a factor of two. Improvements in the measurement of the relevant parameters for the backscatter correction remove most of the sensor drift effects, so that the backscatter induced coupling is no longer a real concern. Now that we can separate the mechanisms of the error contributors much better, we can mitigate them in a more effective way. In this paper we report on the latest progress.

1. Introduction

The rotation rate of the Earth and the orientation of the rotational axis of the Earth in space are the quantities which link the terrestrial (ITRF) and the celestial (ICRF) reference frames. Until now, the only way of obtaining the rotational velocity of the Earth as well as the variation of the orientation of the respective rotational axis with sufficient accuracy has been to interferometrically observe a set of radio sources - quasars at the perimeter of the observable universe form an external set of stable markers. This can be used to link the respective reference frames together. Today residuals of about 10 μs for the measurement of the Length of Day (LoD) and 0.5 nrad (0.1 milli-arc-seconds) for measurement of the pole position are achieved by a network of VLBI radio telescopes and GNSS observations[1,2]. These efforts are carried out by the services of the International Association of Geodesy (IAG). The operation of such a large network requires a significant number of radio telescopes and a very substantial maintenance and processing effort. Huge amounts of data of up to 1 Tb of volume per radio telescope are recorded in each of the 24h measurement sessions, which until recently required physical transport over large intercontinental distances to perform the correlation process in the analysis centers. Data latency, combined with the fact that there is no continuous measurement coverage, suggests that complementary methods for the accurate estimation of Earth rotation and polar motion should be explored. Optical Sagnac interferometry offers an independent technical approach. This is desirable in order to identify any technique related biases if they exist. Large ring lasers are potential candidates for such an alternative measurement technique. This technology is widely used in inertial aircraft navigation and can measure angular velocities absolutely, i.e. independent from an external reference frame. The beat note, δf, of two counter propagating mono-mode laser beams in the ring cavity is proportional to the experienced rate of rotation Ω of the entire apparatus and is described by the ring laser equation

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

where A is the area circumscribed by the laser beams, P the corresponding perimeter, λ the optical wavelength and $\mathbf{n}$ the normal vector on the plane of the laser beams. However, the demands on such instruments for the application in geodesy are extremely high, and cannot be met by existing commercial devices. These requirements can be summarized as below:

- sensitivity to angular motion of less than 0.1 $prad/s$ over an integration time of about 1 h
- sensor stability of 1 part in 10^9 over several months (requirement for the measurement of the Chandler and Annual Wobble with high temporal resolution)
- resolution for the sensor orientation of approximately 1 $nrad$, corresponding to a polar motion effect of around 1 cm at the pole

All these requirements demand a substantial improvement of ring laser technology over existing navigational instrumentation in all aspects of the sensor design. A significant upscaling of the physical parameters of the Sagnac interferometer is the most promising approach in order to make ring lasers a viable technique for applications in space geodesy. The design of the large ring laser gyro G (Grossring), located at the Geodetic Observatory Wettzell in eastern Bavaria is one way of approaching these demands[3]. This single axis gyro is a 16 meter perimeter square ring laser with a length of 4 m on each side, which utilizes a mixture of helium and neon as a gain medium, similar in many ways to the well established systems used in aircraft navigation. However, the vastly increased size of the G ring laser with a Q factor well in excess of 5×10^{12} provides a measurement sensitivity to angular velocities, much higher than any other rotation sensing instrument on the ground. A nearly monolithic sensor block design from the low thermal expansion material ZERODUR located in an underground laboratory provides the necessary passive mechanical stability of the G ring laser body for the desired level of performance. The ring laser G has now matured to the point where small geophysical signals with very long periods such as the Chandler and Annual wobble of the rotating Earth are measurable[4]. This has not been achieved through higher sensitivity but rather through considerable improvements in the overall cavity stability[5]. Such long-term laser stabilization is one of the key requirements for the proposed terrestrial measurements of general relativistic phenomena such as the Lense–Thirring (or frame-dragging) effect[6–8].

2. Backscatter Correction

The most important contributor to the sensor drift arises from the backscatter coupling between the two counter-propagating laser beams, causing frequency pulling and pushing. This quantity is not constant over time, but strongly depends on the phase of the laser beam as it hits each mirror. Variations in ambient temperature and atmospheric pressure cause a tiny change in mirror separation and hence a slow variation in the backscatter coupling. While atmospheric pressure variations can be controlled with the installation of a pressure stabilizing vessel, isolating the ring laser from the rest of the laboratory, changes in temperature are not well enough controlled for a structure as large as G. While the temperature inside the ring laser vessel only varies at a level of 3 – 5 mK per day following the annual temperature cycle of the seasons, this is enough to cause a significant drift of the observed interferometer beat note. By observing the amount of backscattered light in each of the laser beams, a correction value Δf_S can be computed according to Ref. 9 as

$$\Delta f_S = \frac{1}{2} f_S m_1 m_2 \cos\varphi, \tag{2}$$

where f_S is the observed beat note, m_1 and m_2 are the fractional beam modulations and φ the phase angle between them. For a given mirror quality, m_1 and m_2 scale approximately as $L^{-2.5}$ for a cavity of linear size L. The ratio of the correction to the observed interferometer beat note to the beat note itself scales approximately as L^{-5}. This shows how important it is to make the ring laser cavity as large as possible, while sufficient mechanical stability of the entire structure has still to be maintained. In the absence of active control mechanisms it appears that a symmetrical construction with a length of 6 – 10 m on a side seems to be feasible for a large ring laser structure.

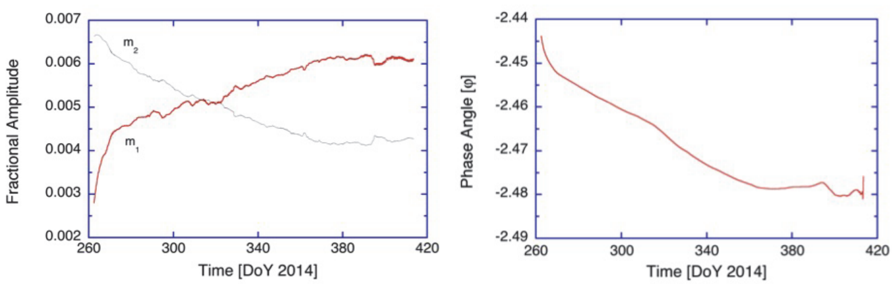

Fig. 1. The parameters m_1, m_2 and φ of the backscatter correction (Eq. (2)) of a time series of 130 days of length. Due to the mechanically monolithic construction of the G ring laser and the active pressure stabilized environment of the gyroscope, there are only small changes in the backscatter pulling observable.

Figure 1 shows the observed variation of the fractional beam modulations and the phase angle between them over a period of more than 130 day. Since this dataset was taken with the atmospheric pressure stabilizing vessel in operation, the observed variations of the correction quantities m_1, m_2 and φ are entirely caused by temperature variation. When these corrections are applied to the gyro observations, we are able to remove the backscatter induced drift in the observation of the Earth rotation signal. However, some short-term fluctuations and some irregular steps still remain in the measurement signal. This signature compares well with the tiltmeter readings obtained from a high resolution tilt sensor, placed on top of the ring laser structure. Figure 2 depicts the observed Earth rotation rate after the backscatter correction has been applied to the full 130 days of observation.

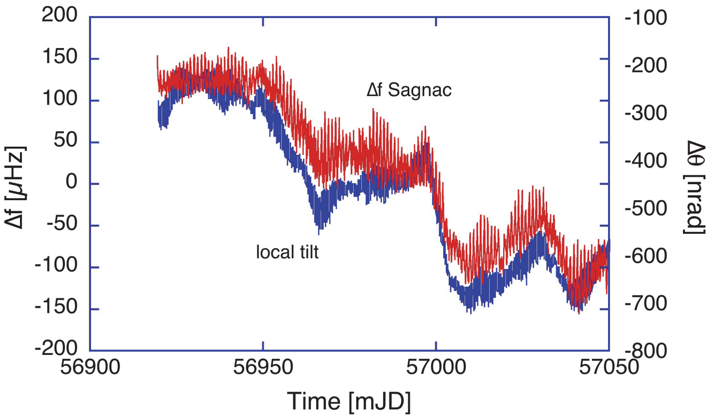

Fig. 2. 130 days of ring laser observation of Earth rotation velocity. After the backscatter correction procedure has been performed, the effects of a number of geophysical signals, like local tilt, diurnal polar motion, solid Earth tides, the Chandler and the Annual wobble remain.

The lower (blue) curve, corresponding to the variation of local g over the same period of time, shows the changes experienced in the North/South tilt of the ring laser monument. The step like drops in $\Delta\Theta$ after day 56950 and around 57000 correspond to the response of the ring laser monument to significant rain falls at the observatory. The response of the tiltmeter corresponds well with the trend in the observed gyro signal represented in the same diagram in the upper (red) curve. After the tilt correction we have computed the known geophysical signals, which cause a change of the projection of Ω on the area vector of our Sagnac interferometer. Figure 3 represents the combined effect of all known signals over the length of the measurement. The section between the two dashed lines is shown enlarged in the inset in order to emphazise the fine structure of the signals. $\Delta\Omega$ is expressed in the units of the observed beat note in accordance with Eq. (1).

Once all the model corrections (diurnal polar motion, solid Earth tides, ocean loading and the variation of latitude) are applied, the Chandler and the Annual wobble, as measured by VLBI are also reduced from the data. The result is a continuous dataset of the rotation rate of the Earth with a spacing of 1 hour between

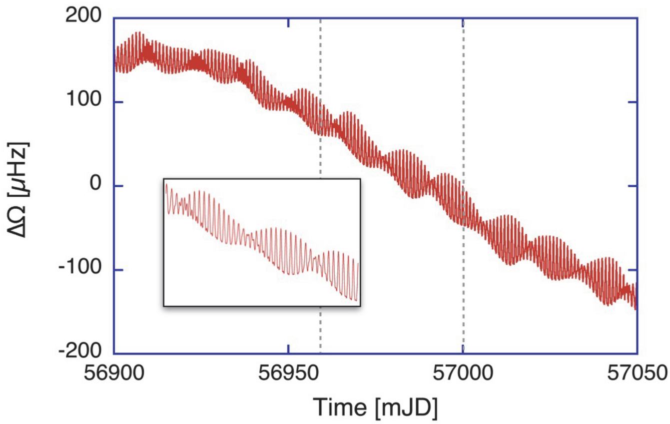

Fig. 3. The combined effect of the known geophysical signals, which have an effect on the North - South projection of the instantaneous Earth rotation vector onto the area vector of the laser gyro. The abscissa shows the variation of the measured angular velocity, expressed as a variation in the beat note of the Sagnac interferogram, derived from Eq. (1). The area between the two dashed lines is shown enlarged in the inset.

the data points as shown in Fig. 4. Although some small short-term variations at the level of less than 1 part in 10^7 remain, a stable rotation rate is obtained over the full span of 130 days. The successful observation of a continuous long dataset of

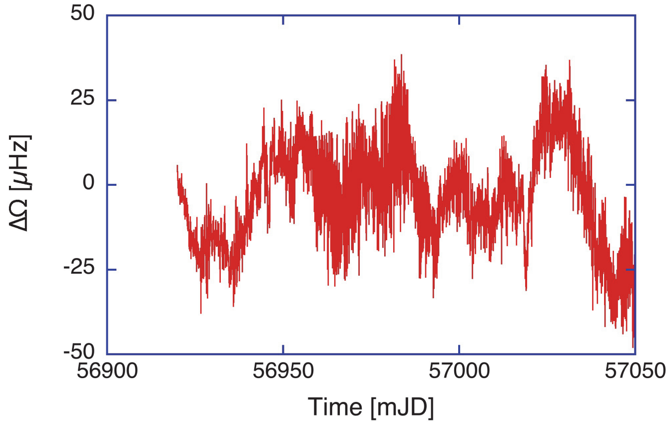

Fig. 4. The backscatter corrected Earth rotation rate over 130 days of observation. Each data point was averaged over 1 hour and the known geophysical signals have been removed from the measurements. The abscissa shows the variation of the measured angular velocity expressed as a variation in the beat note of the Sagnac interferogram, derived from Eq. (1).

high resolution ring laser observations of the Earth rotation velocity over 130 days marks a great progress in the application of Sagnac interferometers on geodetic observations. We note in particular the stability of the measurements. Despite getting close to the target of a gyroscopic observation of the variations in the length of day (LoD), we are not quite there. However the short-term variation is within a factor of two of the order of the typical amplitude of LoD variations. It would appear that small variable non-reciprocal effects are playing a role.

3. Conclusion

Although the application of the backscatter correction has improved the long-term stability of our G ring laser to $\Delta\Omega/\Omega \leq 10^{-7}$ over the entire measurement series, we still consider this work in progress. We have identified the tiltmeters as one weak link in our correction process for a single component ring laser. In addition, the backscatter correction procedure itself will have limitations. The long term stability for the measurement of the fractional amplitudes as well as the corresponding phase angle, remains to be proven. In order to use laser gyros for fundamental physics, it is important to have a three component ring laser of sufficient size in operation. Furthermore it appears to be desirable to locate this gyro in a deep underground facility, such that seasonal temperature variations, excessive noise from the interaction between wind and the top soil and the variability of the hydrology are considerably reduced. Since the Lense-Thirring frame dragging effect appears as a DC quantity, it is also necessary to determine the absolute scale factor of the instrument in order to contribute to fundamental physics. However this ambitious goal appears to be much more practical now than several years ago.

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References

1. R. Haas; *Investigating High-Frequency Earth Orientation Variations with Continuous Geodetic VLBI Campaigns*; IVS 2006 General Meeting Proc. (Concepcion, Chile), pp. 316–319, (2006).
2. M. Rothacher, G. Beutler, R. Weber, J. Hefty; *High-frequency variations in Earth rotation from Global Positioning System data*; J.Geophys.Res., **106** (B7), 13711, (2001).
3. 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*; J. Pure Appl. Geophys., **166**, 1485 (2009).
4. Schreiber, K. U., Klügel, T., Wells, J.-P. R., Hurst, R. B., Gebauer, A. *How to detect the chandler and the annual wobble of the earth with a large ring laser gyroscope*, Phys. Rev. Lett., **107**(17), 173904-1, (2011). http://doi.org/10.1103/PhysRevLett.107.173904.

5. K. U. Schreiber and J.-P. R. Wells; Rev. Sci. Instrum. **84**, 041101 (2013).
6. Everitt, C. W. F., DeBra, D. B., Parkinson, B. W., Turneaure, J. P., Conklin, J. W., et *Gravity Probe B: Final Results of a Space Experiment to Test General Relativity*, Phys. Rev. Lett., **106**(22), 221101, (2011); http://doi.org/10.1103/PhysRevLett.106.221101.
7. I. Ciufolini, E. C. Pavlis, F. Chieppa, E. Fernandes-Vieira, and J. Perez-Mercader; Science 279, 2100 (1998).
8. Bosi, F., Cella, G., Di Virgilio, A., Ortolan, A., Porzio, A., Solimeno, S., et al. *Measuring gravitomagnetic effects by a multi-ring-laser gyroscope*, Phys. Rev. D, **84**(12), 122002, (2011); http://doi.org/10.1103/PhysRevD.84.122002.
9. Hurst, R. B., Rabeendran, N., Schreiber, K. U. and Wells, J.-P. R.; *Correction of backscatter-induced systematic errors in ring laser gyroscopes*, Appl. Opt, **53**(31), 7610–7618, (2014), http://doi.org/10.1364/AO.53.007610.