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# Combining VLBI and ring laser observations for determination of high frequency Earth rotation variation

T. Nilsson[a,*], J. Böhm[a], H. Schuh[a], U. Schreiber[b], A. Gebauer[b], T. Klügel[c]

[a] Institute of Geodesy and Geophysics, Vienna University of Technology, Vienna, Austria
[b] Technische Universität München, Forschungseinrichtung Satellitengeodäsie FESG, Fundamentalstation Wettzell, Bad Kötzting, Germany
[c] Bundesamt für Kartographie und Geodäsie BKG, Fundamentalstation Wettzell, Bad Kötzting, Germany

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ABSTRACT

Data from the Wettzell ring laser gyroscope are combined with Very Long Baseline Interferometry observations in order to estimate polar motion and Universal Time with hourly resolution. The combination is done at the normal equation level. Data from the period 1 May to 14 October, 2010, are used. We find that the impact of the ring laser data is normally relatively small since presently the accuracy of VLBI is about one order of magnitude better than the accuracy of the ring laser measurements. However, in cases when the accuracy of VLBI is of the order of 1 mas or worse the ring laser improves the accuracy of the estimated parameters, especially for y-pole and Universal Time. For the whole period, the combination on average improves y-pole by 16% and Universal Time by 12% compared to when using only VLBI data.
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## 1. Introduction

The rotation angular velocity and the direction of the rotation axis of the Earth undergo small variations in time. These variations occur at a number of different time-scales from several decades down to sub-diurnal scales. These variations are caused by different excitations of the Earth rotation, like gravitational torques and processes in the atmosphere and the oceans. It is important to monitor and model these variations in Earth rotation for a number of reasons. For example, we need to know the orientation of the Earth for all types of precise positioning and navigation on the Earth and in space. Furthermore, by studying the variations in Earth rotation we get valuable information about the excitations causing the variations and how these interact with the Earth.

Normally the rotation of the Earth is measured with daily resolution, while models are used to describe the diurnal and sub-diurnal variations. The IERS (International Earth Rotation and Reference Systems Service) recommends in its Conventions (Petit and Luzum, 2010) a model for these variations consisting of two parts: the main part is a model for the high frequency variations caused by ocean tides (an extension of the Ray et al. (1994) model), the other part is a model of the variations caused by luni-solar torques on the non-axisymmetric part of the Earth (libration). Many studies (e.g. Steigenberger et al. (2006), Englich et al. (2008), Nilsson et al. (2010), Artz et al. (2010)) however detected deficiencies in this model. These deficiencies can for example be due to errors in the ocean tidal model used to develop the IERS model or due to excitations not included in the IERS model, e.g. diurnal and sub-diurnal atmospheric excitations (Brzezinski et al., 2002). As it is important to understand these deficiencies in order to improve the model we need accurate measurements of the variations in the Earth orientation with sub-diurnal resolution.

Presently, the Earth Orientation Parameters (EOP) are mainly measured using space geodetic techniques such as Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS). Both VLBI and GNSS are able to estimate variations in polar motion and in Universal Time (DUT1 = UT1–UTC, where UT1 is dependent on the rotation angle of the Earth and UTC is determined by atomic clocks) with hourly resolution. The two techniques have their own strengths and weaknesses. For example, GNSS is able to provide continuous EOP from a large (>100 stations) global network of GNSS receivers; however it is sometimes problematic to separate EOP variations from variations in the GNSS satellite orbits (especially at diurnal and sub-diurnal frequencies) (Rothacher et al., 2001). VLBI does not have this problem since it observes distant quasars which can be considered not to be moving. On the other hand VLBI normally observes with only a few stations (typically less than 10 during one so-called session of 24 h) making it very sensitive to station specific errors, and the observations are not continuous (typically only two or three 24 h sessions are observed per week).

Ring laser gyroscopes are instruments that can be used to measure rotation. These are commonly applied in e.g. the navigation

* Corresponding author. Tel.: +43 15880112839; fax: +43 15880112896.
*E-mail addresses:* tobias.nilsson@tuwien.ac.at, tbsnilsson@gmail.com (T. Nilsson).

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systems of aircrafts and ships. Advances in the ring laser technology over the last 10 years have made it possible to construct large and very accurate ring lasers which are able to sense variations in the rotation of the Earth, as well as other rotations of geophysical origin (Stedman, 1997). For example, the so-called Oppolzer terms (forced diurnal polar motion, Frede and Dehant (1999)) in the instantaneous rotation pole of the Earth have been successfully detected using ring lasers (Schreiber et al., 2004). Ring lasers are mostly sensitive to the high frequency variations in the Earth rotation, while they are not so useful for determining the low frequency variations and the mean values of the EOP. First of all, in order to estimate the complete Earth rotation vector, at least three ring lasers with different orientations would be needed. Furthermore, there are commonly unknown offsets (and drifts) in the ring laser measurements, making it impossible so far to estimate the mean values of the EOP. However, ring lasers could potentially be useful in a combination with other techniques to estimate accurate high frequency EOP (Mendes Cerveira et al., 2009b).

In this work we investigate the potential usage of ring laser observations by combining them with VLBI measurements. We use five and a half months of measurements from the Wettzell "G" ring laser and combine these on the normal equation level with the data from VLBI sessions observed during these months.

## 2. Ring laser and VLBI data

A ring laser is sensitive to the projection of the instantaneous rotation vector in the terrestial reference frame, $\vec{\Omega}$ ($\vec{\Omega} = \Omega_0\,[m_x,\ m_y,\ 1+m_z]^T$, where $\Omega_0$ is the mean angular rotation speed of the Earth), on to the normal $\vec{n}$ of the ring laser. The Sagnac frequency $f_{sag}$ observed by a ring laser is given by (Mendes Cerveira et al., 2009a; Schreiber et al., 2009):

$$f_{sag} = A\vec{\Omega}\cdot\vec{n} + f_{instr} \qquad (1)$$

where $A$ is a constant and $f_{instr}$ is an instrumental offset. Normally, the actual Sagnac frequency measurements are not used but rather the relative Sagnac frequencies given by (for a horizontally mounted ring laser):

$$\begin{aligned}\Delta S &= \frac{f_{sag}}{A\,\vec{\Omega}_0\cdot\vec{n}_0} - 1\\ &= \cot(\phi)[m_x\cos(\lambda) + m_y\sin(\lambda)] + m_z + \Delta S_{tilt} + \Delta S_{instr}\end{aligned} \qquad (2)$$

where $\vec{n}_0 = [\cos(\phi)\cos(\lambda),\ \cos(\phi)\sin(\lambda),\ \sin(\phi)]^T$ (i.e. the direction the normal would have if the ring laser would be mounted perfectly horizontal), $\phi$ and $\lambda$ are latitude and longitude of the ring laser, respectively, $\vec{\Omega}_0 = \Omega_0\,[0, 0, 1]^T$, $\Delta S_{tilt}$ is the error caused by a tilt of the ring laser, and $\Delta S_{instr}$ is the instrumental error.

Fig. 1 shows the tilt-corrected measurements from the Wettzell "G" ring laser for the period 1 May to 14 October 2010, as well as the expected variations in the relative Sagnac frequency due to EOP variations. The latter was calculated using Eq. (2) with EOP obtained from the IAU 2000A precession/nutation model (Mathews et al., 2002), the IERS 05 C04 EOP series (Bizouard and Gambis, 2009), and the IERS high frequency EOP model (Petit and Luzum, 2010). Most of the high frequency variations in the ring laser data are explained by the variations in EOP. However, there are some variations over longer time scales seen in the measurements which are not explained by the EOP variations. In the beginning of the period these are relatively small, but in the second half of the period (i.e. after day 210 of the year 2010) there is a significant drift. This is most likely due to instrumental effects. In order to successfully combine the ring laser measurements with VLBI, such drifts must be considered and corrected for.

In order to know what weight to give to the ring laser data in a combination we need to know its accuracy. This was estimated by first removing the variations caused by EOP from the observed data, then subtracting the long-term variations by a high-pass filter, and finally calculating the RMS of the remaining residuals. Doing this, we obtained a value of $1.3\times10^{-8}$ for the RMS error of the ring laser measurements, which might not be completely due to measurement noise (although this is probably the dominating part) but could for example also be due to errors in the IERS C04 series or in the IERS high frequency model. Thus we use a slightly lower number for the ring laser accuracy: $1.0\times10^{-8}$.

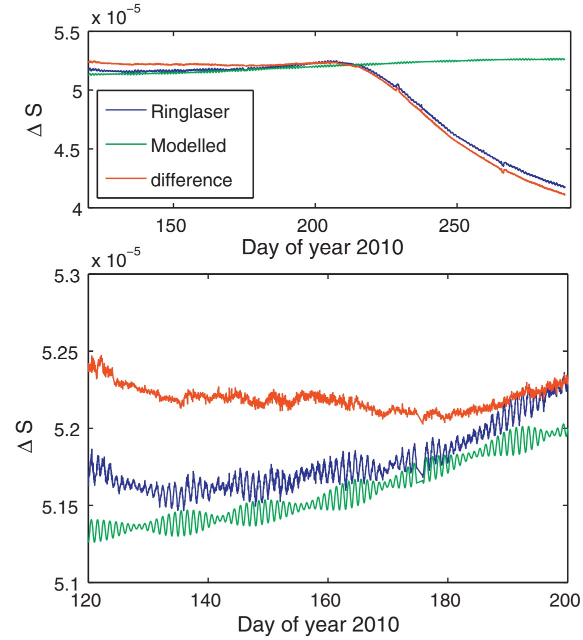


**Fig. 1.** Measured relative Sagnac frequencies ($\Delta S$) by the Wettzell ring laser (blue). Green lines show the $\Delta S$ expected due to EOP variations (offset by $5.2\times10^{-5}$ for better visibility). Red line shows the difference between the measured and modelled $\Delta S$. Upper plot shows the period 1 May to 14 October 2010, lower plot is a zoom in of the first 80 days of the period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In VLBI distant quasars are simultaneously observed by several radio telescopes on the Earth. By comparing the signals received by the different telescopes, the difference in travel time of the signals can be estimated. These time differences depend upon the lengths of the baselines between the telescopes and their directions in a Celestial Reference Frame (CRF). Thus, with VLBI it is possible to estimate (among other parameters) the orientation of the Earth in space, i.e. the transformation matrix between the Terrestial Reference Frame (TRF) and the CRF. Since the rotation of the Earth causes the orientation of the Earth to change in time, VLBI can be used for studying Earth rotation. However, since it is complicated to express the transformation between the TRF and the CRF using the instantaneous rotation pole of the Earth (especially if there are large diurnal and sub-diurnal variations in the pole), another pole is normally used for describing the transformation: the Celestial Intermediate Pole (CIP) (Capitaine, 2002). This is a pole defined to be close to the instantaneous rotation pole, but containing no variations in the CRF with periods less than 2 days. In VLBI data analysis typically the coordinates of the CIP in the TRF (polar motion, $x_p$ and $y_p$) and in the CRF (nutation, $dX$, and $dY$), as well as the rotation angle of the Earth (normally given by $DUT1$), are estimated. These five parameters are referred to as the EOP. Since there are five EOP while only three independent parameters are needed to describe the transformation between two reference frames, conventions are needed to separate polar motion from nutation. According to the definition of the CIP nutation is limited to the frequency range $[-\Omega_0, +\Omega_0]$ and there is no polar motion in the frequency range $[-1.5\Omega_0, 0.5\Omega_0]$.

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