Earth Rotation Determination by Combining Ring Laser Gyroscopes and VLBI

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Abstract Very Long Baseline Interferometry (VLBI) and ring laser gyroscopes are two techniques that sense the rotation of the Earth using different approaches; the former uses a geometric approach while the latter is based on a dynamic one. Combination of the two techniques could improve the determination of high frequency variations of Earth rotation. An attempt to combine recent data sets for the period from August 2011 until October 2013 of the "G" ring laser in Wettzell and VLBI observations was performed. In the cases where the VLBI data had a lower EOP sensitivity, the inclusion of the ring laser data could improve significantly the y-pole and the DUT1 estimates.

Keywords Earth rotation, VLBI, ring laser

1 Introduction

The rotation speed and the direction of the rotation axis of the Earth experience small variations in time. The variations at different scales are caused by various excitations of Earth rotation such as gravitational torques and processes in the atmosphere and the oceans. The rotation of the Earth is not uniform. It is described by the Earth Orientation Parameters (EOP). Presently, the EOP are mainly determined using space geodetic techniques such as GNSS and VLBI. GNSS is the most precise technique for observing polar motion, while VLBI is unique for measuring the coordinates of the Celestial Pole and DUT1. However, a novel technique called ring laser gyroscopes can be used to observe the instantaneous Earth rotation vector, which is different from (but related to) the Celestial Intermediate Pole (CIP) measured by geodetic techniques. Ring lasers are sensitive to high-frequency variations in Earth rotation and can provide an independent method for monitoring Earth rotation without the requirement of an external reference frame. One main drawback of this technique is that the ring laser measurements contain unknown drifts and offsets. Thus, combined with a space technique, ring lasers could be used for the estimation of precise high frequency EOP. A first successful attempt at combining VLBI observations and data from the "G" ring laser at Wettzell was done by Nilsson et al. (2012a). Because the accuracy of VLBI is about one order of magnitude better than the ring laser, the ring laser data had only a small impact in the combination. However, the quality of the ring laser data has been improving in terms of precision and stability within the last few years. In this work, an investigation of the potential gain from the combination of the two different techniques is made by using recent data sets for the period from 2011 until 2013.

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2 Ring Laser Gyroscopes

Ring laser gyroscopes are instruments that can sense rotation about their sensitive axis. These sensing elements are commonly used in navigation systems for aircraft and marine applications. However, over the last two decades, a series of large ring lasers has been built in order to increase the scale factor and thus the precision of the measurements. These large ring lasers improved the sensitivity compared to commercial gyroscopes by more than six orders of magnitude (Schreiber et al., 2013). Thus, ring laser gyroscopes can be used for applications in geodesy by sensing high frequency variations in the rotation of the Earth.

In a ring laser gyroscope, two beams are transmitted in opposite directions. At the point at which the two laser beams interfere, the "Sagnac" frequency can be measured. This beat frequency is proportional to the rotation frequency of the ring, i.e., proportional to the projection of the rotation vector of the Earth onto the normal direction of the ring if the ring is fixed to the Earth's surface. The Sagnac frequency observed by a ring laser is given by:

$$\Delta f_{SAG} = S \cdot \vec{n} \vec{\Omega} \tag{1}$$

where S is the scale factor, $\vec{n}$ the normal unit vector and $\vec{\Omega}$ the rotation vector of the Earth which can be written as $\vec{\Omega} = \Omega_0[m_x, m_y, 1 + m_z]^T$. Ω_0 is the nominal value of the Earth rotation frequency and the terms m_x, m_y, m_z are related to polar motion (x_p and y_p) and DUT1 determined by space geodetic techniques such as VLBI (Brzezinski and Capitaine, 1993):

$$m = p - \frac{i}{\Omega}\frac{\partial p}{\partial t} \tag{2}$$

$$m_z = \frac{\partial DUT1}{\partial t} \tag{3}$$

where $m = m_x + im_y$ and $p = x_p + iy_p$.

The Sagnac frequency Δf is not stable but instead is drifting. Therefore the relative Sagnac frequency ΔS is used. For a horizontally mounted ring laser, the relative Sagnac frequency can be approximated by the following formula:

$$\Delta S = \cot(\phi)[m_x \cos(\lambda) + \sin(\lambda)] + m_z + \Delta S_{tilt} + \Delta S_{instr} \tag{4}$$

where ϕ and λ are the latitude and longitude and ΔS_{tilt} and ΔS_{instr} are the errors caused by the tilt and the instrument, respectively. Equations (2), (3), and (4) enable the ring laser observations to be expressed as a function of geodetic EOP.

3 VLBI and Ring Lasers

VLBI is sensitive to the complete rotation matrix between the network of terrestrial VLBI antennas being part of the ITRF (Altamimi et al., 2011) and the radio sources realizing the ICRF (Fey et al., 2009). The transformation between the two different Reference Frames is realized with the use of the Celestial Intermediate Pole (CIP). The CIP was introduced instead of the Instantaneous Rotation Pole (IRP) for simplicity. VLBI can determine the full set of the EOP:

- the coordinates of the CIP w.r.t. ICRF which rigorously describe the effects of precession, nutation, and frame bias,
- the coordinates of the CIP in the TRF (polar motion, x_p and y_p), and
- the rotation angle of the Earth (DUT1).

Ring laser gyroscopes can directly measure the position of the instantaneous rotation axis of the Earth including the Oppolzer terms. Figure 1 shows the measured relative Sagnac frequencies from the "G" ring laser mounted at the Geodetic Observatory Wettzell, corrected for the latitudinal tilt variations and the expected values due to EOP variations for the period from 5 September 2011 until 18 January 2012. The computed values were obtained from Equation 4, using the IAU 2000/2006A precession nutation model, an EOP series estimated from the Vienna VLBI software VieVS (Böhm et al., 2012) and the IERS high frequency EOP model (Petit and Luzum, 2010). At the beginning, the measured and the modelled relative Sagnac frequencies show small variations, while starting at about the middle of the period there is a significant drift. This drift is apparently caused by instrumental effects.

4 Data Analysis

The combination of the ring laser and the VLBI data was performed at the normal equation level (Nilsson et al., 2012b). Using the software VieVS, approximately 170 IVS-R1, IVS-R4, and CONT11 VLBI sessions were analyzed for the period from August 2011 until October 2013. For each session the normal equation matrices N_{VLBI} and the vectors of the right hand side b_{VLBI} were set up by the software. Polar motion and

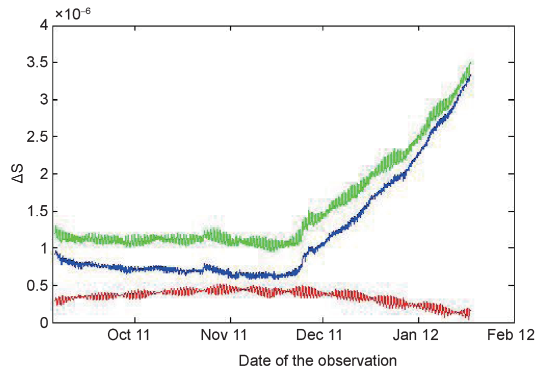

Fig. 1 Measured relative Sagnac frequencies ΔS by Wettzell ring laser (green (top) line). Expected values of ΔS due to EOP variation from VLBI (red (bottom) line). Difference between the modeled and the measured ΔS (blue (middle) line).

DUT1 were estimated with an hourly resolution, while the celestial coordinates of the CIP were fixed to the IAU 2006/2000A model plus the IERS 08 CO4 correction. The celestial coordinates of the CIP could not be estimated with an hourly resolution, because high correlation between the polar motion and celestial coordinates of the CIP would occur. Polar motion and DUT1 were computed by solving the normal equation system through the combination of the normal equation matrices of VLBI and ring laser:

$$N = N_{VLBI} + N_{RLG} \quad (5)$$

$$\vec{b} = \vec{b}_{VLBI} + \vec{b}_{RLG} \quad (6)$$

where N_{VLBI} and $\vec{b}_{VLBI}$ were obtained as described in Nilsson et al. (2012b).

5 Results

The estimates of polar motion and DUT1 were computed using two approaches: (i) from VLBI data only and (ii) combining VLBI and ring laser data. In order to compare the results from the two different approaches, the Root Mean Square (RMS) difference relative to the a priori IERS 08 C04 and the IERS high frequency EOP model were computed. Tables 1-3 show the mean RMS of the estimated polar motion and DUT1 computed for the session types IVS-R1, IVS-R4, and CONT11.

Table 1 RMS difference for X-pole estimated from VLBI only and from VLBI and ring laser.

Type of Session	X-pole VLBI only [mas]	X-pole VLBI+RL [mas]	Difference ["%"]
R1	0.403	0.407	+1
R4	0.447	0.434	-2.8
CONT11	0.2735	0.2731	-0.16

Table 2 RMS difference for Y-pole estimated from VLBI only and from VLBI and ring laser.

Type of Session	Y-pole VLBI only [mas]	Y-pole VLBI+RL [mas]	Difference ["%"]
R1	0.375	0.371	-1
R4	0.623	0.583	-7.5
CONT11	0.258	0.253	-1.8

Table 3 RMS difference for DUT1 estimated from VLBI only and from VLBI and ring laser.

Type of Session	DUT1 VLBI only [μ s]	DUT1 VLBI+RL [μ s]	Difference ["%"]
R1	21.5	20.9	-2.6
R4	25.8	24.1	-6.6
CONT11	17.3	16.8	-2.8

Since the accuracy of VLBI is approximately one order of magnitude better compared to the ring laser, the RMS differences for the two solutions show rather small but noticeable improvements up to 7.5%, as presented in Tables 1-3. Larger impacts can be detected on the y-pole and DUT1. Since the location of the ring laser is at a small longitude (∼13°) and a middle latitude (∼49°), its sensitivity is greater to the x and z components of the IRP. The x component of the IRP is related to the x-pole and time derivative of the y-pole of the CIP (Mendes et al., 2009b). Therefore, for the ring laser located at Wetzell, at high frequencies it is expected that the y-pole and DUT1 would be more significantly affected than the x-pole.

Figure 2 shows the estimated polar motion and DUT1 for session IVS-T2089 (23-24 April 2013). The original purpose of the IVS-T2 type of session was to determine high quality station coordinates without optimizing the EOP. The RMS values for polar motion/DUT1 estimated using only VLBI are 0.71 mas for x-pole, 0.62 mas for y-pole, and 64 μs for DUT1. The corresponding values when combining VLBI and ring laser are 0.68 mas for x-pole, 0.52 mas for y-pole, and 61 μs for DUT1. Polar motion and DUT1 estimates therefore improve when combined with the ring

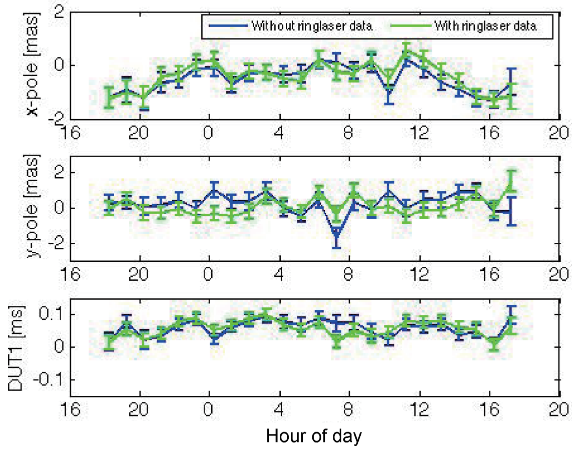

Fig. 2 Analysis of session IVS-T2089 (23-24 April 2013). The estimated polar motion and DUT1 are shown from only VLBI (blue line) and from the combination of VLBI and ring laser (green line).

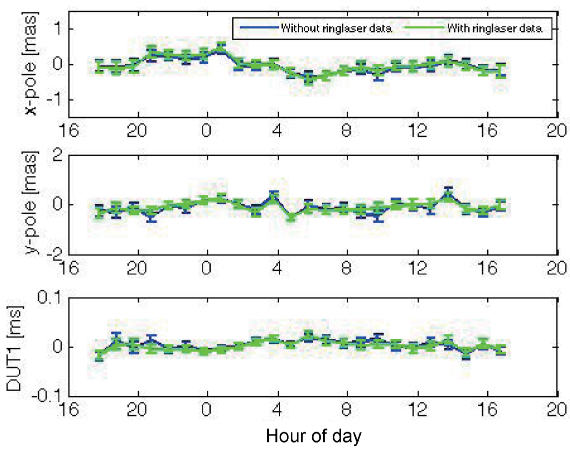

Fig. 3 Analysis of session IVS-R4574 (28-29 January 2013). The estimated polar motion and DUT1 are shown from only VLBI (blue line) and from the combination of VLBI and ring laser (green line).

laser data. The original purpose of the IVS-R4 type of session included also the accurate determination of the EOP. For session IVS-R4574 (28-29 January 2013), the VLBI data get a larger weight during the adjustment, and thus the impact of ring laser data in the combination is very small. In Figure 3, hardly any differences between the two solutions are noticeable.

6 Conclusions

The two different data types, ring laser and VLBI data, could be successfully combined for the period of August 2011 until October 2013. The inclusion of the ring laser in the combined solution with VLBI for the estimation of polar motion and DUT1 usually had a noticeable but small impact, since the accuracy of VLBI is higher. Only for the VLBI sessions where the estimates of polar motion and DUT1 had lower accuracy, the ring laser could significantly improve the results. If more ring lasers would be available, the improvement of polar motion and DUT1 estimates by ring lasers would be more significant as shown in simulations of Nilsson et al. (2012a). Furthermore, the quality of the ring laser data has improved in terms of precision and stability within the last years. If the accuracy of ring laser data continues to improve, it would be of great interest to operationally combine ring laser data and VLBI data.

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